A Multidimensional Assessment of Natural Gas as an Alternative Transportation Fuel

By

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Abstract

Natural gas vehicles (NGVs) have seen increased attention as a way to reduce reliance on petroleum (diesel/gasoline) for transportation, but adoption rates lag behind conventional vehicles. There are multiple challenges connected to a globally large scale expansion of natural gas as an alternative transportation fuel including refueling infrastructure, safety, vehicle range, natural gas supply chain emissions, engine performance, engine durability, vehicle cost, public acceptability and policy options. Therefore to maximize the benefits of natural gas as an alternative transportation fuel, these factors must be considered. The aforementioned challenges are the focus of this thesis. The overall aim of the thesis is to identify and analyze the technological, strategic and environmental aspects of compressed natural gas (CNG) as a viable alternative transportation fuel option in the international as well as in Pakistani context.

The thesis links twelve journal papers to present a cohesive body of research with the aid of 6 brief contextual chapters. The findings from the papers address three core themes in natural gas as an alternative transportation fuel. The first theme supported with five papers introduces and discusses the technical aspects of CNG technology with the particular focus on the environmental competitiveness of natural gas vehicles (NGVs), safety issues with NGVs, performance of natural gas fueled engines, durability of NGV's engine parts and current research progress in using natural gas as an alternative transportation fuel. The second theme supported with five papers discusses the strategic framework and transitions to NGVs in four particular respects: addressing the barriers towards natural gas vehicles, policy options for the development of natural gas vehicles, strategies ranking for NGVs' market and analysis of a specific CNG market by using Pakistan as a case study. The final theme supported with two paper presents a comparative life cycle (Well-to-Wheel) assessment of energy use and greenhouse gas (GHG) emission of natural gas vehicles.

The research associated with the first theme identifies comparative drawbacks and advantages of NGV technology. Some of the identified drawbacks include 15–20% loss in brake horsepower, dependence of NGVs safety on the materials, operating conditions and maintenance of CNG system, the build-up of high combustion deposit between engine's valve face and seat and lack of empirical work which examines the comparative maintenance cost-effectiveness of NGVs over total vehicle lifespan. On the other hand, the identified advantages include relatively lower

tailpipe emission of CO_2 (20-25%), CO (50-68%), PM (10-75%) and NMHC (50-70%). The research findings associated with the second theme suggest that the principle driving force in the successful removal of barriers to the growth of NGVs program is the user economics. Therefore setting CNG retail prices of 30–50% below the price of gasoline and diesel prices can play a key role in wide adoption of NGVs. In addition the findings suggest that there is no universal policy for the implementation of natural gas as a transportation fuel and it is identified that a combination of the various policy measures is required to remove the existing barriers to NGVs. The findings also suggest that, although due to the Government's consumer friendly policy and the price differential between CNG and gasoline/ diesel, the NGVs sector in Pakistan has shown significant growth but due to lack of sustainable natural gas supply plans, Pakistan's gas supplies cannot support the high demand of the CNG sector. The findings of the third theme suggest that on Well-to-Wheel (WtW) basis 80 - 89% energy consumption and 73 - 86% greenhouse gas (GHG) emissions for all fuel pathways comes from the Tank-to-Wheel (TtW) phase. Moreover on WtW basis, the GHG emissions for dedicated NGVs may be reduced by 20% and 12% against gasoline and diesel fuel.

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List of Abbreviations

ANL	Argonne National Laboratory
BP	British Petroleum
BTU	British Thermal Unit
CH4	Methane
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO2	Carbon Dioxide
COG	Center of gravity
DISI	Direct injection spark ignition
EETPL	Engro Elengy Terminal Private Limited
EIA	Energy Information Administration
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FMVSS	Federal Motor Vehicle Safety Standards
GHG	Greenhouse Gas
GNI	Gross National Income
GP	Goal Program
GREET	Greenhouse emissions and energy use in transportation
GWP	Global Warming Potential
HCNG	Hydrogen Enriched Compressed Natural Gas
HDIP	Hydrocarbon Development Institute of Pakistan
IC	Internal Combustion
IEA	International Energy Agency
IEA	International Energy Agency
IEO	International Energy Outlook
IFCO	Iran Fuel Conservation Organization
IGU	International Gas Union
IMF	International Monitoring Fund
IP	Iran-Pakistan

ISGC	Inter State Gas Systems
ISO	International Organization for Standardization
IVE	International Vehicle Emissions
LCA	Life cycle assessment
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MCDM	Multiple-Criteria Decision-Making
NFPA	National Fire Protection Association
NGVs	Natural Gas Vehicles
NMHC	Non-Methane Hydrocarbon
NOx	Nitrogen Oxides
NRC	National Research Council
OCAC	Oil Companies Advisory Council
OECD	Organization for Economic Co-operation and Developmen
OGRA	Oil and Gas Regulatory Authority
OPEC	Organization of the Petroleum Exporting Countries
PISI	Port-injection spark ignition
PM	Particulate Matter
SEM	Scanning Electron Microscope
SI	Spark Ignition
SNGPL	Sui Northern Gas Pipelines Limited
SSGCL	Sui Southern Gas Company Limited
SWOT	Strengths, Weaknesses Opportunities and Threats
TAPI	Turkmenistan-Afghanistan-Pakistan
TGA	Thermo gravimetric analysis
TtW	Tank-to-Wheel
VRI	Vehicle Refueling Index
WtT	Well-to-Tank
WtW	Well-to-Wheel
XRD	X-ray Diffractio

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Chapter 1: Introduction

1.1. Introduction

Climate change and energy security are two key challenges which are currently confronting policy-makers. In particular, one of the central concerns of the policy is to ensure the access to adequate, endurable and economical modern energy services to meet basic human needs and sustain economic growth on the one hand, while reducing greenhouse gas (GHG) emissions on the other. The transport sector is playing a key role in this challenge owing to its heavy dependence on fossil energy (gasoline and diesel) and the anticipated growing demand for road transport, particularly in developing economies (Kalghatgi, 2018; BP, 2018). Diesel and gasoline which currently share 94% of the total world energy consumption by transport sector (BP, 2018), increase emissions of pollutants causing serious negative externalities and environmental degradation (An and Sauer, 2004; Baumert et al., 2005; Hensher, 2008; Timilsina and Shrestha, 2009; Andres et al., 2012; Gutiérrez and Méndez, 2012; Akhatar et al., 2014). Recently, environmental concerns and geo-political issues related to the oil market have spurred an interest in developing solutions to reduce vehicle fuel consumption and exploring the use of alternative fuels (Akhatar et al., 2014). Currently, various types of alternative fuel vehicles (AFVs) are available in the market, including electric/hybrid electric, biodiesel, fuel cell/hydrogen and natural gas. BP Energy Outlook, suggests that under an evolving transition scenario, oil (diesel/ gasoline) demand is expected to decrease from the current 94% to 85% of total transport energy consumption in 2040. The basket of fuel containing, natural gas, electricity and a mixture of other fuel sources are each projected to share 5% of the road transportation fuel by 2040 (BP, 2018).

Out of these available alternate fuels, compressed natural gas (CNG) has gained the largest market share for AFVs today (Figure 1.1). CNG has been considered as one the best short to medium term solutions for reducing emissions due to its high hydrogen-to-carbon (H/C) ratio (4:1) as compared to gasoline/diesel which has an H/C ratio of about 1.85:1 (Kakaee and Paykani, 2013). Because of higher H/C ratio, theoretically combusion of natural gas produces 25% less CO_2 compared to their gasoline and diesel counterpart considering the same engine efficiency (Maji et al., 2004). Moreover burning natural gas produces virtually no sulfur and no particulate or metallic emissions (Nersesian, 2014). However natural gas vehicles have NOx emissions that are comparable, lower (Thiruvengadam, 2018, Vojtíšek-Lom, 2018) or higher (Yoon et. al., 2013; Huang et al., 2016; Vermeulen et al., 2017; Habib, 2018) than the amount of NOx emitted by diesel and gasoline vehicles depending upon type of natural gas engine and operating conditions. The current US EPA NOx emissions standard for heavy duty vehicle is 0.2 g/bhp-hr and the current prevailing cleanest heavy-duty diesel engines are certified at 0.2 g/bhp-hr while the modern heavy-duty natural gas engine is resulted in average NOx level of 0.02 g/bhp-hr, 90% below than the EPA NOx emissions standard (Gladstein et al., 2014; Han, 2016; Johnson and George, 2018). More recently, there has been an increased interest to use natural gas vehicles (NGVs) because of their low environmental impact, especially with regard to local air pollution. e.g., concerns regarding the air quality have lead India and South Korea to a massive application of NGVs in public transport (Vandewalle, 2014).

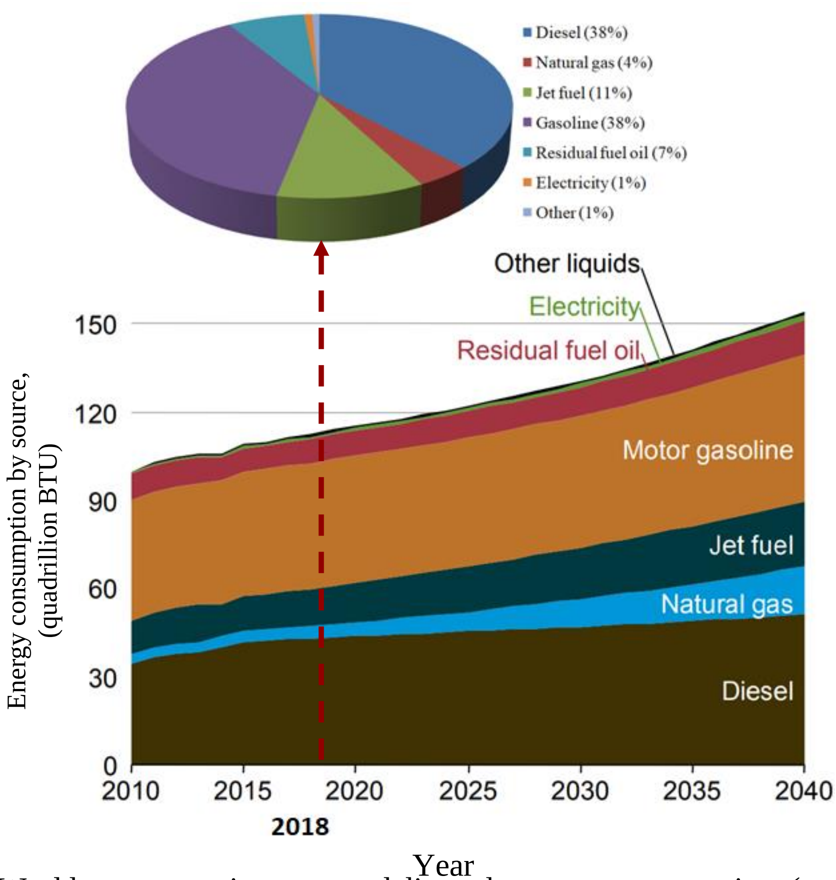

Figure 1.1. World transportation sector delivered energy consumption (quadrillion BTU) by source, 2010–40 (EIA, 2016)

According to the US Energy Information Administration (None, 2016) world share of natural gas as transportation fuel is slightly above 3%, and is expected to reach 11% in 2040. Abundant natural gas resources with proved reserves of 6595.93 quadrillion BTU (BP, 2018) and robust production of 125.48 quadrillion BTU/year aided by the growing supplies of LNG will give natural gas a competitive advantage among other resources. The recent editions of energy outlook reports i.e. BP - Energy Outlook (BP, 2018), EIA - World Energy Outlook (EIA, 2018) and IEA - International Energy Outlook (IEA, 2018), consider natural gas as a fastest growing fossil fuel and expected to overtake coal by 2025 - 2031 to become the second-largest fuel after oil in the global energy mix. In addition, US Energy Information Administration predicted that 50%, 17% and 7% of world energy consumption of public transport buses, freight rail and light-duty vehicles, respectively is projected to be natural gas in 2040 (EIA, 2016). Moreover, natural gas automotive system is fully compatible with renewable gas (Van Basshuysen, 2015), therefore together with advances in power-to-gas technologies (renewable gas), relatively low CO_2 output, inherently clean combustion, maturity technology, availability and competitive fuel price are key factors to enhance its role in alternative transportation fuel.

Recent energy/economic modeling studies (IEA, 2015; NRC, 2013) suggest that achieving the “2 degree” target of Paris accord will need significant adoption of electric vehicles as light duty vehicles over the next few decades with plug-in battery electrics (PEVs) playing major role.
In this context, natural gas is often argued as a possible “bridge” fuel in transition towards the renewable as ultimate transportation fuel aiming towards zero emissions (Devineni, 2011; Jaffe, 2017). Especially natural gas can become a mainstream alternative to diesel for heavy-duty and long-haul road transport where battery technology is not ready to power heavy-duty powertrain. For instance replacing the equivalent energy of 100 litres of diesel fuel would require ~3.5 tons Li-ion batteries (Gastec, 2018).

1.2. Background Knowledge of the Research Area

This section provides brief introduction and background information on NGVs technology and its market status.

1.2.1. Natural gas as a transportation fuel

Natural gas is being used in two forms to fuel the vehicles: compressed natural gas (CNG) and liquefied natural gas (LNG). In the case of CNG, pipeline quality natural gas is compressed to less than 1% of the original volume it will occupy at standard conditions of ambient pressure and temperature and stored in cylindrical shaped metallic or composite cylinder at a pressure of 200–248 bar. On the other hand, LNG is produced by removing heat from natural gas. As heat is removed, the vapor of gas cools and condenses, resulting in liquid product with boiling point of about -162 °C at atmospheric pressure. Liquefaction increases the energy density (about 1/600th of its original volume) of natural gas, thereby reducing its on-board vehicle storage volume for a given range and payload. The composition of LNG is different from that pipeline natural gas as result of the liquefaction process. Most of the hydrocarbon constituents remain soluble in LNG. However, other component, such as water, CO_2 and sulfur compounds are removed during liquefaction process. When using LNG as a vehicle fuel, it is stored in insulated tanks. Regardless of the type of engine i.e. spark ignition (SI) or compression ignition (CI) used in an liquefied natural gas (LNG) vehicle, fuel is always delivered to the engine as a gas, and not as a liquid. CNG is suitable for short-distance transportation e.g. taxis, city buses and waste collection trucks while heavy-duty vehicles requiring greater driving range such as inter-city buses and cargo vehicles are the typical users of LNG fuel systems.

In some countries CNG is mixed with hydrogen (5% - 30% by volume) (Ma et al. 2008). This new blended fuel is known as hydrogen enriched compressed natural gas (HCNG). Main drivers for introducing HCNG for automobiles are to improve the thermal efficiency of CNG engines, reduce emissions and to expand the role of hydrogen in transport sector.

1.2.2. Liquefied Petroleum Gas

LPG also known as auto-gas, is a chemical mixture of primarily two hydrocarbons called propane and butane that are gaseous under standard conditions of ambient pressure and temperature (1.013529 bar, 15.5 °C) but are liquefied by cooling or compression to facilitate the handling, storage and transportation (Speight, 2015). LPG is currently being used as an alternative transportation fuel in many countries across the world e.g. Korea, Turkey, Japan, Poland, Italy (Raslavičius et al., 2014). The chemical composition of LPG can vary based on location and season (Paczuski et al., 2016). For example, LPG available in the Netherlands has composition of 60% propane and 40% butane, but in northern regions such as Canada and United States, LPG contains mainly of propane (IEA-AMF, 2019). LPG comes from either natural gas processing or petroleum refining and is stored in metallic cylinders at a pressure of about 20 bar (Mokhatab et al., 2018). LPG vehicles operate similarly to gasoline vehicles with spark ignition (SI) engines.

1.2.3. Type of Natural Gas Vehicles (NGVs)

In terms of fuel supply, NGVs can be divided into three main categories i.e. dedicated NGVs, Bi-fuel NGVs and Dual-fuel NGVs. Dedicated NGVs have spark ignition (SI) engines that are operated only on natural gas. The compression ratio of these engines is optimized to utilize the advantage of high-octane number (120-130) of natural gas and accordingly dedicated NGVs are designed and manufactured with higher compression ratio (11-13) in contrast of conventional gasoline engines (9.5-11) and thus the thermal efficiency is enhanced (Chen, 2018). Most of the NGVs operated in developed countries are equipped with dedicated natural engine technology.

Bi-fuel vehicle can run on either natural gas or gasoline. The engine type they use is a regular gasoline IC engine. The driver can select what fuel to burn by simply flipping a switch on the dashboard. Any existing gasoline vehicle can be converted to a bi-fuel vehicle. Most of the CNG vehicles operated in developing countries are retrofitted from the gasoline engine (Reynolds and Kandlikar, 2008).

Dual-fuel vehicle are based on compression ignition (CI) engine technology. They run either on diesel only or utilize a mixture of natural gas and diesel, with the natural gas/air mixture ignited by a diesel "pilot". During the idle condition these engines tend to operate only on diesel (Khan et al., 2015a). As the vehicle starts to pick the load, the natural gas substitutes the diesel fuel up to 60–90% (Khan et al., 2015a). However, in the case of a dual-fuel vehicle, direct conversion is not possible due to the very high auto-ignition temperature (540 °C) of natural gas, which necessitates adoption of a dual-fuel system (Ghazi, 2015). Heavy duty vehicles e.g. buses and trucks are equipped with dual fuel CNG engine technology (Khan et al., 2015a).

1.2.4. Overview of International NGVs Market

Historically, prospects for natural gas as a transportation fuel have to some extent had a direct relation with the price of oil (Marbeck, 2010). When the price of oil (and gasoline/diesel) rose in the late 1970s and early 1980s, markets for NGVs appeared more promising (Marbeck, 2010). Nevertheless, the extended period of low oil prices from the late 1980s to the early 2000s ($12 and $10 per barrel, respectively), made it difficult for natural gas to compete as an alternative transportation fuel (National Research Council, 2013).

From 2008 (Figure 1.2), the worldwide population of NGVs has increased rapidly and as per the recent reliable sources, currently there are over 27.38 million Natural Gas Vehicles (NGVs) and over 32,206 CNG refueling stations distributed through 85 different countries (Khan et al, 2017a; NGV Global, 2018). According to NGV Global (2018) in the last ten years, worldwide the NGVs population has escalated at an annual rate of 24% with the biggest contribution coming from the Asia-Pacific and Latin America regions (Figure 1.2). This trend is projected to continue with average annual growth rate of 3.7% up to 2030, with major fraction of growth contributed by non-OECD countries. The current world leader of CNG market (with respect to number of NGVs in use) is China, with 6.1 million NGVs (NGV Global, 2018). Following behind China is Iran, with 4.5 million NGVs (NGV Global, 2018). Figure1.3 shows the top 10 countries with the highest number of NGVs. The majority (93%) of CNG vehicles are light duty car and commercial vehicles (NGV Global, 2018).

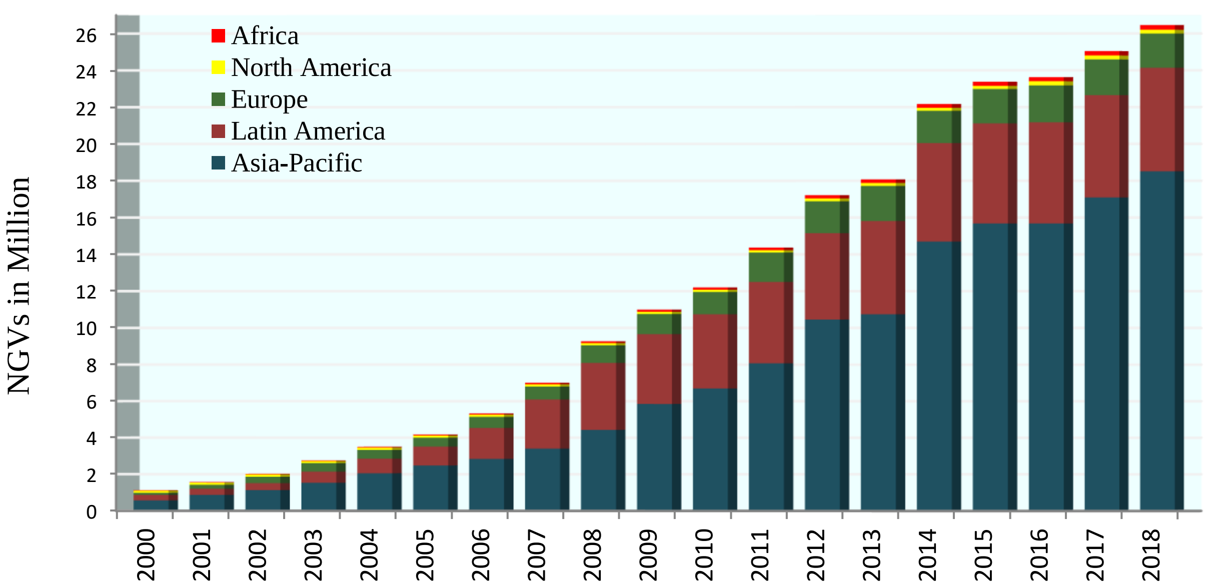

Figure. 1.2. Worldwide NGVs Growth by Region (Khan, 2017; NGV Global, 2018)

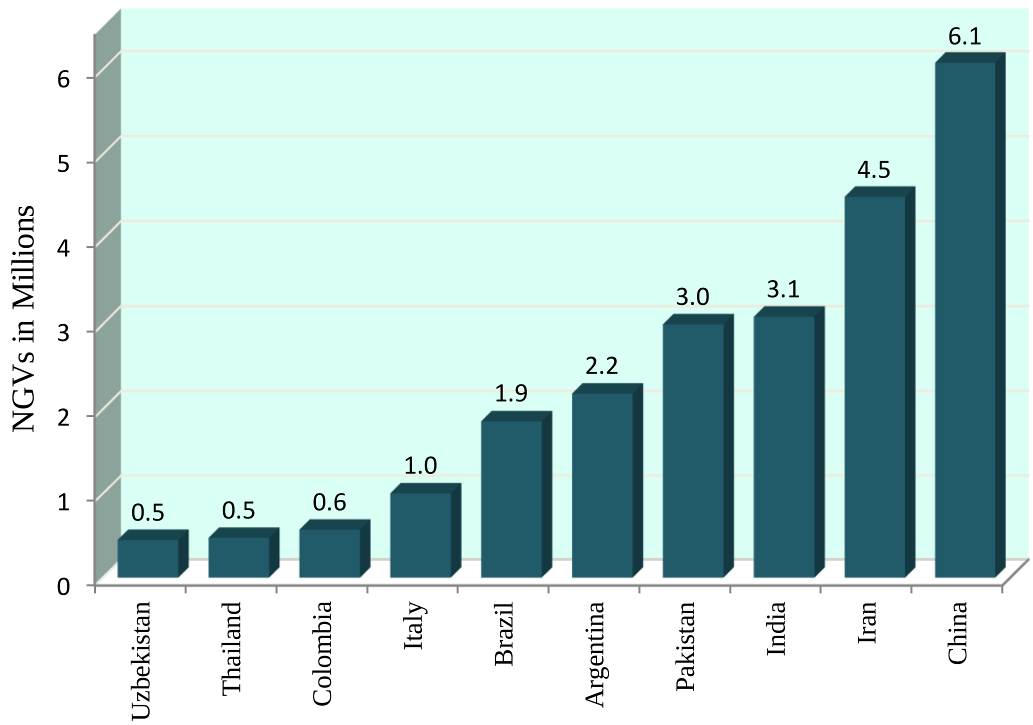

Figure 1.3. Top 10 countries with respect to number of NGVs (NGV Global, 2018)

1.2.5. Overview of Pakistani CNG Market

In a step towards adopting environment friendly fuel and to save foreign exchange, Compressed Natural Gas (CNG) was introduced by the Government of Pakistan in the country in 1992. At present, Pakistan stands 4th in the world with respect to number of natural gas vehicles. Figures1.4 and 1.5 reflect the continuous increase in the number CNG stations and CNG vehicles respectively.

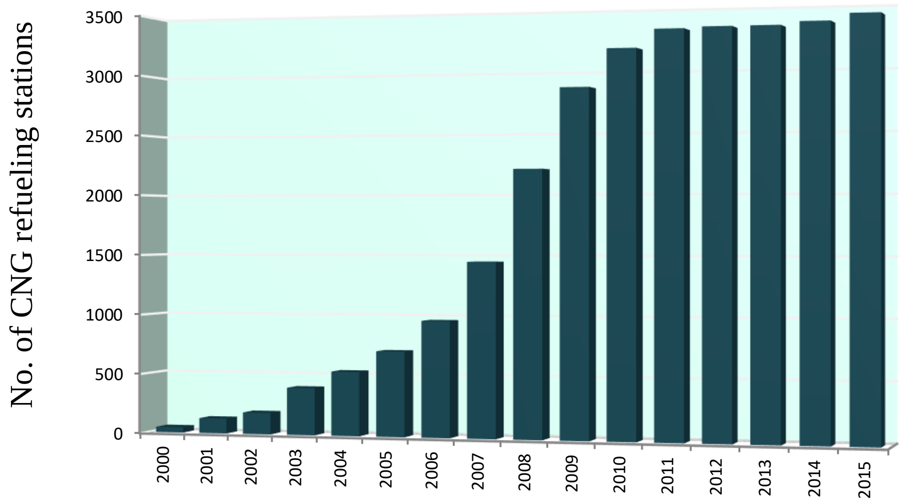

Figure 1.4. CNG refueling station growth in Pakistan (Khan and Yasmin 2014, Khan, 2017)

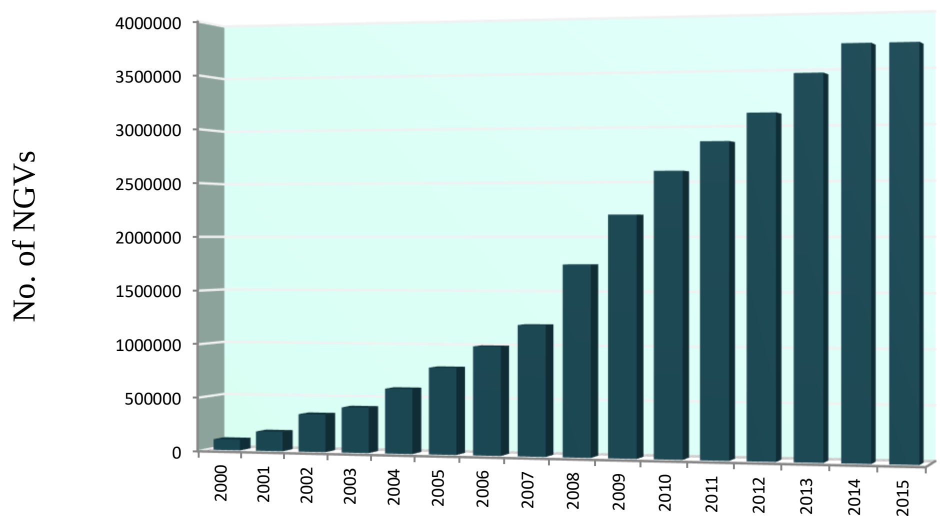

Figure 1.5. CNG vehicle growth in Pakistan (Khan and Yasmin 2014, Khan, 2017)

1.3. Research problem, aim and objectives

Wider adoption of natural gas as alternative transport fuel faces a variety of economic, institutional, and technological barriers that need to be overcome. The preceding information raises the following research question: Why, is the deployment of natural gas vehicles so low, despite the its potential to limit negative environmental impacts, operating cost advantage, and support for achieving sustainable development goals?

The aim of this study is to identify and analyze the technological, strategic and environmental aspects of compressed natural gas (CNG) as a viable alternative transportation fuel in the international as well as in Pakistani context. To achieve this aim, the objectives of this research are:

i. To investigate the key technical challenges associated with the CNG technology including engine performance, tail pipe emissions, safety, cost benefits, and durability of natural gas engine components.
ii. To examine the strategic framework and transitions to NGVs in four particular respects: addressing the barriers towards natural gas vehicles, policy options for the development of natural gas vehicles, strategies prioritization for natural gas vehicles' market and analysis of Pakistani CNG industry.
iii. To conduct a comprehensive life cycle (Well-to-Wheel) assessment of energy use and greenhouse gas (GHG) emissions associated with natural gas vehicles.

1.4. Publications Submitted

The above mentioned objectives of this study have been achieved through the detailed study of the subject and the outcomes have been published in twelve journals papers which are itemized in chronological order in Table 1.1.The set of publications presents a research undertaken under a general theme of a multidimensional assessment of natural gas as an alternative transportation fuel with a particular focus on Compressed Natural Gas (CNG) technology. This thesis is concerned with three inter-related themes. The first theme introduces and discusses the technical aspects of CNG technology with the particular focus on the environmental competitiveness of NGVs, safety issues with NGVs, performance of natural gas fueled engines, durability of natural gas engine components and current research progress in NGVs technology. The second theme discusses the strategic framework for promoting the adoption of NGVs e.g. market barriers, policy measures, and strategies prioritization. The final theme presents a life cycle assessment of energy use and greenhouse gas (GHG) emissions of NGVs.

Table 1.1. Published journal papers submitted for inclusion in the PhD by Published Work.

Paper no.	Paper Title	Journal	Year	Publisher	Available at
1	Development of natural gas as a vehicular fuel in Pakistan: Issues and prospects	Journal of Natural Gas Science &Engineering	2014	Elsevier	Annex-A
2	Technical overview of compressed natural gas (CNG) as a transportation fuel	Renewable & Sustainable Energy Review	2015	Elsevier	Annex-B
3	International Experience with Compressed Natural Gas (CNG) as Environmental Friendly Fuel	Energy Systems	2015	Springer	Annex-C
4	Safety Issues Associated with the Use and Operation of Natural Gas Vehicles: Learning from Accidents in Pakistan	Journal of the Brazilian Society of Mechanical Sciences & Engineering	2016	Springer	Annex-D
5	Research progress in the development of natural gas as fuel for road vehicles: A bibliographic review (1991–2016)	Renewable & Sustainable Energy Review	2016	Elsevier	Annex-E
6	Falling Oil Prices: Causes, Consequences and Policy Implications	Journal of Petroleum Science & Engineering	2017	Elsevier	Annex-F
7	Identifying and Addressing Barriers to Adoption of Compressed Natural Gas as Automotive Fuel	International Journal of Hydrogen Energy	2017	Elsevier	Annex-G
8	Policy options for the sustainable development of natural gas as transportation fuel	Energy Policy	2017	Elsevier	Annex-H
9	Evaluating the Strategies of Compressed Natural Gas Industry Using an Integrated SWOT and Multi-Criteria Decision Making Approach	Journal of Cleaner Production	2018	Elsevier	Annex-I
10	Failure Analysis of the Exhaust Valve from Natural Gas fueled Engine	Engineering Failure Analysis	2018	Elsevier	Annex-J
11	Comparative Well-to-Tank energy use and greenhouse gas assessment of natural gas as a transportation fuel in Pakistan	Energy for Sustainable Development	2018	Elsevier	Annex-K
12	Life cycle (well-to-wheel) energy and environmental assessment of natural gas as transportation fuel in Pakistan	Applied Energy	2019	Elsevier	Annex-L

In order to contextualize, integrate and represent coherence of the author's contribution to the knowledge, a research framework (shown in Figure 1.6) has been developed, that describes the published work discussed in this thesis. For ease of reference, this research framework groups the author‘s relevant papers into the above mentioned three themes, with each theme addressing a related contribution, which are mapped against the specific objectives formulated in section 1.3.

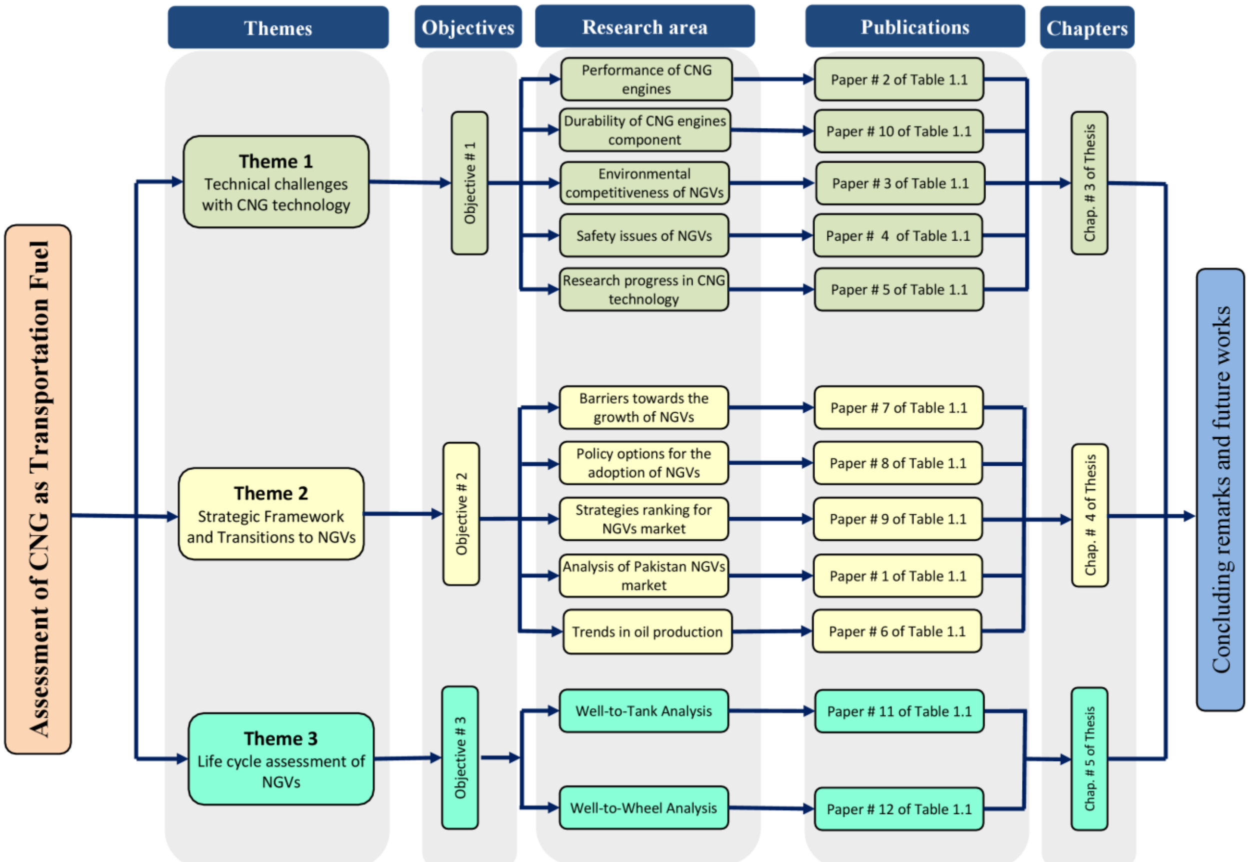

Figure 1.6. Schematic of integrating three themes into 12 publication

1.5. Research Journey

The author's interest in the analysis of natural gas as an alternative transportation fuel dates back to 2010, when he started working in Pakistan natural gas industry. In spite the tremendous growth CNG fuel which makes Pakistan the world leader in the CNG market, no research was conducted about any aspect (e.g. economic, policy and environmental) of Pakistan CNG sector at that time (2010). Given the lack of research in this arena, a study (paper # 1) was conducted to consider the various success factors, advantages and challenges for the future growth of CNG market in Pakistan. While conducting the literature review for the study reported in paper # 1, it was observed that there was no comprehensive academic work pertinent to techno-economic attributes of compressed natural gas (CNG) technology available in the literature. Therefore, research reported in paper # 2, was conducted with aim to contribute to a better understanding of techno-economic aspects of NGVs. The core themes (such as environmental competitiveness of NGVs, safety issues, durability of natural gas engine, strategic framework and transitions to NGVs) resulted from outcome of paper # 1 were further developed in paper # 3, 4, 5, and 7 - 8, respectively. In the research reported in paper # 3 regarding the tail pipe emission of NGVs vis-à-vis gasoline and diesel vehicles, it was observed that to evaluate the competitive advantage of NGVs, a holistic approach such as Well-to-Wheel need to be considered. Therefore, a comparative Well-to-Wheel (WtW) assessment of energy consumptions and greenhouse gas (GHG) emissions for natural gas as a transportation fuel was conducted in and outcome were reported as tandem of two papers (paper # 11 and 12). In paper # 9, the outcome of the research reported in paper # 7 and 8 regarding strategic framework for NGVs, was implemented by analyzing the CNG market of Iran. The fuel price margin and NGVs growth can be significantly affected by conventional fuel (diesel/gasoline) prices and these conventional fuel prices in turn are highly correlated to crude oil prices (Liu and Ma, 2014). Therefore, the paper # 6 was published to presents an evaluation of factors associated with sharp decline of oil prices since 2014.

1.6. The structure of the thesis

This thesis is organized into six chapters, commencing with an introduction outlining the field of study, scope of the work undertaken and establishes the coherent research themes among the published work included in this thesis. Following this introduction, Chapter 2 examines the applicable research design, leading to a discussion of the research approaches used in the published work. Chapters 3, 4 and 5 describe a summary of each of the published works in terms of background, research design and substantive findings using a thematic approach. Chapters 6 presents the conclusions and future work required for the development of natural gas as an alternative transportation fuel. Finally annexures A to L provide the printed copies of the published works.

Chapter 2: Research design and methodological approach

2.1. Introduction

This chapter describes the research design and methods adopted to achieve the research objectives. The research design here refers to a systematic approach or framework to be adopted to accomplish the goal and objectives of this thesis. The research design chosen to undertake the thesis is not limited to only one research paradigm but in fact, a number of different approaches have been adopted. Looking to the nature of the research objectives, initially exploratory work was carried out in the area of NGVs and later descriptive and explanatory research methods were used for the study. The philosophy for adopting the initial exploratory research approach is to get insights into, and establish a comprehension of the problem in order to mark out it more precisely before determining the appropriate course of action.

To help the designing of an appropriate research methodology, the research onion model (Figure 2.1) suggested by Saunders et al. (2012), is used as a guiding principle behind the research design. According to research onion model, every research process comprises of six layers, including philosophies, strategies, approaches, choices, time horizons, techniques, and procedures. The Saunder's research onion offers a significant and an effective consecution towards establishing a research methodology. Bryman (2016) argues that the effectiveness of the 'research onion' lies in its adaptability aspect to practically all kind of research methodologies and can be applied in a variety of contexts.

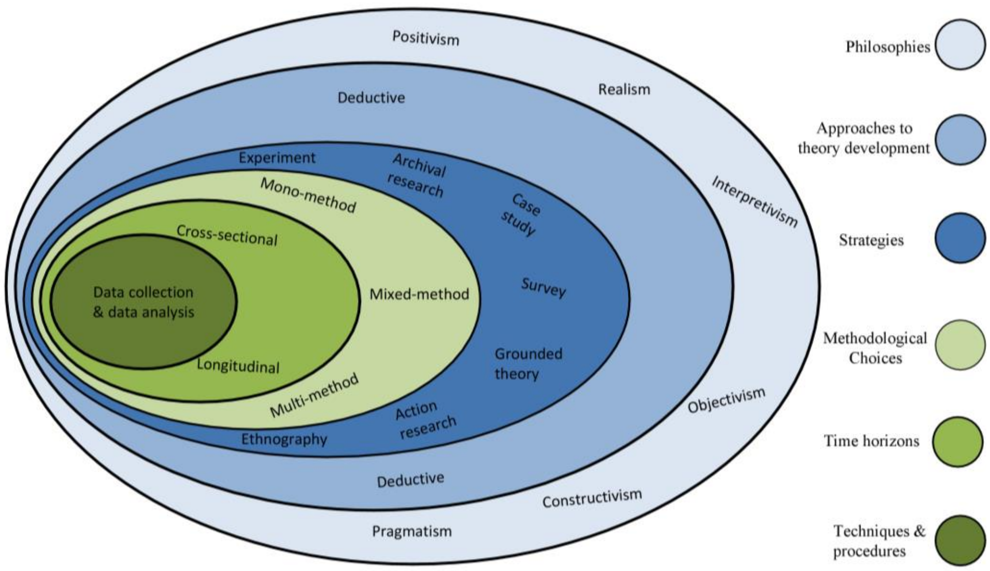

Figure 2.1. Research Onion Model (Saunders et al., 2012)

2.1.1. Layer 1: Research Philosophy

A research philosophy is a belief about the ways in which data about a phenomenon should be collected, analyzed and used (Blaxter et al, 2006). The main philosophical theories that describe the presence of a research entity include objectivism, positivism, constructivism, realism, interpretivism and pragmatism. Keeping in view the three inter-related themes that can be identified running through the publications presented in this research, a number of different research philosophies have been used mainly in the domain of positivism. Positivist research is characterized by understanding of reality by objective viewpoint and a single outcome of the phenomena - that is without interfering with the phenomena being studied. (Saunders et al., 2012). The publications associated with Themes 1 and 3 (paper # 1, 2, 3, 4, 5, 11& 12) of the published work are concentrated on the quantitative data analysis and the research findings are objectively reported, hence in terms of an overall philosophy, the research in the above mentioned themes is closest to the positivist philosophy. Similarly, the contribution of publications connected to Theme 2 are assessed on the basis of how true, correct and valuable the policies are pertinent to the diffusion and development of NGVs market and the research philosophy can be better placed under pragmatism. According to pragmatism, ideas and practices are evaluated according to their workability, effectiveness and practicality (Saunders et al., 2012). It considers that no single point of view can ever give a complete picture and that there can be multiple realities. Table 2.1 illustrate the philosophical approach of the submitted published work

Table 2.1. Philosophical Approach of the Published Work

S/N	Theme	Paper #	Research Philosophy
1	Technical challenges with CNG technology	2	Positivism
		3	Positivism
		4	Positivism
		5	Positivism
		10	Positivism
2	Strategic Framework and Transitions to NGVs	7	Pragmatism
		8	Pragmatism
		9	Pragmatism
		1	Positivism
3	Life cycle assessment of NGVs	6	Positivism
		11	Positivism
		12	Positivism

2.1.2. Layer 2: Research approach

According to Babbie (2015) a research approach chiefly determines the foundation of the research strategy and offers guidance for the selection of appropriate research methods. The prime research approach to this published work is inductive in nature. The research presented within this published work start with real-world data, patterns, models, and eventually, conclusions emerge from this input which is consistent with the inductive research approach. Through the inductive approach, data collection plans are developed, followed by data analysis to explore whether there might be any patterns in the collected data to suggest a meaningful relationships between variables in the data set. From these observations generalizations and relationships are constructed where appropriate.

2.1.3. Layer 3: Research strategy

Research strategy is defined as a roadmap towards the goal of research and how to accomplish this aim, to address the research questions (Saunders et al., 2012). This layer is associated with the selection of applicable research technique that could be useful in identifying the data collection. In this published work, a number of different research strategies have been used to address the research questions and/or accomplish the aim and objectives. This includes an in-depth case study analysis to survey and experimental methods. The published work required a considerable amount of data about the different aspect of using CNG as transportation fuel e.g. number of available NGVs, type of NGVs technology, safety issues and fuel economy, hence a survey method was deemed appropriate to collect the desired data. A survey method provides the researchers a very economical way for collecting greater number of data elements to answer the who, what, where, when and how of a particular research problem. The research projects reported in publications 1 and 9 are based on the NGVs market analysis of Pakistan and Iran, respectively and follow a case study approach. Yin (2017) identifies a case study as a strategy for carrying out research involving how or why question about an empirical inquiry of a particular contemporary phenomenon in its real-life context. Similarly, the research work reported in publication 10 involves various material characterization techniques (e.g. XRD analysis, microscopic analysis) and its research strategy can be categorized as experimental.

2.1.4. Layer 4: Methodological Choices

Methodological choices are related to the nature of the study which can be defined under two major categories: quantitative, and qualitative. Quantitative approach is primarily used in the type of research where quantification of data collection technique and data analysis procedure is required. For data collection it uses some kind of instruments (e.g. questionnaire) that is then converted into numbers (numerical data). In contrast, qualitative approach is predominantly used in the type of research where non-numerical data collection and analysis (such as categorizing data) is involved (Saunders et al., 2012). The research reported in this published work is not confined to either quantitative or qualitative methods, allowing for the objective and research questions to determine the most appropriate method for each aspect of the study. In general, the methodological choices can be divided in three broad categories i.e. mono-method, mixed method and multi-method. In Mono-method, researchers follow one type of data collection technique (either purely quantitative or purely qualitative approach) in all stages of the inquiry followed by a corresponding qualitative or quantitative analysis procedure.

The mixed methods research attempt to combine both qualitative and quantitative data collection techniques and analysis in a single study (Saunders et al., 2012). Similarly, in multi-method research, multiple data collection methods are used with associated data analysis techniques, but this is restricted within either a qualitative or quantitative worldview (Abbas and Charles, 2003). The methods chosen to undertake the work published in this thesis are not limited to only one research paradigm, but in fact, all the three-mentioned methodological choices are used as per the requirement of research objective concerned. The methodological choice of the each publication is highlighted in Table 2.2.

Table. 2.2. Methodological Choice of the Published Work

Paper #	Methodological Choices
1	Mono Method (Quantitative)
2	Mono Method (Quantitative)
3	Mixed Method (Quantitative & Qualitative)
4	Mono Method (Quantitative)
5	Mono Method (Quantitative)
6	Mono Method (Quantitative)
7	Multi-Method (Quantitative)
8	Mixed Method (Quantitative & Qualitative)
9	Multi-Method (Quantitative)
10	Mono Method (Quantitative)
11	Mono Method (Quantitative)
12	Mono Method (Quantitative)

2.1.5. Layer 5: Time horizons

This layer refers to time period required to complete the search. According to Bell et al. (2018) the research design can be of two types i.e. cross sectional and longitudinal. A cross-sectional approach is used for the relatively shorter period to collect and analyze the data of a defined sample population at a given time. In contrast, a longitudinal study suited to documenting how phenomena change over time (Rubin and Bellamy, 2012). Longitudinal studies draw attention to patterns of change or stasis that are generally invisible in short-term studies. Longitudinal studies play key role in the type of research targeting social, health, behavioral sciences, educational, economic, agricultural and biological sciences.

2.1.6. Layer 6: Data collection and data analysis

This layer deal with the data collection and data analysis tools used in the published work included in this thesis. Here, the researcher makes the decisions about selecting the most suitable data collection and analysis tools. The content related to the questionnaire, sample selection, sample size and their profiles are covered at this stage of data collection. Regardless of the approach used in the published work, the collected data can be categorized into two types: primary and secondary.

The primary data refers to the data collected for the first time by this research from the field of investigations with specific objectives in mind and thus happen to be original in character. However, collecting primary data is time-consuming and not always practically possible. Furthermore, it is not always possible to get direct access to the subject of research (Walliman, 2017). On the other hand, the secondary data refers to the data that have been collected by this research from different existing sources. Secondary data may be an effective means of research tool where primary data collection is uneconomic, impractical or unfeasible, and secondary data is available at a level of analysis suitable for answering the researcher's questions (Nayak, 2015). The quality of the secondary data depends on the source and the methods of presentation. Table 2.3 shows the type of data used in the published work.

Table 2.3. Methods of data collection

Theme	Paper #	Method and Source of data collection
Technical challenges with CNG technology	2	*Primary data:* discussion with stakeholders, *Secondary data:* academic literature, government policy documents, international agencies publications, expert presentations, technical reports and policy documents
	3	*Secondary data:* academic literature, govt. publications, international agencies publications, expert presentations, technical reports and policy documents
	4	*Primary data:* observation, discussions with stakeholder
	5	*Secondary data:* academic literature
	10	*Primary data:* experiment
Strategic Framework and Transitions to NGVs	7	*Secondary data:* academic literature, govt. publications, international agencies publications, expert presentations, technical reports and policy documents
	8	*Primary data:* semi-structure discussion with stakeholders *Secondary data:* academic literature, govt. publications, international agencies publications, expert presentations, technical reports and policy documents
	9	*Primary data:* structured questionnaire
	1	*Primary data:* structured questionnaire, discussion with stakeholders *Secondary data:* academic literature, govt. publications, expert presentations, technical reports and policy documents
Life cycle assessment NGVs	6	*Secondary data:* academic literature, govt. publications, international agencies publications, expert presentations, technical reports and policy documents
	11	*Primary data:* simulation, structured questionnaire, observation *Secondary data:* academic literature, govt. publications, international agencies publications and technical
	12	*Primary data:* Simulation, structured questionnaire, observation *Secondary data:* academic literature, govt. publications, international agencies publications and technical

2.2. Research Process

The research process involves an objective and systematic process that focus on collecting a large amount of information for analysis so that researchers can reach a conclusion. It aligns and integrates various elements of a study in a coherent and logical way to form an outline for the data collection, measurement and analysis (De Vaus, 2001). The research process employed in this thesis is exhibited in Figure 2.2. The research process reported here evolved over time and was based on a number of separate or discrete studies under the general theme of 'natural gas as an alternative transportation fuel'. The methods applied in the initial study were developed or expanded upon in subsequent research, as the findings led to further research ideas and possible research questions. The overall research process associated with the twelve publications included in this thesis consists of five phases that guide the author from the formulation and development of researchable problems to confirmation of probable answers:

i. Conceptual Phase - crystallization of the problem and how this relates to literature from previous research and theory;
ii. Design and Planning Phase - a plan is developed that specifies a research design, the subjects to be studied, the research approach and instruments to be used for data collection and how the data will be analyzed;
iii. Empirical Phase - the study plan is implemented and data is collected according to the pre-established plan
iv. Analytic and Interpretive Phase - data analysis and results interpretations are completed ensuring statistically and pre-defined research objectives are answered and placed within context;
v. Dissemination Phase – the results are examined for their relevance to the potential of natural gas as an alternative transportation fuel and future research. The results are communicated to research consumers and ideas for further research conceived.

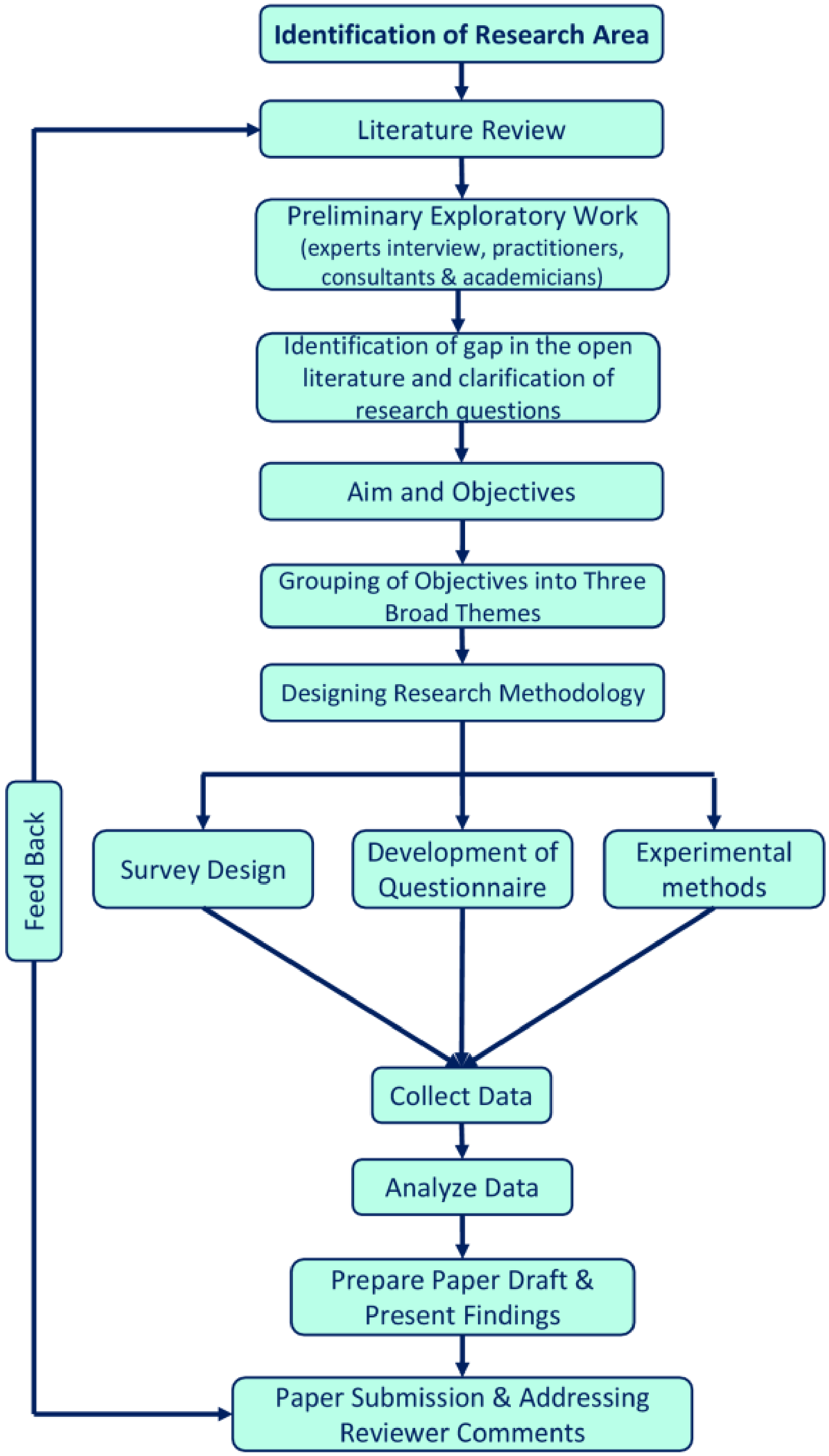

Figure 2.2. Flow chart of research process

2.3. Methodological summary

In this chapter, a brief overview of the research design and methods adopted in this thesis are presented. The research philosophy, research approach, research strategy, methodological choices, time horizon, sources and methods of data collection followed are discussed with reference to the publications included in this thesis. The Research Approach associated with each individual paper are summarized in Table 2.4.

Table 2.4. Research methods followed in publications

Research Theme	**Research Design**						**Research Output**
	Research Philosophy	*Research approach*	*Research strategy*	*Methodological Choices*	*Time horizons*	*Data collection*	
Technical challenges with CNG technology	Positivism	Inductive	Survey and analytical	Mono method (quantitative)	Cross sectional	Primary and secondary data	Paper # 2
	Positivism	Inductive	Analytical	Mono method (quantitative)	Cross sectional	Primary and secondary data	Paper # 3
	Positivism	Inductive	Survey	Mono method (quantitative)	Cross sectional	Primary data	Paper # 4
	Positivism	Inductive	Narrative Review	Mono method (quantitative)	Cross sectional	Secondary data	Paper # 5
	Positivism	Inductive	Experimental	Mono method (quantitative)	Cross sectional	Primary data	Paper # 10
Strategic Framework and Transitions to NGVs	Pragmatism	Inductive	Survey and analytical	Multi-method (quantitative)	Cross sectional	Primary and secondary data	Paper # 7
	Pragmatism	Inductive	Survey and analytical	Mixed method (quantitative & qualitative)	Cross sectional	Primary and secondary data	Paper # 8
	Pragmatism	Inductive	Case study	Multi-method (quantitative)	Cross sectional	Primary data	Paper # 9
	Positivism	Inductive	Case study	Mono method (quantitative)	Cross sectional	Primary and secondary data	Paper # 1
Life cycle assessment of NGVs	Positivism	Inductive	Analytical	Mono method (quantitative)	Cross sectional	Secondary data	Paper # 6
	Positivism	Inductive	Modeling	Mono method (quantitative)	Cross sectional	Primary and secondary data	Paper # 11
	Positivism	Inductive	Modeling	Mono method (quantitative)	Cross sectional	Primary and secondary data	Paper # 12

Chapter 3: Technical aspects of CNG technology

3.1. Introduction

This chapter presents an analysis of the selected works pertinent to technical, environmental, safety analysis of NGVs technology by considering each article individually in this thesis in terms of background and antecedents, research design, substantive findings and outcome.

3.2. Paper # 2

Khan, M.I., Yasmin, T. and Shakoor, A., 2015. Technical overview of compressed natural gas (CNG) as a transportation fuel. Renewable and Sustainable Energy Reviews, 51, pp.785-797.

3.2.1. Context, Background & Problem Addressed

Despite all the advantages of natural gas as transportation fuel described in Chapter 1, the market share of NGVs was only 0.75% at time when the idea of this paper was conceived. So it was desired to explore the techno-economic aspects of compressed natural gas (CNG) vehicles. At that time to the best of our knowledge, there was no comprehensive academic work pertinent to techno-economic attributes of compressed natural gas (CNG) technology available in the literature.

3.2.2. Aim and Objectives

The overarching aim of this study was to explore the techno-economic aspects of fueling the vehicle with natural gas.

The objectives given below were set to accomplish the above aim.

- To assess and present the current state-of-the art NGVs and their infrastructures, i.e. CNG and LNG filling stations;
- To analyze CNG as a fuel for internal combustion engines for the vehicle propulsion in terms of advantages and disadvantages of natural gas engines.
- To workout the economics of running the CNG vehicles vis-à-vis its fossil fuel alternatives i.e. gasoline and diesel fuel.

3.2.3. Content

The study presents the key issues in the CNG technology (for transportation fuel) domain which have a close linkage between economic and technical factors and the impact of these two factors on the overall competitiveness of NGVs. Technical aspects of natural gas fueled engines including the overall 15–20% loss in brake horsepower of CNG engines and causes responsible for such power loss are discussed. The key indicators considered for the power loss in CNG fueled engines are volumetric efficiency and low flame propagation of natural gas. The physics behind the 10% and 5–10% engine brake horsepower loss in CNG engines due to low volumetric efficiency and flame propagation speed respectively are thoroughly discussed. To clarify the cost benefits of NGVs vis-à-vis gasoline and diesel vehicles, the study first explores the cost of CNG in various countries around the world and then workout the comparative fuel economy of running CNG vehicles by using primary real-world data. In addition, the study identifies and discusses the key technical challenges (e.g. safety, loss of cargo space, driving range) preventing or delaying the widespread deployment of natural gas vehicles.

3.2.4. Research Approach

The paper applies desk research methodology by using existing literature as empirical text. The existing literature include, peer reviewed journal publications and grey literature comprising of government publications, reports, statistical publications, news- letters, fact sheets, working papers, technical reports, conference proceedings, published reports by a variety of international agencies e.g. Natural & bio Gas Vehicle Association (NGVA Europe), International Association for Natural Gas Vehicles (IANGV). The data was further supplemented through field research. The field research involved the discussions with the key stakeholders of CNG market e.g. individual vehicle's drivers, fleet operators, refueling station operator and engineering professionals having research backgrounds in IC engines. This approach of filed research allowed the asking of already prepared questions and the using of interview prompts wherever more detail was deemed necessary but allowed the interviewee to share their views at length and in their chosen style. The discussions covered topics such as performance issues in using the NGVs, environmental impacts, knowledge of NGVs, type of NGVs e.g. dedicated or retrofits, NGVs purchase decisions, fuel economy and the overall level of satisfaction with NGVs. Interviewees were asked to provide evidence where possible to support their answers and this gave rise to a degree of document analysis both within and after the discussion event.

After the obtaining the results of literature review and expert opinion through field research, an online survey was designed and conducted. It aimed at identifying further research issues and prospective trends in NGVs technology. It was carried through a Google Form and contained three different parts:

i. Semi-directive questions regarding performance compatibility of natural gas vehicles vis-à-vis diesel and gasoline fuel;
ii. Open questions regarding research trends, remaining technical problems, and suggested solutions .
iii. Questions addressed to economic compatibility of natural gas vehicles

The survey was sent first and foremost to the corresponding authors of the papers who had previously published some such study considering any of the area includes engine performance of NGVs, emissions analysis of NGVs, fuel economy of NGVs and combustion analysis of natural gas in IC engine. We also handed the survey to some industrial (natural gas engine manufacturer e.g. Cummins Westport Inc; NGVs manufacturer e.g. Honda Civic GX; CNG conversion kit and cylinder manufacturers e.g. Landi Renzo, Luxfer Gas Cylinders) and institutional (e.g. IEA, NGVA Europe, NGV Global).

To compare the fuel economy of NGVs with gasoline and diesel fueled vehicles, three type vehicles (CNG, gasoline & diesel) with same engine sizes were arranged and tested their fuel economy under real world driving conditions.

3.2.5. Major Outcome

The major outcomes of this study are listed below:

- Worldwide CNG vehicle technologies are well established and commercially available for all types of road transport vehicles.
- To keep the torque and brake horsepower, of CNG vehicles comparable to their diesel or gasoline counterparts, dedicated CNG engines research should be accelerated.
- CNG has several advantages over both diesel and gasoline fuels, including considerable emission and cost reductions, and making the countries more energy sovereign by reducing the dependency on oil.

- The placement of the high-pressure storage system especially in relatively small vehicles needs to be improved in terms of vehicle volume, accessibility and cost competitiveness.

3.2.6. Value and Significance

Until this research was undertaken there had been no comprehensive academic work covering the techno-economic attributes CNG technology. So far the paper has been cited over 125 times across the world (e.g. Sharafian et al., 2016; Barik et al., 2017; Alrazen and Ahmad, 2018; Verma et al., 2017; Jiao et al., 2017; Liu et al., 2017; Boulahlib et al., 2018; Lather et al., 2019; Hönig et al., 2019; Chen et al., 2019) by academic journals, PhD/Master thesis and technical books. Some of the reputable energy journal in which the paper has been cited includes Applied Energy, Renewable and Sustainable Energy Reviews, Energy Conversion and Management, Journal of the Energy Institute, Journal of Cleaner Production, Fuel, Applied Thermal Engineering. It is notable that authors from USA, Canada, Brazil, UK, France, Germany, Poland, Italy, Spain, Australia, China, Malaysia, India and others have cited this paper.

3.2.7. Author Contributions

Khan M.I., conceived the idea of this paper, designed the research, collected and analyzed the data. Khan M.I., and Yasmin T., together drafted the manuscript with input from Shakoor A. Shakoor A., checked and approved the final version of the manuscript to be published. Khan M.I., addressed the reviewer' comments.

3.3. Paper # 4

Khan, M.I., Yasmin, T. and Khan, N.B., 2016. Safety issues associated with the use and operation of natural gas vehicles: learning from accidents in Pakistan. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 38(8), pp.2481-2497.

3.3.1. Context, Background & Problem Addressed

The gaseous and pressurized (248 bar) nature of CNG fuel, raise safety concerns, and consumers may ask a simple question: whether the CNG vehicles are as safe as the conventional vehicles. At the time when the idea of this paper was conceived, the NGVs market of Pakistan had witnessed over 70 accidents related to CNG vehicles. Therefore, there was a need to investigate the safety aspects of CNG vehicles running in Pakistan.

3.3.2. Aim and Objectives

The aim of this research was to identify lessons that could be useful to guide countries in their efforts to deploy CNG as safe alternate fuel for vehicles.

To achieve the above aim, the following objectives were formulated.

- To study the causes of CNG-related accidents in Pakistan
- To identify the “lessons to be learned” for CNG vehicles from the 55 accidents which happened in Pakistan

3.3.3. Content

The paper included a discussion on the relevant codes, standards, and regulations regarding safe usage of CNG as a transportation fuel. The discussion noted the safety measures which must be considered and highlighted the significant impacts of the safety rules and codes for the design of vehicle and refueling station. After reviewing some accidents involving CNG vehicles and their consequences in other countries including USA, Malaysia and South Korea, the paper systematically investigated the cause and consequences of 55 accidents (which caused over 250 casualties) related to CNG vehicles. These accidents had occurred from 2008 to 2014. The nature and consequences of each accident is presented and main areas of concern to improve safety in the Pakistani CNG industry are discussed. The discussion pertaining to the 55 accidents are categorized into two parts: (i) fire explosion, and (ii) cylinder explosion. Fire explosion accidents are then subdivided in the following three categories: (i) gas leakage, (ii) sparking, and (iii) collision of CNG vehicles. After analyzing the causes of accidents on the basis of the above mentioned categories, some recommendations are provided to:

- avoid CNG cylinder explosion, and
- fire explosion

3.3.4. Research Approach

In the first step, the study analyzed various academic databases to present a comprehensive review of safety aspects of natural gas vehicles. In second step a database of past-accidents involving NGVs was built. A total of 55 accidents were included in the database, which had occurred in Pakistan from 2008 to 2014. The major part of data for the 55 accidents analyzed in this work was collected from the annual reports of Hydrocarbon Development Institute of Pakistan (HDIP) and Oil and Gas Regulatory Authority (OGRA). These two organizations are responsible for checking the quality of CNG kits and cylinders in Pakistan. In addition to the data obtained from the aforementioned two organizations, the data was further supplemented through following sources:

National highway police and city police vehicle accident reports: where possible the detail about the 55 case-study accidents were reviewed from the nearest police station of accident vicinity.

Available literature: The information pertaining to accidents involving natural gas vehicles in Pakistan and other part of the world were reviewed with the help scientific literature, websites (e.g. NGVA Europe, NGV Global), print/electronic news media and interrogating specific open-source databases reporting data on vehicle accidents.

Field Survey: To explore the issues with the use of NGVs in Pakistan, semi-structured discussions were undertaken with key stakeholders pertinent to Pakistan CNG market (e.g. NGVs drivers, fleet operators, CNG refueling stations operators, federal/state agencies responsible for implementing the safety regulations). Some questions of the said interviews were open-ended, thus permitting the interviewee to respond without any form of prior suggestion or be required to select from a pre-determined set of options. Interviewees were asked to provide evidence where possible to support their answers and this gave rise to a degree of document analysis both within and after the interview event.

After consulting all the above-mentioned source of data collection, the data retained for the analysis was organized into the following two categories:

i. CNG cylinder explosion (where explosion of a vehicle’s gas cylinder involved)
ii. Fire explosion (where fire erupted in a vehicle)

The data pertaining to the above two categories was further categorized in major influential sub-categorical factors. To analyze the 55 case-study NGVs accidents, the following three questions were considered:

- Whether the accident occurred because of CNG system failure or violation of safety procedures by the vehicle operator
- At what point did the flammable fuel-air mixtures occur?
- What sources ignited the flammable mixture?

3.3.5. Major Outcome

The major outcomes of this study are listed below:

- Safety of CNG vehicle is highly reliant on the design, materials, installation, operating conditions and maintenance, not only on the cylinder or other parts in isolation.
- The study revealed that due to low-quality CNG system material, e.g., CNG cylinder, CNG design and installation, maintenance system, lack of strict government CNG vehicle safety regulations and driver negligence every year several CNG vehicles' accidents took place in Pakistan which showed a major threat to life in Pakistan.
- The main reason for the CNG accidents which occurred in Pakistan was due to lack of awareness about safety precautions and regulation and driver negligence.
- The main reasons of CNG cylinders explosion in Pakistan were the usage of unapproved cylinders, welded cylinders and cylinders that were not manufactured for CNG use, e.g., oxygen cylinder.
- Pakistan CNG safety rules 1992 do not cover all the required safety measures (e.g. competency framework for drivers) to prevent CNG vehicle accidents. These rules must be updated in light of prevailing international standards such as FMVSS 303 & 304, ECE R-110, ISO 11439 and NFPA 52.

3.3.6. Value and Significance

At the time when this study was produced limited academic literature existed (Carpenter and Hinze; 2004; Utgikar and Thiesen, 2005; Rodionov, 2011; Zhang, 2014) regarding the safety issues of other type of alternative fuels like hydrogen or fuel cell vehicles but to the best knowledge of the author of this thesis, a systematic empirical research addressing the safety issues associated with the use and operation of natural gas vehicles did not exist. Since its publication the paper has been cited 10 times by international journals including Journal of the Brazilian Society of Mechanical Sciences and Engineering, Journal of Hazardous Materials and International Journal of Hydrogen Energy.

3.3.7. Author Contributions

Khan M.I., conceived the idea of this paper, designed the research and collected the data. Khan M.I., analyzed the data with scientific input from Khan N.B. Khan M.I., was also responsible for developing and writing the first draft of the manuscript while all authors contributed to revising/editing the manuscript. Yasmin T., revised the manuscript critically for important intellectual content. Khan M.I., addressed the reviewer' comments.

3.4. Paper # 03

Khan, M.I., Yasmin, T. and Shakoor, A., 2015. International experience with compressed natural gas (CNG) as environmental friendly fuel. Energy Systems, 6(4), pp.507-531.

3.4.1. Context, Background & Problem Addressed

The environmental performance of transport modes is a crucial area and the one driven by stringent emission standards. Natural gas has a higher hydrogen-to-carbon ratio (H/C) (almost 4:1) than either gasoline (1.86:1) or diesel fuel (1.85:1), so theoretically its combustion can produce 20% less CO_2 emissions in contrast to a gasoline engine operating with the same condition (Kato et al., 2001, Kakaee and Paykani, 2013). However, under real world vehicle operations there are many factors (e.g. methane slip) which can weaken the environmental advantage of natural gas vehicles. Therefore this study was conducted to explore the general consensus about the real-world emission levels of natural gas fueled vehicles.

3.4.2. Aim and Objectives

The overall aim of this study was to contribute to assess the environmental attributes of natural gas vehicles.

The objectives given below were set to accomplish the above aim.

- To analyze the worldwide experience of NGVs in terms of various emission factors i.e. CO_2, CO, NOx, NMHC and PM.
- To analyze the comparative tailpipe emissions of NGVs vis-à-vis its fossil fuel alternatives i.e. gasoline and diesel fuel, both under laboratory and real world conditions.

3.4.3. Content

This paper analyzed the worldwide experience of CNG vehicles with respect to its environmental competitiveness to diesel and gasoline fueled vehicles. To provide better understanding of comparative emission rates of NGVs for policy-makers, investors, and other decision-makers, the paper analyzed real world emission data of NGVs across different countries. The study discusses and compares the following major pollutants emitted from CNG, diesel and gasoline vehicles:

- Carbon dioxide—CO2
- Carbon monoxide—CO
- Nitrogen oxides—NOx
- Particulate matter—PM
- Non-methane hydrocarbon (NMHC)
- Impact of CNG composition on emission characteristics

The above-mentioned vehicles' exhaust emissions are discussed in terms of their impact to climate as well as human health.

3.4.4. Research Approach

The transportation modes in this study included both light-duty and heavy -duty road vehicles. These vehicles were fueled with three type of fuels i.e. natural gas, gasoline and diesel. Only the on-site or direct fuel combustion emissions were considered, while indirect emissions, such as those from fuel supply chain, were excluded. Additionally, to make apples-to-apples comparison of the emission performance of different powertrain, the exhaust emissions factor of each powertrain was converted to the unit of gram per kilometer (g/km). First, a quantitative analysis of emission factors using real world and laboratory secondary data was carried out. The secondary data sources included academic literature, published reports by a variety of international agencies, expert presentations, and grey literature comprising of government publications, working papers and technical reports. In the next step, the results were incorporated in International Vehicle Emissions (IVE) Model to establish the comparative emission index score, which includes five emission factors i.e. CO2, CO, Particulate Matter (PM), NOx and NMHC. IVE model is jointly developed by International Sustainable Systems Research Center and the University of California at Riverside. The model allows the user to modify the default emission rates as per user specified emission data. The model estimates emission rates using equation (1) by adjusting for eight different correction factors.

$$Q_{[t]} = B_{[t]} * K_{(Base)[t]} * K_{(Tmp)[t]} * K_{(Hmd)[t]} * K_{(IM)[t]} * K_{(Fuel)[t]} * K_{(Alt)[t]} * K_{(Cntry)[t]} * K_{(d)[t]} \qquad (1)$$

where,

$Q_{[t]}$	adjusted emission rate for each technology (start (g) or running (g/km);
$B_{[t]}$	base emission rate for each technology (start (g) or running (g/km).
$K_{(Base)[t]}$	an adjustment factor to the base emission rate
$K_{(Temp)[t]}$	values for temperature
$K_{(Hmdt)[t]}$	humidity
$K_{(IM)[t]}$	inspection/maintenance correction factor
$K_{(Fuel)[t]}$	fuel quality
$K_{(Alt)[t]}$	altitude
$K_{(Cntry)[t]}$	area correction factor
$K_{(d)[t]}$	driving pattern

3.4.5. Major Outcome

The major outcomes of this study are listed below:

- The real-world emission results revealed that in contrast to gasoline/ diesel vehicles, the CNG vehicles produces lower emission of CO_2 (20-25%), CO (50-68%), PM (10-75%) and NMHC (50-70%).
- The study revealed that in contrast to diesel fuel, there is large variation in the non-methane hydrocarbon (NMHC) emissions data of CNG fuel. Some cases revealed that CNG could significantly reduce NMHC emissions while others concluded that CNG increases the NHMC emissions.
- There is large variation in emission data of the vehicles with the same engine technology. It is shown that the condition of vehicles is an important determinant of the emission levels, often more important than fuel or engine type. Vehicles with properly operating engine and emission control systems consistently produce lower exhaust emissions than vehicles with malfunctioning or poorly tuned systems, regardless of fuel type used.
- The development of advanced diesel engines has led to considerable lower emissions. However, this study concluded that CNG engines were more advantageous regarding emissions of particulate matter compared to traditional diesel engines without particulate capturing technologies.

- CNG engines resulted in lower emissions of toxic compounds of PAHs and formaldehyde to that of gasoline engine.

3.4.6. Value and Significance

This research generated a real-world tail-pipe emission database for CNG, gasoline and diesel fuel which was used in the study of comparative Well-to-Wheel analysis of CNG vehicles discussed in Chapter # 05 of this thesis. Since its publication the research has been cited over 18 times across the world (e.g. Chainikov et al., 2016; Otene et al., 2016; Mahmood et al., 2017; Song et al., 2017; Li et al., 2018; Yang et al., 2018).

3.4.7. Author Contributions

Khan M.I., conceived the idea of the paper, designed the research, collected and analyzed the data with iterative feedback from Shakoor A. Khan M.I., and Yasmin T., together drafted the first draft of the manuscript while Shakoor A., contributed to revising/editing the manuscript. Yasmin T., addressed the reviewers comments.

3.5. Paper # 10

Khan, M.I., Khan, M.A. and Shakoor, A., 2018. A failure analysis of the exhaust valve from a heavy duty natural gas engine. Engineering Failure Analysis, 85, pp.77-88.

3.5.1. Context, Background & Problem Addressed

One of the important indicators for comparing the economic aspects of vehicular technology is the associated maintenance costs. As noted in section 1.2.3, dedicated and bi-fuel natural gas vehicles are equipped with SI engines similar to those used in conventional gasoline engines, but instead uses natural gas fuel storage either in compressed or liquefied form and gaseous fuel delivery system. However in case of natural gas vehicles some engine retrofitting e.g. hardened exhaust valves and valve seats are required to accommodate the combustion characteristics of natural gas. While such retrofication do not affect the visual appearance of the engine, they may alter the service and maintenance requirements of the engine (AFDC, 2018). Unlike diesel/gasoline fueled engines, gaseous fuel engines tend to run at higher temperatures (165°C to 235°C higher exhaust temperature than diesel/gasoline) and produce more complete combustion (Tabar et al., 2017). The high combustion temperature increases the oxidation and nitration of the engine oil which can subsequently enhance the wear mechanism of exhaust valve. Therefore combustion of natural gas in IC engines causes relatively large degree of valve seat wear in contrast to diesel and gasoline fuel engines (Londhe and Kshirsagar, 2014).

3.5.2. Aim and Objectives

The aim of this study was to examine the process of exhaust valve failure in a heavy duty natural gas engine, in order to understand the failure mechanism of the component.

To achieve the above aim, following objectives were formulated:

- To compare the mechanical properties of a failed exhaust valve (remained exposed to natural gas combustion) with unused exhaust valve of the same material.
- To investigate the effect of natural gas combustion on the thermal stability of the exhaust valve's material.

3.5.3. Content

The study presents a case of premature failure of a natural gas engine's exhaust valves; where the failure occurred at approximately 5000 operating hours, whilst the standard expected service life of the valves is 20,000 hours. The effects of natural gas on the wear leading to failure of the exhaust valves of natural gas operated engines were determined. The study also discussed various factors affecting the life of the exhaust valve e.g. combustion temperature, combustion deposits, loading/seating and engine oil.

3.5.4. Research Approach

Several examinations were carried out in order to identify the failure's root cause including:

- Visual examination of inner and outer surfaces
- Energy dispersive spectroscopy (EDS) analysis for elemental composition
- Hardness measurement
- Scanning electron microscope (SEM) examination of the valve head
- Optical microscopy of the valve head
- X-ray diffraction (XRD) analysis of valve-face deposits
- Thermo gravimetric analysis (TGA) for thermal analysis of valve material

First, the inner and outer surfaces of the failed exhaust vales were visually examined, the amount of the obvious guttering was listed and the typical macro-morphology was taken using the digital camera (NIKON L100). Then the sample pieces of failed valves were cut from the corresponding parts based on the requirements of different tests. Some of the samples were cross-sectioned and mounted in epoxy. They were then grounded by different grit size silicon carbide (Sic) emery papers in a sequence of 320, 600, 800, 1000, and 1200 and subsequently mechanically polished with diamond paste (6, 3, and 1 μm) and 0.05 μm alumina suspension. Pressurized water coolant was applied during grinding process to prevent sample heating. Ultrasonic cleaning for 2 min was carried out after each step of diamond paste polishing to remove any diamond abrasive on the sample surface. The samples were then etched for 60 s using etching solution of Modified Glyceregia (30 ml HCl, 25 ml Glycerol, 10 ml HNO3). After etching microstructure analysis of the polished samples were performed using SEM (JSM-5910, JEOL Japan). After thermal aging, microstructure of the polished samples was performed using optical microscope (Olympus GX51, *Olympus Co. Japan) and Scanning Electron Microscope - SEM (JSM-5910, JEOL Japan). The chemical composition of the exhaust valves was analysed using EDS (Oxford Ins Inca-200) coupled with SEM on the basis of ASTM A751-2008. Hardness of the valve materials was found with micro-hardness tester (Model HMV-2T, Made by Shimadzu). X-ray diffraction (XRD) measurements were carried out in order to determine the constitution of the phases present combustion product of valve surface deposits.

3.5.5. Major Outcome

The exhaust valves were analyzed to be typical of Nickel based superalloy Inconel-751. The valves failed as a result of overheating. The possible cause for overheating is lack of tappet clearance, which results in light seating and carbon build up on the seating face. Additionally the significant overaging of the alloy caused the particle coarsening which subsequently resulted in the decrease of hardness.

3.5.6. Value and Significance

The valves and seats in an internal combustion engine play a key role in engine breathing, compression, performance and longevity. When the idea of this paper was conceived, at that time to the best of our knowledge, there was no academic work available pertinent to thermo-mechanical failure mechanism of exhaust valve from natural gas engine. Since the publication of this paper in 2018, the research has been cited three times by academic journals e.g. Kolarević et al., 2018; Muthukumar et al., 2018; Thakare and Keche, 2018.

3.5.7. Author Contributions

Khan M.I., conceived the idea of the paper and designed the research. Khan M.I., and Shakoor A., contributed to the interpretation of the results. Khan M.I., was jointly involved with Khan M., A., in conducting the required experimental work. Khan M.I., was also responsible for developing and writing the first draft of the manuscript while Shakoor A., and Khan M., A., contributed to revising/editing the manuscript. All authors were jointly involved in addressing the reviewers comments.

3.6. Paper # 5

Khan, M.I., Yasmeen, T., Khan, M.I., Farooq, M. and Wakeel, M., 2016. Research progress in the development of natural gas as fuel for road vehicles: A bibliographic review (1991–2016). Renewable and Sustainable Energy Reviews, 66, pp.702-741.

3.6.1. Context, Background & Problem Addressed

This review presents the research progress in using the natural gas as alternative transportation fuel.

3.6.2. Aim and Objectives

The aim of this study was to present a comprehensive review of research progress in various aspects of natural gas as an alternative transportation fuel.

To achieve the above aim, the following objectives were formulated:

- To provide a summary of the publications that were published between 1991 and 2016 on the subject including: Regional Experience with CNG Vehicles; Economic Aspect of CNG Vehicles; CNG Engine's Design, Control and Performance; Combustion and Fuel Injection Characteristics of CNG Engines; CNG/ Diesel Dual Fuel Operations; Hydrogen Enriched CNG Vehicles; Environmental Aspect of CNG Vehicles; Safety Aspect of CNG Vehicles.

3.6.3. Content

The review provides 1102 references to journal' papers, conference proceedings and theses/dissertations published between 1991 and 2016. The bibliography is divided into the following parts and concerns:

- Regional Experience with CNG Vehicles

- Economic Aspect of CNG Vehicles
- CNG Engine's Design, Control and Performance
- Combustion and Fuel Injection Characteristics of CNG Engines
- CNG/ Diesel Dual Fuel Operations
- Hydrogen Enriched CNG Vehicles
- Environmental Aspect of CNG Vehicles
- Safety Aspect of CNG Vehicles

3.6.4. Research Approach

A bibliometric approach was applied to analyze the scientific publications in the field using the Web of Science Core Collection database together with Scopus Elsevier. The articles were searched using different keywords related to natural gas as transportation fuel. In addition, the study reviewed the literature from conference proceedings, PhD thesis, and reports published by international agencies e.g. IEA, US-EPA, EIA, IGU, NGV Global etc. The articles identified were critically analyzed and content was categorized under themes including: (i) regional experience with NGVs, (ii) economic aspect of NGVs, (iii) natural gas engine's design, (iv) control and performance, (v) combustion and fuel injection characteristics of natural gas engines, (vi) natural gas/diesel dual fuel operations, (vii) hydrogen enriched NGVs, (viii) environmental aspect of NGVs and (ix) safety aspect of NGVs.

3.6.5. Major Outcome

The available literature shows that CNG has seen some significant success in terms of adoption as a transport fuel in various countries around the world. According to the latest studies, putting together the short lifetime of methane (12.4 years, while for CO_2 the range is from 20 years to centuries) and a high estimate for fugitive methane emissions can result in lifecycle emissions for CNG vehicles exceeding those of modern diesel engine technology equipped with exhaust emission filter. Until this issue is settled, the environmental benefits of natural gas vehicles are uncertain. Currently there is a lack of empirical works which examine the issue of maintenance cost competitiveness of the latest NGV with diesel/gasoline technologies based on total lifecycle costs.

Similarly, a hurdle facing the NGVs right now is the price of oil, which has halved in the last year (from around $114 per barrel in June 2014 to $46 per barrel in January 2015). The questions the industry needs to confront are firstly, how long will the relatively lower oil prices last and what impact will this have on the development of NGVs. In the prevailing low oil prices, securing a return on investment is pivotal to the success of NGVs and at present, this may be a challenge. Governmental incentives, such as incremental costs of purchasing NGVs, tax deductions and credits for NGVs purchases, may help.

3.6.6. Value and Significance

At the time of publication of this study there was no comprehensive technical review that presents the progress in the mentioned eight aspects of natural gas as automotive fuel. Most of the recent research developments about natural gas vehicles are published in the last ten years (2006-2015). Hence the author of this thesis hopes that this review will be effective to apprehend the potential impact of this growing alternative fuel for the researchers intends to embark their research journey in the area of natural gas as vehicular fuel as well as to the existing researchers in this area to evaluate the progress achieved in this field.

So far the paper has been cited over 54 times across the world (e.g. Sharafian et al., 2016; Barik et al., 2017; Alrazen and Ahmad, 2018; Verma et al., 2017; Jiao et al., 2017; Liu et al., 2017; Boulahlib et al., 2018) by academic journals, PhD/Master thesis and technical books. Some of the reputable energy journal in which the paper has been cited includes Applied Energy, Renewable and Sustainable Energy Reviews, Energy Conversion and Management, Journal of the Energy Institute, Journal of Cleaner Production, Fuel, Applied Thermal Engineering. It is notable that authors from UK, Canada, China, Italy, Poland, Russia, Malaysia, Brazil, Australia, Nigeria, Columbia, Pakistan, and Switzerland have cited this paper.

3.6.7. Author Contributions

Khan M.I., conceived the idea of the paper and collected the data. Khan, M.I., Yasmeen, T., and Khan, M.I., contributed to the research design and analysis. Khan, M.I., drafted the first draft of the manuscript while all authors contributed to revising/editing the manuscript. M.I., Farooq, M. and Wakeel, M., revised the manuscript critically for important intellectual content. Khan M.I., was jointly involved with Wakeel, M for addressing the reviewers’ comments.

Chapter 4: Strategic Framework and Transitions to CNG Vehicles

4.1. Introduction

The Introduction of alternative fuel vehicles is a difficult, uncertain and slow process, mainly because of the difficulties linked with the major transformations in the social and infrastructural systems needed for new technologies (Kemp et al., 1998). Therefore, considering how to maximize the chances of success while minimizing costs and risks is likely to be worthy (Farrell et al., 2003). Despite the fact that currently there are over 26.5 million natural gas vehicles and over 31000 CNG refueling stations distributed through 85 different countries worldwide (Perry, 2018), there are a number of hindrances to their large scale market penetration and diffusion.

The collection of the papers included in this chapter, consider range of topic including barriers to NGVs, policy options; strategies rankings to adopt/develop NGVs and case study of NGVs adoption in Pakistan. Moreover, due to interconnection between the growth of alternative fuels vehicles (AFVs) and the trend in oil prices, a paper considering the trend in oil production is included in this chapter.

4.2. Paper # 7

Khan, M.I., 2017. Identifying and addressing barriers for the sustainable development of natural gas as automotive fuel. International Journal of Hydrogen Energy, 42(40), pp.25453-25473.

4.2.1. Context, Background & Problem statement

Despite the growing number of NGVs in recent years, the progress has been limited by variety of factors, including large sunk investments in traditional technologies, lack of widespread of refueling infrastructure, the higher incremental cost of NGVs, and the relatively low oil prices. Therefore it is essential to investigate the relative importance of these barriers to help develop both short- and long-term policies with clear and measurable targets that take natural gas beyond fleet applications into widespread transport markets.

4.2.2. Aim and Objectives

The overall aim of this study was to present a framework, which can be used by policy-makers to identify and evaluate the barriers to NGVs as well as possible solution to address these barriers. To achieve the above aim, the following objectives were formulated.

- To identify and categories the barriers deterring the increased use of natural gas as road transportation fuel in new as well as in mature markets.
- To analyze how the identified barriers can affect various stakeholders.

4.2.3. Contents

By studying the CNG industry of the case-study countries, the research identifies and discusses the following barriers to the adoption and growth of natural gas vehicles:

i. Financial barriers, which include additional costs to consumers, capital and operating costs for investors and resource constraints on public finances;
ii. Technical or commercial barriers, which might limit market availability and commercial feasibility;
iii. Institutional and administrative barriers;
iv. Public acceptability;
v. Legal or regulatory barriers;
vi. Policy failures and unintended outcomes;
vii. Physical barriers;
viii. Information-related barriers to NGV purchasers and fueling infrastructure providers;
ix. Barriers to private investment in NGVs and fueling infrastructure;

4.2.4. Research Methodology

This paper systematically examines NGVs adoption patterns and the evolution of pertinent market structures throughout the world but mainly concentrates on eleven countries. The eleven countries are divided into two groups:

i. Developing Countries: Those countries having GNI per capita less than $12,475 as specified by World Bank (World Bank, 2015). The selected courtiers are China, Iran, Pakistan, Argentina, India and Brazil.
ii. Developed Courtiers: Those countries having GNI per capita higher than $12,475 as specified by World Bank (World Bank, 2015). The selected courtiers are Italy, United States, Germany, Sweden and South Korea.

These case study countries were divided in the above two groups because the adoption of any alternative fuel technology has a strong connection with socio-economic status of the end user. For example as shown in Figure 1.2 (of Chapter # 01), NGVs have shown significant penetration in the Asian road transport (with overall worldwide NGVs market share are: Asia Pacific 70%, Latin America 21%, Europe 7%, Africa 1% and North America 0.8%). However, despite substantial public and private investment of more than 2.5 billion Euros, NGVs have been adopted far slower in most OECD markets than expected (von Rosenstiel et al., 2015). Moreover these case study countries represent the top NGVs countries (with respect to number of NGVs) in their respective group i.e. developed or developing countries. The selected case study countries have a wide range of market experience, spanning early development (India, Argentina, Italy), sustained growth/high penetration (China, Iran, Pakistan), and low penetration (United States).

The study uses secondary data from academic literature, published documents by the governments, published reports by a variety of international agencies, expert presentations, and grey literature comprising of government publications, reports, statistical publications, news-letters, fact sheets, working papers, technical reports, conference proceedings and policy documents. The overall methodology was based on the well-known technique known as Problem Tree Analysis, a participatory tool for identifying the main problems (barriers in this study), as well as their causes and effects, so it can be a helpful tool to identify the barriers with NGVs adoption and the strategies of how to overcome them. The methodology provides a holistic approach to the problem with the adoption of NGVs and seeks a broad perspective on all issues related to a topic and how they relate to each other. The author believes that it is ideally suited to discuss the complex interrelated issues associated with the implementation of a successful NGVs program. Its use in the context of establishing a research agenda is not common but the author believes that this approach to be a powerful tool that can provide consensus on main problems associated with NGVs market and then develop research objectives much faster than other traditional methods such as interviewing, surveys, the Delphi technique etc.

4.2.5. Main Outcomes of the Study

The main outcomes of this study are listed below:

Key lessons for developed countries include:

- In developed countries, technical and performance related issues, refueling stations and public perceptions are viewed as potential barriers to market growth. Similarly initial purchase price is perhaps the most salient for new NGVs buyers in these countries. Although the motivations of NGVs buyers are complex, purchase price and operating costs are generally the most important considerations. Financial incentives should be designed to be readily understandable by consumers and their availability should be well publicized.
- Lack of awareness, unfamiliarity and the perceived risk of purchasing NGVs appear to be the most important non-financial barriers to NGVs adoption in developed countries.
- In developed countries the government needs to encourage the aftermarket conversion of gasoline vehicles to bi-fuel CNG vehicles. This move will not only avoid the lack of CNG infrastructure that constrains the deployment of dedicated NGVs but would also decrease the incremental cost associated with NGVs.
- In developed countries, the low ratio of vehicles per refueling station is a critical challenge to balance the NGVs growth.

Key lessons for developing countries include:

- In developing countries like Pakistan, India, Brazil and China the availability of natural gas for CNG station is the major hurdle for NGVs growth.
- In developing countries economic factors such as fuel costs weigh more heavily in most consumers' purchase decisions than environmental attitudes, therefore establishing retail CNG prices of 30–50% below gasoline and diesel prices is the key to accelerate the growth of NGVs in the case-study countries.

Key lessons applicable to both developed and developing countries include:

- The main driving force in the successful removal of barriers to CNG conversion program is user economics. There must be sufficient direct operating cost savings for vehicles to provide financial incentives that result in a payback period of 2-3 years or less.
- To overcome the high cost associated with the construction of CNG refueling station, government should allow modular additions to the existing conventional liquid fuel stations. This lesson has been derived from CNG market of Pakistan where CNG refueling station

infrastructure has expanded very sharply due the fact that over 50% of CNG refueling stations has been established by upgrading the existence gasoline/ diesel station facilities to offer CNG.

- The analysis of vehicle refueling index (VRI) values suggests that successful NGVs markets have the tendency to gravitate toward VRI of 1.1 in developing countries while settle to 0.2 in developed economies. In developing countries, the trend of VRI values suggest an upper limit of 1.25 – 1.5. At VRI > 1, refueling stations increase at slower rates than the number of NGVs and the drivers have to wait for hours in long queues (e.g. Pakistan, India, Iran) to get their tanks filled.

4.2.6. Value and Significance

At the time when this study was conducted limited academic literature (Francchia, 2000; Flynn, 2002; Janssen et al., 2006; Von Rosentiel et al., 2015) was available about the market penetration and barriers faced by NGVs considering case of a single specific country. This study systematically examines NGVs adoption patterns and the evolution of pertinent market structures throughout the world but mainly concentrating on eleven countries. Since its publication the paper has been cited 6 times (Cao, 2018; Sauter-Servaes, 2018; Bufoni et al., 2018; Bishoge et al., 2019; Mamat et al., 2019) by academic journals and conference proceedings including International Journal of Hydrogen Energy, 7th International Symposium on Energy from Biomass & Waste, International Transportation and International Journal of Energy Sector Management, respectively.

4.3. Paper # 8

Khan, M.I., 2017. Policy options for the sustainable development of natural gas as transportation fuel. Energy Policy, 110, pp.126-136.

4.3.1. Context, Background & Problem statement

An increasing number of countries across the globe are considering to make use of natural gas as transportation fuel. However, due to the complex adoption dynamics and diffusion processes (the process by which new technology spread within and across economies) most endeavors to introduce and build sustainable demand for CNG vehicles have been underachieved.

There is a significant body of literature about natural gas as transportation fuel with focus on sustainable development and particular attention to: regional experiences with NGVs, economic aspect of NGVs; CNG engine's design, control and performance, combustion and fuel injection characteristics of CNG engines, Hydrogen enriched CNG and environmental and safety aspects of NGVs. However, there are limited numbers of studies focusing on developing a framework for the introduction and development of natural gas as an alternative transportation fuel in new as well as mature markets. Moreover, some countries have had successful adoption of natural gas as an alternative fuel for transportation (e.g. Pakistan, Iran, Italy) while some other countries had unsuccessful attempts in terms of transition towards NGVs (e.g. Germany, Canada, New Zealand). It was therefore desirable to examine the experience of existing natural gas vehicles programs in both developed and developing countries to provide insights into appropriate policy options for moving to sustainable natural gas transport system.

4.3.2. Aim and Objectives

The overall aim of this study was to identify the lesson to be learned from various countries that had successfully developed natural gas as an alternative transport fuel, as well as from countries that had failed or get very little success with the implementation of natural gas as an alternative fuel.

The objectives given below were set to accomplish the above aim.

- To examine the policy measures for eradicating the barriers discussed in Paper # 7 of this chapter, transition to CNG and promoting CNG as a transportation fuel without limiting the evaluation to a particular national system boundary.
- To examine the existing NGVs programs in the case study countries (mentioned in section 4.3.3) to provide insights on applicable strategies for developing natural gas as an alternative transportation fuel in other countries.

4.3.3. Contents

The study examines several success and failure fators for the introduction of natural gas vehicles (NGVs) and compares government policies for the adoption of NGVs throughout the world but mainly concentrating on twelve countries: China, Iran, Pakistan, Argentina, India, Brazil, Thailand, Italy, United States, Germany, Sweden and South Korea. The study offers a series of suggestions as to how a national government might encourage NGVs. It describes a series of steps that might be taken such as a feasibility study, demonstration trials, etc., and discusses various incentives and mandates that might be used. The study draw on the experiences of a number of countries that have developed NGVs programs to one extent or another to illustrate what has worked in the past. The study concludes with a series of observations and policy suggestions to help ease a transition towards a country's NGVs program.

4.3.4. Research Methodology

This study adopts a systems approach to the analyses of entire chain of government NGVs programs, the technical development and choices that have been made throughout the world but mainly focuses on twelve countries. Systems approach means developing a portfolio of options for the deployment and development of NGVs program and crucially by fitting them together in the best combinations to deliver value for all stakeholders. This study departs thus from examining individual policy instruments by considering the cumulative impacts of many combined programs and including frame-work conditions, such as, collaboration among key stakeholders, govt incentives and others.

Content analysis was used to analyze the worldwide NGVs policy options to determine its type and the instruments it contained. Content analysis is a research method which allows the quantitative and qualitative data collected in research to be analyzed systematically and reliably so that generalizations can be made from them in relation to the categories of interest to the researcher. Considering policy options associated with the devolvement of natural gas as an alternative transportation fuel which involves both quantitative (tax rate, fuel price, excise duty etc.) and qualitative data (reserved parking, access to HOV lanes, No-Wait' taxi zones, etc), so content analysis was believed to be an appropriate method for analyzing policy options associated with the development of NGVs. Initially, the content analysis approach was applied in this research for the basic analysis of documents and their categorization according to their relevance and significance to the subject and context. In addition, according to the results of the documents analysis, they were classified in subtopics as market-based instruments, non-monetary incentives and Command and control measures.

To analyze the transition to natural gas based transportation system, the following questions were considered:

i. How can a country adopt natural gas as a domestic transportation energy source towards sustainable transportation.
ii. Who are the stakeholders in the adoption of natural gas as domestic transportation energy source and what are their entrenched interests?
iii. How can the country balance the stakeholders' interests, navigate and implement a successful natural gas adoption strategy in domestic transportation?
iv. What steps should the country take and within what time frame, to achieve successful adoption of natural gas in domestic transportation?

4.3.5. Main Outcomes of the Study

Keeping in view the international experience with natural gas as an alternative transportation fuel, this study suggests a strategic framework for transition challenges to NGVs and examines the policy instruments, incentives, and economic drivers associated with the adoption of NGVs in selected case-study countries. Key outcomes of the study include:

- There is no universal policy for the implementation of natural gas as a transportation fuel. Different policy models have been applied in different economies with varying levels of success. It is identified that a combination of the various policy measures is required to accelerate the growth of NGVs.
- Introduction of natural gas as transportation fuel and establishment of sustainable market is considerably and effectively done in developing countries when compared with developed countries. This is mainly due the availability of financial support to lower income families who also owns a vehicle.
- Ultimately, the government should take the main responsibility to balance the stakeholders' interests and knitting stakeholders for introduction of NGVs. At the initial stage it is important that the government crafts the necessary regulatory and other related frameworks by taking the pertinent industry (e.g. auto maker, fuel supplier) on board.
- It is important that government establishes a network of competent players specifically in the areas such as NGVs producers, operators for fleet, natural gas suppliers and existing petroleum fuel retailers. It is also important for NGVs program to duly address the concerns of stakeholders who have major role in the NGVs market pick e.g. related players have in-depth knowledge of the relevant business (gasoline/ diesel station owners).

- The engagement of a national automotive manufacturing industry in the introduction of NGVs greatly accelerate the market growth.
- The importance of providing substantial and sustained financial incentives to reduce the costs of NGVs for consumers is the most consistent finding in the case-study countries that have received substantial growth of their NGVs program in terms of number of NGVs and refueling stations. Therefore the government should institute predictable and persuasive financing options to overcome incremental costs associated with the NGVs.
- Establishing predictable profit margins to influence the retail station investment decisions.
- Sending clear, reliable and enduring CNG price signal to consumers.
- Government policies need to be consistent and stable to assure customers of long term market initiatives.

4.3.6. Value and Significance

At the time when this study was conducted limited academic literature was available pertinent to the policy options for the development of alternative fuel vehicles (AFVs). Most of the available studies either considered electric AFVs (Zheng, 2012) or hydrogen fuel cell AFVs (Kang and Park, 2011) or both type of AFVs (Kwon, 2012; Tran, 2013). In addition the available studies (Zhang et al., 2011; Kwon, 2012; Ardila and Franco, 2013; Tran, 2013) have used mathematical modeling (e.g. agent-based model, strategic niche management) that incorporates a number of statistical assumptions regarding the creation of sample data. A further shortcoming of the available studies is the fact that they are country specific (Åhman, 2006; Yao, 2011; Dietrich, 2017). Hence, in this studying by analyzing the policy options for NGVs in multi-countries (from developed and developing economies) would address the literature's gap since perception of natural gas as alternative fuel may vary between countries and cultures. Since the publication this study, it has been cited 12 times (e.g. Lorenzi and Baptista, 2018; Rowland et al., 2018; Osička et al., 2018; Li et al., 2018, Mamat et al., 2019) by academic journals and conference proceedings including Journal of cleaner production, Journal of the American Chemical Society, Energy Policy, and others.

4.4. Paper # 9

Khan, M.I., 2018. Evaluating the strategies of compressed natural gas industry using an integrated SWOT and MCDM approach. Journal of Cleaner Production, 172, pp.1035-1052.

4.4.1. Context, Background & Problem statement

Although Iran holds the largest share (12.5%, 52 thousand million tons of oil equivalent) of total global proven oil and gas reserve (BP Energy Outlook, 2018), it lacks refining capacity to produce gasoline which accounts for approximately 50% of energy consumption of the Iranian transport sector (Sarabi, 2011; Kachoee et al., 2017). As of 2013, the country was heavily (~40%) dependent on imported gasoline making Iran the second largest importer of gasoline in the world (Ogunlowo et al., 2015). However, in recent years, due to the heavy investment of the country in petroleum refining sector, the reliance on imported gasoline decreased to 16% in 2017 (EIA, 2018). Given the number of light-duty vehicles in Iran by 2011, the average daily consumption of gasoline for each car was 10.5 liters, which is about 5.2 and 2.6 times that of the same index in Europe and the United States respectively (IFCO, 2012). Owing to high petroleum fuel consumption of the Iranian transport sector, high emissions associated with the local petroleum fuels (gasoline, diesel) and high gasoline imports, the country's energy security and environmental considerations are indispensable. Currently Iran's most significant energy policy is to reduce shares of oil and oil products in the national energy basket and to substitute it for natural gas and renewable energies (Hafeznia et al., 2017).

Energy security and economic interests instigated the use of natural gas as a transportation fuel in Iran (Korin and Luft, 2006; and Nijboer, 2010). In this context, the Iranian parliament passed a law in 2001 about the development of NGVs program and consequently in the same year the Government started to plan and execute national scale NGVs projects via Iranian Fuel Conservation Organization (IFCO). Substituting gasoline with CNG therefore offered a potential solution to a number of challenges (Korin et. al., 2006; Nijboer, 2010). However, if energy policy for road transportation is developed on the basis of political motivations rather than careful scientific evaluation of multiple criteria, it likely fails in terms of sustainability and acceptability (Rahman et al., 2016). This is due the fact that political decisions usually avoid considering a number of feasible options under particular circumstances and places them in clusters of 'competing strategies' to accomplish policy goals (Howlett, 2019). Therefore, in order to model the energy policy of road transport, it is necessary to explicitly consider multiple objectives that can appropriately meet the interests of stakeholders and the criteria for sustainability. For this reason, policymakers require detailed information and insights into multiple objectives to endorse appropriate policy measures (Strachan et al., 2009). However since the inception of Iranian CNG program no systematic study was conducted to evaluate the strategic portfolio management of the country's CNG market that provides the insight to reflect the future direction and lead to mitigate the risks for future CNG market's growth. Given this lack of research about Iranian CNG program, this study aims to fill the research gap by identifying the key features of CNG economy in Iran and rank strategies for promoting its development towards a more environmental-friendly alternative at a reasonable financial cost.

4.4.2. Aim and Objectives

The overall aim of this study is to develop a sustainability decision support framework for the strategies prioritization of Iranian CNG industry which can ensure a long-run trade-off among environmental integrity, technical compatibility and economic efficiency while facilitating stakeholder engagement.

The objectives given below were set to accomplish the above aim.

- To formulate the strategies for the development of Iranian CNG sector by applying strengths, weaknesses, opportunities and threats (SWOT) analysis.
- To establish appropriate multi-criteria decision-making (MCDM) technique for prioritizing the strategies obtained through SWOT analysis

4.4.3. Contents

In this study, the method of SWOT analysis is applied to explore the strengths, weaknesses, opportunities and threats of Iranian CNG industry. Consequently, the strategies were proposed for stimulating its growth by applying strengths, minimizing weaknesses, exploiting opportunities and avoiding threats. Based on SWOT analysis nine strategies were suggested. While the SWOT method does not provide an analytical way to quantify the effectiveness and to prioritize the proposed strategies according to their importance, a multi-criteria decision-making (MCDM) method was developed to rank the preferable sequence of the strategies. By combining the MCDM and SWOT methods, the stakeholders/ decision-makers can make appropriate decisions by considering top priority to these strategies that have significant effect on the development of CNG economy. The study further analyzed the roles of the different stakeholders involved in the decision making process and their impacts on the overall ranking of options, from a weighting perspective.

4.4.4. Research Methodology

SWOT and MCDM were combined to present a framework for the strategies formulation. SWOT was used to examine the CNG market in Iran and to design the productive future strategies to stimulate the growth of CNG industry in Iran. SWOT analysis has several examples of its application in the area of regional energy planning (Fertel et al., 2013), sustainable energy development (Markovska et al., 2009, bioenergy (Catron et al., 2013), wind energy (Iglinski et al., 2016), solar energy (Sindhu et al., 2017), environmental policy and management (Groselj and Stirn, 2015; Alvarez et al., 2016) and development of shale gas (Xingang et al., 2013). However one of the major limitations of traditional SWOT method is that the significance of each element in the process of decision making cannot be quantified, and it is hard to evaluate which element is more influential for the strategic decision (Pesonen et al., 2001). SWOT method is unable to propose an analytical approach to find the relative significance of the individual factors, or the capacity to evaluate the suitability of alternate options (European Commission, 2004). Therefore, the comprehensive appraisal of the strategic decision-making process cannot be made through SWOT (Hill and Westbrook, 1997). Hence, SWOT analysis was integrated with a suitable MCDM technique like Goal Programming to be able to quantify the significance of individual factors involved in decision making process.

For SWOT analysis, this study used the author's own personal data collected during several years of experience with CNG industry, secondary data from academic literature, published reports by a variety of Iranian agencies, expert presentations, and supplemented by a questionnaire survey.

As SWOT method does not provide an analytical way to quantify the effectiveness and to prioritize these strategies according to their importance. Fuzzy Goal Programming (GP) as an MCDM technique was subsequently employed to rank the proposed strategies in terms of their relative importance on promoting the sustainable development of Iran's CNG industry. By combining the MCDM and SWOT methods, the stakeholders/ decision-makers can make correct decisions by giving top priority to these strategies that have significant effect on the development of CNG economy in Iran. In this study, an MCDM method by integrating Goal Programming (GP) and fuzzy theory has been developed for prioritizing the strategies for promoting CNG economy of Iran, in which, the fuzzy theory was used as a bridge to link the linguistic variables and crisp numbers by membership functions of the linguistic variables.

The proposed decision-making matrix consists of nine alternatives strategies, twenty criteria factors, and goals of the stakeholders/decision-makers. In the proposed fuzzy GP method, linguistic terms were applied to measure the effectiveness of each strategy and selecting the strategy that can fulfill the goals set by decision makers/stakeholder in best possible manner.

4.4.5. Main Outcomes of the Study

In the SWOT analysis, twenty sub-factors (Figure 4.1) were identified to depict the current status of CNG market in Iran.

Strengths (S) S_1: Owner of world largest proven natural gas reserves. S_2: Well-developed natural gas infrastructure and availability of various models of NGVs from local auto maker. S_3: Strong government support. S_4: Favorable CNG price compared to gasoline. S_5: Great development potential.	**Opportunities (O)** O_1: Enhancement of energy security and national self-reliance. O_2: Economic opportunity value of the abundant indigenous reserves of natural gas O_3: Reduction of urban air pollution and health effects. O_4: Potential for job creation and export of CNG technology. O_5: Substitution of imported gasoline and saving of foreign exchange.
Weaknesses (W) W_1: Lack of CNG usage in heavy duty public road transport e.g. buses W_2: The high price of CNG as compare to diesel. W_3: Lack of public access to the reliable and comprehensive government's CNG policy. W_4: Heterogeneous geographical distribution of CNG refueling stations. W_5: Lack of dedicated CNG engine technology.	**Threats (T)** T_1: Lack of private investment in CNG refueling station. T_2: Decrease in government's support and incentive in recent years. T_3: U.N. sanctions on Iranian banks, trade and technology transfer. T_4: Lack of Public's safety awareness and enforcement of safety and emissions regulations. T_5: Strong lobby from diesel fueled fleet operators who prefer to maintain a liquid fuel "status quo"

Figure 4.1. Key SWOT factors for CNG Industry of Iran.

Based on the above twenty SWOT factors, four types of strategies were obtained including:

i. Strength – Opportunity (SO) strategies,
ii. Weakness – Opportunity (WO) strategies,
iii. Strength – Threats (ST) strategies,
iv. Weakness – Threats (WT) strategies,

- The SO strategies consisting of developing large scale CNG technologies, adopting vehicle emission standards and desulfurization of gasoline/ diesel,
- WO strategies comprising enhancing CNG Price differential with respect to diesel, encouraging private investment in CNG refueling infrastructure and foreign capital importation,
- ST strategies including establishing CNG development as preferable strategy in Iran and government subsidies/ incentives allowance, and
- WT strategies consisting of establishing a comprehensive fuel pricing mechanism.

The developed MCDM method by integrating Goal Programming with fuzzy theory was then applied to prioritize the strategies for appropriate budget planning and setting the roadmap for the development of CNG industry in Iran. To apply fuzzy GP method to this study, first nine strategies were proposed and then experts/stakeholders were asked to evaluate the performance of alternatives for each criterion by using the linguistic variables including worst, worse, bad, medium, good, better, and best. The weightage to each criterion were then assigned by using nine linguistic including:

i. significantly high,
ii. very very high,
iii. very high,
iv. high,
v. medium,
vi. low,
vii. very low,
viii. very very low, and

ix. significantly low.

Subsequently the linguistic terms were first converted into triangular fuzzy numbers (Mazloumzadeh et al., 2008) and triangular fuzzy numbers were then transformed into crisp number by center of gravity (COG) method (Ross, 2016).

The proposed methodology allows the stakeholders/decision-makers using linguistic terms to express their options and views on the sustainability of various strategies and the critical success factors for sustainable growth of natural gas as transportation fuel in Iran. The sequence of the strategies from the most effective and important to the least was measured to be:

- establishing CNG development as preferable strategy,
- government subsidies and incentives allowance,
- encouraging private investment in CNG refueling infrastructure,
- desulfurization of gasoline and diesel,
- establishing a comprehensive fuel pricing mechanism,
- foreign capital importation,
- developing large scale CNG technologies,
- enhancing CNG Price differential with respect to diesel, and
- adopting stringent vehicle emission standards e.g. Euro VI, US EPA Tier 3.

According to the sequence of priority, stakeholders/decision-makers can draft the future actions towards a better future of CNG economy in Iran.

4.4.6. Value and Significance

Assessments of energy planning for road transportation system scenarios with MCDM have been carried out before but there are very limited studies which integrate SWOT analysis with MCDM approach. Moreover the MCDM approach used in the available studies are different in terms of the theoretical background, questions type and the achieved findings. Most of MCDM studies (Yedla Shrestha, 2003; Macharis et al., 2004; Tzeng et al., 2005; Brey et al., 2007; Mohamadabadi et al., 2009; Vahdani et al., 2011; Tsita and Pilavachi, 2012; Zubaryeva et al., 2012; Yang and Regan, 2013; Tsita and Pilavachi, 2013; Shiau, 2013; Jones et al., 2013; Streimikiene et al., 2013; Lanjewar et al., 2015; Zhang et al., 2016; Maimoun et al., 2016) pertinent to automotive fuel and technology have been focusing on suitability of a specific fuel among various available options. There are very limited MCDM studies addressing the strategies prioritization for a particular type of fuel. By the time of publication this study, to the best of the author's knowledge, there was no systematic empirical research existed addressing the question of strategies prioritization for CNG industry. CNG sector often cope with many concerns related to economic, environmental, legal and technical issues, which should be addressed to get a successful market penetration of natural gas as transportation fuel. A common approach that integrates the stakeholder visions into the evaluation process of CNG options is currently lacking. In this study, a methodology is proposed that addresses the above mentioned problem. Taking into account the current and midterm state of Iran's natural resources, as well as environmental and sustainability issues, the results of this study could provide useful insight on the diversification of natural gas as vehicular fuel and overcome the research and policy gaps in the context of Iran. The suggested technique is not limited to Iran, and it is a generic practice that can also be applied to evaluate the CNG market in other countries. Since its publication this study has been cited 18 times (e.g. Gottfried et al., 2018; Wang and Tsai, 2018; Xu and Dong, 2019; Hashemizadeh and Ju, 2019, Erdogan et al., 2019) by academic journals and conference proceedings including Journal of Cleaner Production, Energies, Clean Technologies & Environmental Policy, International Journal of Environmental Science and Technology, respectively.

4.5. Paper # 1

Khan, M.I. and Yasmin, T., 2014. Development of natural gas as a vehicular fuel in Pakistan: issues and prospects. Journal of natural gas science and engineering, 17, pp.99-109.

4.5.1. Context, Background & Problem statement

With the aim to curtail the reliance on imported oil and improving urban air quality, in 1998 the government of Pakistan announced a two year goal of establishing 150 CNG stations and conversion of 100,000 vehicles to natural gas fueled vehicles. Soon after the implementation of the program, the NGVs market had witnessed a significant growth at an unprecedented rate of around 40% per annum till 2013 (year of this study). Within the ten year period Pakistan became the world leader in CNG market with highest number of vehicles operating with natural gas. By 2013, about 80% of the total fleet of light vehicles (3.5 millions) in the country consisted of bi-fuel CNG vehicles. The rapid development of CNG in Pakistan brought a series of problems as well. In spite the tremendous growth CNG fuel which makes Pakistan the world leader in the

CNG market, no research was conducted about any aspect (e.g. economic, policy and environmental) of Pakistan CNG sector at the time of this study. Given the lack of research in this arena, this study was conducted to consider the various success factors, advantages and challenges for the future growth of CNG market in Pakistan.

4.5.2. Aim and Objectives

The aim of this study was to examine the natural gas vehicle (NGVs) implementation approaches and outcomes in Pakistan and to identify ways forward to modify and improve the country CNG program.

The objectives given below were set to accomplish the above aim.

- To analyze the key factors associated with the rapid growth of CNG technology in Pakistan;
- To assess the current problems associated with CNG industry;
- To assess the economic benefits of substituting the oil based fuel (gasoline and diesel) with CNG and enhancing the national energy security by breaking the current petroleum fuel (diesel and gasoline) dominance in road transport sector;
- To explore the risks of future lock-in effects and undesirable path dependencies associated with promoting natural gas as transportation fuel.

4.5.3. Content

The study attempts to systematically analyze the key steps in the deployment of natural gas as an transport fuel in Pakistan and to determine important policy implications for the sustainable future growth of NGVs market. The study starts with a brief outline of the CNG industry development in Pakistan and describes the government role in promoting natural as an alternative transportation fuel. This description is followed by the analysis of the prospects and challenges of CNG market in Pakistan. The study analyses the economic and environmental advantages associated with the CNG program in Pakistan. In addition, the study discusses the problems caused by the rapid growth of the country's CNG industry, both for the government and for the general public.

4.5.4. Research Methodology

To explore the intricacies of the Pakistan CNG program and the transport energy challenges confronting Pakistan, this study relied on an inductive, narrative case study approach derived from data collected through narrative inquiry from various stakeholders pertinent to CNG program in Pakistan (e.g. natural gas suppliers, automakers, fleet operators, regularity authorities, environmental agencies). This method enabled us to ask expert participants a set of standard inquiries but then allowed the conversation to build and deviate to explore new directions and areas of inquiry. We relied on both quantitative and qualitative methods because many of the variables of interest to us, such as the factors explaining the benefits and challenges to the Pakistan CNG program, are difficult to measure, and cannot be described with quantitative data alone. During the discussion, experts were asked about (i) what are the most serious energy challenges facing Pakistan transport sector, (ii) what are the key benefits of Pakistan CNG program, and (iii) what are the key barriers to Pakistan CNG program. The data was further supplemented through secondary data from academic literature and grey literature comprising of expert presentations, news-letters, working papers, technical reports, published reports by a variety of international agencies e.g. Natural & bio Gas Vehicle Association (NGVA Europe), International Association for Natural Gas Vehicles (IANGV). Documents published by Pakistani government were gathered to help understand the historical processes and developments of the government's policies for the development of natural gas as transportation fuel in Pakistan. The documents collected include government policy papers, the annual reports of the Hydrocarbon Development Institute of Pakistan (HDIP), Oil & Gas Regularity Authority (OGRA), Ministry of Petroleum & Natural Resources, the files for the loan applications and project financing for the 12 industrial enterprises, etc. This approach to data collection was used for triangulating data and helping to counteract the biases of other approaches such as in-depth interviews and experts' opinions and to supplement sources of information. In order to understand the consumer preferences and identify the causes of the current problems associated with CNG market growth, walk-through surveys were held with a number of drivers/professionals having experience in CNG market. In the last content analysis was used to analyze the various attributes of Pakistan of CNG program to determine its type and the instruments it contained.

4.5.5. Main Outcome

The main outcomes of this study are listed below:

- Due to Government's consumer friendly policy, ample regulatory framework and available price difference between CNG and gasoline/ diesel, NGVs have increased significantly at an average rate of around 40% per annum during 1998 - 2013.

- The country has an efficient gas transmission and distribution networks for utilization of natural gas transportation fuel. CNG is going to witness a phenomenal growth with growth of transmission pipeline network and implementation of city gas distribution network in various cities of the country.
- In Pakistan, from the vehicle owner's prospective the attraction for CNG is not due to its environmental impact, but its cost advantage over gasoline and diesel.
- Due to lack of sustainable gas energy plans, the Pakistan's gas supplies cannot support the high demand of CNG sector while also facilitating the gas demands of power generation, fertilizer industries and other gas-dependent businesses. So the officials are now struggling with the difficult task of trying to turn back the country's NGVs policy in order to divert the natural gas to industry and power plants. The decision by the government to curtail the gas supply to CNG sector will adversely affect hundreds of thousands of workers associated with $5 billion CNG industry of the country.
- CNG has substituting around 20% of oil (gasoline & diesel) consumption in road transport sector of the country and save foreign exchange amounting to billions of dollars. Therefore discontinuing the use of CNG as a transportation fuel will add to the economic woes of the government that will have to spend 5 - 6 billion US dollars more to import additional quantities of gasoline and diesel.
- The CNG sector has created more than 121,000 cumulative (direct and indirect) job opportunities. So the decision by the government to curtail the gas supply to CNG sector will adversely affect hundreds of thousands of workers.
- To quantify the environmental benefit of the country CNG program, there is a need for quantitative assessment of ambient air of quality in the major cities of Pakistan.
- In order to meet the shortfall of gas for CNG industry, it is essential that natural gas need to be imported on fast-track basis either through Turkmenistan-Afghanistan-Pakistan (TAP) or Iran-Pakistan (IP) gas pipeline project or LNG.
- The pricing of all fuels needs to be rationalized and brought at par in order to create a level playing field and to ensure there is not over-consumption of a particular fuel.

4.5.6. Value and Significance

Until this study was undertaken there had been no previous studies pertinent to the deployment of natural gas as transportation fuel in a specific country. However in recent years, several peer review studies on the subject have been produced in different regions, including Ma et al., 2013 (case study of China); Kirk et al., 2014 (case study of UK); Simmer et al., 2014 (case study of Austria); Wang et al., 2015 (case study of China); Ogunlowo et al., 2015 (case study of Nigeria); von Rosenstiel et al., 2015 (case study of Germany); Hao et al., 2016 (case study of China); Chikishev et al., 2016 (case study of Russia); Patankar and Patwardhan, 2017 (case study of India).

So far the paper has been cited 38 times across the world (e.g. Khamforoush, et al., 2014; Shah and Zeeshan , 2016; Song et al., 2017; Hegab et al., 2017; Hamid et al., 2018; Ullah et al., 2018; Goulding et al., 2019; Kalinichenko et al., 2019) by academic journals. Some journals in which the paper has been cited includes Journal of Natural Gas Science and Engineering, Atmospheric Environment, Environmental Science and Pollution Research, Renewable & Sustainable Energy Reviews, Science of the Total Environment, Energy, Renewable Energy, Journal of Energy Institute. It is notable that authors from universities of UK, China, USA, Thailand, Pakistan, Nigeria, Russia, Brazil, Malaysia, Iran, Oman, Ireland, Bangladesh and World Bank have cited this paper.

4.5.7. Author Contributions

Khan M.I., conceived the idea, designed the research, collected the data. Khan M.I., contributed to the data analysis and interpretation of the results with input from Yasmeen T. Khan M.I., was also responsible for developing and writing the first draft of the manuscript while Yasmeen t., contributed to revising/editing the manuscript critically for important intellectual content. Khan M.I., addressed the reviewer' comments.

4.6. Paper # 6

Khan, M.I., 2017. Falling oil prices: Causes, consequences and policy implications. Journal of Petroleum Science and Engineering, 149, pp.409-427.

4.6.1. Context, Background & Problem statement

Due to heavy reliance of the transportation sector on oil (gasoline and diesel), analyzing the trend of oil price is important in making decisions about alternative fuel vehicles (AFVs) policy, capital investment in AFVs infrastructure, risk and portfolio management. A prolonged decline in oil prices is significant as low fuel prices are known to trigger a trend towards vehicles with greater fuel consumption e.g. SUVs (sport utility vehicles), trucks and bigger cars (Baur and Todorova, 2018) which subsequently leads to decline in alternative fuel vehicle growth. Moreover the oil prices largely drove innovation dynamics in alternative transportation fuel technologies. For instance, results from the recent studies (Kim, 2014; Guillouzouic-Le Corff, 2018) suggested that increases in oil prices were greatly spurred innovation in AFVs technologies. This is because, customers who face high fuel prices prefer to select vehicles with high fuel efficiency or alternative vehicles rather than the conventional vehicles. This is in turn increase the demand for efficient or alternative vehicles in the market. Driven by the increased customer demand, automakers start to raise their investment in the innovation of alternative fuel vehicles (Kim, 2014). In Paper # 7 of this chapter, it is observed that a significant fuel cost difference between oil (gasoline/ diesel) and CNG provides noticeable fuel cost savings. This differential cost shrinks the payback period associated with an incremental cost of purchasing natural gas vehicle in contrast to the cost of comparable gasoline/ diesel vehicle.

Therefore the oil price is considered as an important measure for the sustainability and penetration of alternative transportation fuel in low-carbon world (Winchester and Ledvina, 2017). In a recent study by Wallington et al. 2017, explored the trends in oil production and their implications for alternative fuel powertrains sustainability studies. They argued that when comparing alternative fuel-vehicle systems, life cycle analysis (LCA) studies should consider the trends in oil production. Therefore before conducting the Life Cycle Analysis of vehicular fuel in Pakistan, this study was carried out regarding the dynamics (prices, demand/supply and extraction technology) of current oil market. The main objective of this paper is to assess the causes and consequences of the sharp decline in crude oil prices since 2014 and to apprehend the impact of the latest technology on future oil extraction. However the secondary objective is to consider the trends in future oil markets for conducting the life cycle assessment study of automotive fuel presented in Chapter # 5 (paper # 11 & 12). At time when the idea of this paper was conceived, an unexpected fall in oil prices was observed, from around $114 in June 2014 to $46 in January 2015. So this study was conducted to investigate the factors responsible for this decline and suitability of oil market in coming future.

4.6.2. Aim and Objectives

The overall aim of this study was to presents an evaluation of factors associated with sharp decline of oil prices since 2014.

The objectives given below were set to accomplish the above aim.

- To analyze role of the major influencers: global oil demand and supply, OPEC, US dollar in falling oil prices.
- To compare the recent plunge in oil prices with previous episodes.
- To analyze attribution of shale revolution and hydraulic fracturing in falling oil prices.
- To analyze the future trend of oil market.

4.6.3. Content

In the introduction the study discusses previous literature about 2014 oil prices plunge. Most the studies available in literatures have concluded that the oil production boom in the United States and Iraq is the main cause for the plunge in oil prices since 2014. The literature review follows a historical perspective of oil prices dynamics and presents the comparative evaluation of the recent decline in oil prices with previous episodes during the period 1996–2014. The study then describes the world oil supply and demand and quantitatively analyzes the effect of the various factors associated with the fall in oil prices since 2014. It is shown that the supply and demand formula cannot be applied to the recent decline in oil prices. The role of the key players, including US shale oil evolution, OPEC, Saudi Arabia and U.S. dollar exchange rate are discussed in detail. This is followed by contribution of the geopolitical strategies of US and Saudi Arabia to the falling oil price since 2014. Subsequently the study focuses on the consequences of low oil prices since 2014. Finally, the study analyzes the projections of oil prices.

4.6.4. Research Methodology

The study applies desk research methodology by using secondary data from academic literature, expert presentations, statistical publications, and published reports by a various international agencies including: U.S. Energy Information Administration (EIA), International Energy Agency (IEA), International Monitoring Fund (IMF), World Bank, Organization of the Petroleum Exporting Countries (OPEC), OECD (Organization for Economic Cooperation and Development and New York Mercantile Exchange (NYMEX) data of WTI Crude Oil prices and Baker Hughes data show US oil-rig count. The data was further supplemented through expert's opinion. A number of international crude oil analyst were contacted to get their expert opinion through a semi-structured questionnaire. Some of the key experts included in the survey are listed below:

- Terry Macalister (former energy editor of the Guardian)
- Thomas D. Cabot (a professor of Economics at Harvard University)
- Bruce McCain (Chief Investment Strategist for Key Private Bank)
- Art Berman (an expert on U.S. shale oil)
- Neil Irwin (a senior economics correspondent for The New York Times)
- Kenneth Rogoff (a professor of Economics at Harvard University)
- Clifford Krauss (a national energy business correspondent based in Houston)
- Lutz Kilian (Professor of Economics at University of Michigan)
- Christiane Baumeister (an economist at Bank of Canada)
- Chris Lafakis (a Senior Economist at Moodys)
- Paul Stevens (a professor of Petroleum Policy and Economics)
- Luay al-Khatteeb (director of the Iraq Energy Institute)
- Russell Gold (a senior energy reporter for the Wall Street Journal)
- Robert Rapier (an Energy Strategist)
- Tim Daiss (an oil markets analyst)
- James Hamilton (Editor of Econbrowser)
- Steve Austin (Editor for OIL-PRICE.NET)
- Dr Salman Ghouri (an Oil & Gas advisor)
- Arthur E. Berman (a petroleum geologist)

To analyze the analyze the causes and impacts of falling oil prices, the following questions were considered:

- How does the recent plunge in oil prices associate with previous episodes?
- What causes a sharp drop in oil prices?
- How the oil prices looks in future?
- How falling oil prices could affect oil exporting and importing countries
- What are the financial and macroeconomic implications?
- What are contributions of geopolitical strategies toward recent plunge?

4.6.5. Main Outcome

Both long- and short-term factors contributed to the recent plunge in oil prices, including:

- a surge in oil supply due to the shale revolution in the U.S. and Canada,
- robust production in the Middle East from Saudi Arabia and Iraq,
- change in OPEC policy objectives,
- a slowdown in the Chinese economy that has diminished expectations of future demand, and
- a rapid rise in the value of the dollar relative to other currencies.

While U.S. shale oil producers will struggle to stay profitable amongst low oil prices, their rise has significantly changed the economics of global oil production. The very fact that Saudi Arabia and other OPEC members chose not to cut production in order to boost oil prices because they are wary of losing market share suggests that a future oil embargo like that of the 1970s is unlikely. Any attempts to cut production and limit the supply to the rest of the world will quickly revive shale oil production in order to fill the supply gap. One of the implications of the recent oil revolution is that U.S. production can play a significant role in balancing global demand and supply, and this in turn implies that the current low oil prices environment could be persistent. Some high-cost shale production is closing, but once wells are drilled, it usually makes sense to keep pumping, even at a loss. It is very difficult to make firm projections about the future oil prices, as there are several contradictory variables that that affect oil prices, from supply and consumption, technological development, global financial environment and geopolitics (which is inherently unpredictable), but it is important to be conversant with some factors that have a high probability to force the oil prices lower for next couple of years.

4.6.6. Value and Significance

The recent collapse in oil prices has prompted to a large body of literature evaluating the causes of this abrupt drop in oil prices and its macroeconomic implications. However, most of these literatures are produced mainly by international organization e.g. the IMF blog by Rabah and Oliver (2014), World Bank Policy Research Note (Baes et al., 2015), IMF Staff Discussion Note (Aasim et al., 2015), investment banks (such as Goldman Sachs Global Investment Research division's report on "The New Oil Order" (Damie et al., 2015)), and internal reports by oil and gas companies. By the time of publication this study, to the best of author knowledge, there was limited peer-reviewed academic studies (Tokic, 2015; Mănescu and Nuño, 2015; Fantazzini, 2016) available analyzing the recent oil prices plunge. This study extended the literature in a number of respects e.g. attribution of shale revolution and hydraulic fracturing, geopolitical strategies of oil exporting countries and disparities of recent oil prices plunge with the previous.

Since its publication this study has been cited 22 times (e.g. Reddy and Xie, 2017; Ansari, 2017; Menhat, 2017, Leung et al., 2018; Uriondo et al., 2018; Ghaithan et al., 2018; Azadeh et al., 2018; Talebbeydokhti, 2018; Ediger and Berk, 2018) by academic journals, PhD thesis and technical books including Renewable and Sustainable Energy Reviews, Energy Policy, PhD Thesis - University of Central Lancashire, Transportation Research Part D, Fuel, Applied Mathematical Modelling, Journal of Petroleum Science and Engineering, PhD Thesis - University of Padua Italy, Energy economy, finance and geostrategy- Book, respectively.

Chapter # 5: Life Cycle (Well-to-Wheel) Assessment of Natural Gas as a Transportation Fuel

5.1. Introduction

To cut greenhouse gas (GHG) emissions and their environmental impact, worldwide costumers and organizations are looking for low-carbon alternatives transport fuel options to conventional gasoline and diesel fuel. The higher hydrogen-to-carbon ratio of natural gas makes it ~25% less carbon-intensive than diesel and gasoline. However, there is disagreement as to the magnitude of benefit that natural gas can deliver. Some argue that while natural gas burns cleaner at the consumer stage, it can produce considerable GHG emissions at the exploration and production stage, mostly due to fugitive methane, which may be under-reported (Kollamthodi et al., 2016). Therefore to evaluate the overall impact of fuels the whole supply chain has to be considered.

To evaluate and assess the environmental effectiveness of automotive fuels and vehicle technologies, a holistic or comprehensive approach has to be considered. The approach, often referred to as life cycle approach, or life cycle assessment (LCA), which must include all the steps required to produce a fuel, to manufacture a vehicle, and to operate and maintain the vehicle throughout its lifetime including disposal and recycling at the conclusion of its life cycle. A lifecycle analysis of energy consumed and emissions generated is especially important for technologies that employ fuels with different primary energy sources and fuel production processes. A vehicle's LCA consists of four stages – vehicle production, fuel production, use and end of life. A vehicle LCA study may consider the whole life of the vehicle, or just part of it, such as well-to-wheel or cradle-to-gate.

The well-to-wheel (WtW) analysis indicates the study of the energy use and environmental emissions in the production of the fuel and its use in the vehicle or engine, hereinafter called WtW analysis. The WTW approach does not consider energy or emissions involved in the construction of the facilities, the vehicles, consumption of other materials, water, and end of life disposal (Di Lullo et al., 2016). The whole WtW cycle is comprised of two independent stages, as shown in Figure 5.1. These include (i) a Well-to-Tank (WtT) stage, which includes the recovery or production of the feedstock for the fuel, transportation and storage of the energy source through conversion of the feedstock to the fuel and the subsequent transportation, storage, and distribution of the fuel to the vehicle tank, and (ii) a Tank-to-Wheel (TtW) stage, which refers to the vehicle in utilizing the fuel for traveling purposes throughout its lifetime.

This chapter as tandem of two papers is concerned with the Well-to-Wheel (WtW) analysis of natural gas as transportation fuel considering Pakistan as case study. The WtT results of part-I (Paper # 11) are combined with the TtW results reported in part-II (Paper # 12) to provide the comprehensive WtW (Well-to-Wheel) results for the operation of conventional and CNG passenger vehicle drivetrains specific to Pakistan.

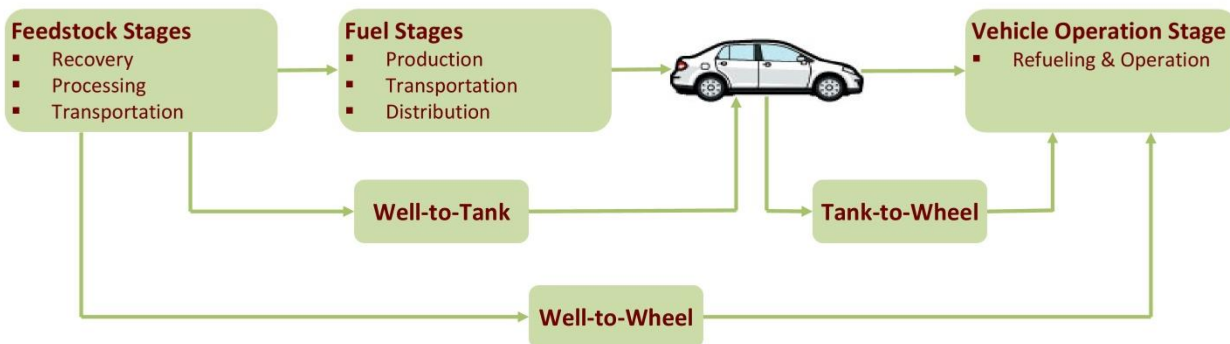

Figure 5.1. System Boundary of Well-to-Wheel Analysis of the Case Study Fuels

5.2. Paper # 11 and 12

Khan, M.I., 2018. Comparative Well-to-Tank energy use and greenhouse gas assessment of natural gas as a transportation fuel in Pakistan. Energy for sustainable development, 43, pp.38-59.

Khan, M.I., Shahrestani, M., Hayat, T., Shakoor, A. and Vahdati, M., 2019. Life cycle (well-to-wheel) energy and environmental assessment of natural gas as transportation fuel in Pakistan. Applied Energy, 424, pp. 1738-1752

5.2.1. Context, Background & Problem statement

Being the world's 6th most populated nation, its energy requirement establishes Pakistan as a major contributor of GHG emissions. Therefore, the reduction of the GHG emissions in Pakistan has attracted substantial attention. The energy consumption of the road transportation sector accounts for 33% of the total energy consumption in Pakistan (Pakistan Energy Yearbook, 2017) and is responsible for a significant share (around 25%) of GHG emissions nationwide (Ministry of Climate, 2016). Therefore, the reduction of GHG emissions in the transportation sector is a top priority of the government (Khan & Yasmin, 2014). In this context, Pakistan embarked its journey with natural gas as an alternative transportation fuel in 1998. Although, a significant growth in the NGVs adoption was observed in the country (Khan & Yasmin, 2014), however, WtW comparison between the emerging NGVs technologies and their conventional competitors are vital to support policy development, applicable research, and investment decisions. At the time when the idea of this study was conceived, there was no application of the LCA approach to transportation fuels in the Pakistani context available in the literature. Thus, the knowledge gap was the principal motivation in this study which present results of the WtW analysis carried out for 25 combinations of automotive fuel and matching powertrain systems, with a special focus on the natural gas pathways.

5.2.2. Aim and Objectives

The overall aim of this study was to provide a comparative Well-to-Wheel (WtW) assessment of energy consumptions and greenhouse gas (GHG) emissions for natural gas as a transportation fuel in the Pakistani context.

To achieve the above aim, the following objectives were formulated.

- To perform a Well-to-Tank (WtT) energy consumption and greenhouse gas (GHG) emission analysis of 10 different petroleum and natural gas fuels pathways, i.e., gasoline, diesel, CNG and LNG.
- To conduct Tank-to-Wheel (TtW) energy consumption and greenhouse gas (GHG) emission analysis for seven different vehicle technologies.
- To provide Well-to-Wheel (WtW) assessment of energy consumptions and GHG emissions for 25 combinations of automotive fuel and matching powertrain systems, with a special focus on the natural gas pathways.
- To construct a comprehensive GHG emission database that can be applied for assessing other vehicle and fuel options e.g. electric and fuel cell vehicles.

The above objectives addressed the following questions.

- Based on the evaluation of the WtW cycles of automotive fuels specific to Pakistan, which fuel option among the selected fuel/power types would have the least harmful environmental impact overall?
- Which WtW cycle phase contributes the most to each of the different possible environmental impacts?
- Which uncertainties in WtW analyses could most drastically affect the environmental performance of CNG vehicles?

5.2.3. Contents

The study presents a detailed WtW analysis to compare vehicles fueled with one of the following sources of energy: CNG, LNG, gasoline and diesel. The comparison is based on two indicators: (i) primary energy consumption; (ii) GHGs emissions. Instead of simply listing the comparisons, this study discusses the reasons that cause the changes in the efficiencies and emissions that are brought about by automotive fuels. The analysis in this study focuses on transportation fuels available at commercial level rather than on advanced vehicle powertrain (e.g., hybrid vehicles, plug-in hybrids or fuel cell vehicles). The Part-1 of the study (paper # 11) discusses the WtT analysis for the following 10 different fuels pathways:

i. Gasoline produced at local refineries from indigenous crude oil sources
ii. Gasoline produced at local refineries from imported crude oil sources
iii. Gasoline imported from the Middle East
iv. CNG produced from indigenous gas sources
v. CNG produced from imported gas through IP Pipeline
vi. CNG produced from imported gas through TAPI Pipeline
vii. CNG produced from imported LNG
viii. Diesel produced at local refineries from indigenous crude oil sources
ix. Diesel produced at local refineries from imported crude oil sources
x. Diesel imported from the Middle East

In the second part (paper # 12) of the study, first a TtW for seven different vehicle technologies is presented that then results are discussed in combination with part-1 (paper # 11) to analyze the WtW energy consumptions and GHG emissions for 25 combinations of automotive fuel and matching powertrain systems. The seven different powertrains include:

i. Bi-fuel CNG port-injection spark ignition (PISI) engine
ii. Bi-fuel CNG direct injection spark ignition (DISI) engine
iii. Bi-fuel CNG port-injection spark ignition (PISI) engine
iv. Bi-fuel CNG direct injection spark ignition (DISI) engine
v. Gasoline fueled port-injection spark ignition (PISI) engine
vi. Gasoline direct injection spark ignition (DISI) engine
vii. Diesel direct injection spark ignition (DISI) engine

5.2.4. Research Methodology

As mentioned above the WtW cycle consist of two stages i.e. (i) WtT stage, and (ii) TtW stage. The WtT and TtW stages are covered in paper # 11 and paper # 12 of this two-part study. Later both stages were integrated (paper # 12) in a well-to-wheel stage where relevant indexes were proposed and discussed.

The GREET (Greenhouse Emissions and Energy Use in Transportation) model, developed by the U.S. Argonne National Laboratory, was adopted as a tool for WtT calculation. Amongst available LCA tools (e.g. GHGenius (S&T, 2018), SimaPro (Pre-sustainability, 2018), GaBi (PE-international, 2018), Tsinghua-CA3EM (Hao, 2010)) GREET model (ANL, 2018) has been widely used and extensively peer reviewed (Huang and Zhang, 2006; Haller et al., 2007; Wang et al., 2011; De Kleine et al., 2014). For emissions, the GREET model includes three major GHGs (carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) and five criteria pollutants (VOCs, CO, NOx, PM10, and SOx). Because the original GREET model and default parameters were designed based on the energy production chain in the United States, the authors changed default data in GREET for Pakistani application. Thus, the results generally reflect the actual operation conditions in Pakistan. The Pakistani data were mainly provided by following government and private organization operating in Pakistan:

- Hydrocarbon Development Institute of Pakistan (HDIP)
- Sui Northern Gas Pipelines Limited (SNGPL)
- Sui Southern Gas Company Limited (SSGCL)
- Inter State Gas Systems (ISGC)
- Oil and Gas Regulatory Authority (OGRA)
- Oil Companies Advisory Council (OCAC)

- Engro Elengy Terminal Private Limited (EETPL)

In order to customize the GREET model as per Pakistani setting, the study follows a bottom-up life cycle assessment framework by dividing the crude oil and natural gas based fuel system in five stages including fuel production, fuel transportation, fuel processing and fuel distribution. The studies consider two types of emissions sources i.e. combustion and non-combustion (i.e., fugitive) emissions. Combustion sources include emission associated with well surface production operations, fuel transportation, plant processing, and fuel distribution. Non-combustion sources include intentional venting (e.g. pneumatic valves) and non-intentional leakage (e.g. leaks from pipelines).

An additional analysis was also performed for the refining process which was the most energy-intensive part of the fuel life cycle. A process-level allocation technique was used to calculate consumption of individual petroleum product (e.g. diesel, gasoline) during refining process.
Further information was collected by literature surveys, Pakistan's oil refineries and author personal data collected during several years of experience with oil and gas production companies in Pakistan. Author's personal data collection include emission (e.g. flaring, vents from storage tanks) and energy consumption (processing , compression) information obtained through direct on-site measurement in three oil fields and one natural gas field (largest gas field) located in Pakistan. The default values of GREET model and literature data, coming from other studies covered the cases where actual Pakistani data were not available. In addition, three major Pakistani upstream oil and gas production companies and five downstream oil and gas production companies have been contacted and requested specific and disaggregated data per process. As the companies were reluctant to share their data in written form, so verbal communication was made with them.

TtW analysis was performed using AVL Cruise, a commercially-available backward vehicle simulator for GHG emission and energy use (AVL Cruise, 2018). AVL Cruise is an example of a micro-scale instantaneous emission model based tool which enables the user to design a specific passenger vehicle and simulate fuel consumption and emissions under different operating conditions. It is considered to be one of the industry's most powerful, robust and adaptable software for vehicle system and driveline analysis with advanced simulation and optimization features (Wahono, 2015).

5.2.5. Main Outcomes of the Study

The key findings of this study are listed below:

- In contrast, natural gas fueled vehicles are at a disadvantage from the standpoint of energy consumption e.g. on WtW basis, NGVs are 5 – 17% and 23 – 36% less fuel efficient, depending on the engine technology employed as compared to gasoline and diesel powertrain, respectively.
- Natural gas pathways show advantage over oil pathways regarding GHG emissions, especially compared to gasoline. Dedicated NGV equipped with direct injection technology is even more efficient and may result in 20% and 12% less GHG emissions as compared to gasoline and diesel pathways, respectively. The environmental and energetic assessments of NGV appear to be very favorable to this technology (i.e. dedicated DISI) and make CNG a promising fuel for light duty road transport vehicles. However WtW GHG emissions of the prevalent bi-fuel NGVs are 12% higher than those of their diesel counterparts with the baseline estimates of 100-year GWP.
- In terms of WtW GHG emissions, natural gas pathways can attain better or comparable performance as compared to petroleum pathways. However retrofitted bi-fuel engine technology and Methane leakage during gas fuel production and vehicle operation stage, can negate the benefits of using NGVs. Thus without significant improvements in both methane leakage and engine efficiency, using natural gas in light-duty transport will not provide substantial GHG benefits. There are cost-effective technologies to reduce methane leakages in natural gas pathways. For instance a natural gas engine with closed crankcase design that has reached the market can significantly reduce the TtW part of methane emission. Similarly for WtT pathway, technologies are now available which can capture methane vented during gas production/processing and stored or used it for energy at no net cost.
- Relatively larger uncertainty and variability was observed in WtW GHG emissions of natural gas pathways as compared to conventional gasoline and diesel fuel. Moreover the choice of GWPs and methane emission estimates are other important factors to assess the absolute emission levels and relative rankings of natural gas fuel pathways. Using 20-year GWPs

instead of 100-year GWPs increases WtW GHG emissions by 19–26% for natural gas pathways.

- While this paper focuses on GHG emissions, natural gas based fuels may provide other environmental benefits, such as the reduction of other air pollutants include CO, SOx and particulates as well as significant economic advantage over petroleum based pathways. However these are outside the scope of this work and will be addressed in future research.
- The results of this study serve as valuable inputs not only for policy decision-makers in Pakistan, but the method of analysis would also be applicable to other countries having similar characteristics, i.e., oil importing developing countries with their own or easy access to natural gas resources (e.g., via relatively short distance pipelines); some countries in Latin America, Africa and Southeast Asia would seem to fit this description.

5.2.6. Value and Significance

Most of the WtW studies available in the literature (Ally and Pryor, 2007; Ou et al., 2010; Torchio and Santarelli, 2010; Shen et al., 2012; Rose et al., 2013; Choi and Song, 2014; Curran et al., 2014; Edwards et al., 2014; Waller et al., 2014; Yazdanie et al., 2014; Rahman et al., 2015; Tong et al., 2015) focus either on high-income economies or upper-middle-income economies as classified by World Bank (World Bank, 2015). The nature of choices and assumptions made in these WtW studies are likely to be subjective. Therefore results of WtW studies focused on developed economies like USA, Europe may not be appropriate for developing countries applications. It is problematic to apply the results of WtW analysis conducted for developed countries to developing countries fuel markets like Pakistan, since the local conditions and respective vehicle powertrain technologies are considerably different. To the best of author's knowledge, no comprehensive WtW assessment of transportation, has been fully investigated in the developing countries (with low and lower-middle-income economies) except for India (Patil et al, 2016). But the methodology and scope of this study is considerably different from the WtW study performed by Patil et al, 2016 in Indian context.

Moreover most of the WtW studies available in the literature used the GREET model to estimate the emission reduction potentials and the fuel efficiency of natural gas pathways compared to petroleum fuels. However these studies failed to include a comprehensive set of pathways and used outdated data with regard to global warming potential (GWP) of methane. In addition they largely ignored uncertainty and variability, especially those related to fugitive methane emissions from natural gas systems. The present study addresses these limitations and distinguishes itself from previous efforts in the following ways:

- This is the first study to consider a detailed WtW analysis of CNG fuel with three different pathways (i.e. domestic natural gas, interstate gas pipeline and LNG) in developing and energy importing countries like Pakistan. Moreover, this study is the first initiative in the developing countries to consider TtW analysis for a C-segment passenger car equipped with gasoline (PISI and DISI), diesel, dedicated CNG (PISI and DISI) and bi-fuel CNG engine (PISI and DISI) technology. This combined with the variety of fuel pathways considered makes this study, to the best of author's knowledge, the most comprehensive WtW analysis of fossil fuels available to date.
- Other than being the first comprehensive country specific WtW study for Pakistan, the novelty of this work lies in the use of a consistent framework across multiple powertrain types with the same operating conditions to assess energy consumption and operating emissions.
- The study integrates the microscopic base emission model AVL Cruise coupled with the macroscopic base emission model GREET for WtW analysis under specific regional conditions.
- This study reports a comparison of WtW GHG emissions for CNG, diesel and gasoline vehicles taking into account the global warming potential(GWP) with both 100-years and 20-years based on the latest 5th assessment report released by Intergovernmental Panel on Climate Change (Stocker, 2014).
- The results of this study serve as valuable inputs not only for policy decision-makers in Pakistan, but analysis would also be applicable to other countries having similar characteristics, i.e., oil importing developing countries with their own or easy access to natural gas resources (e.g., via relatively short distance pipelines); some countries in Latin America, Africa and Southeast Asia would seem to fit this description.

Chapter 06: Concluding Remarks and Future Research

6.1. Conclusion

The aim of this study was to identify and analyze the technological, strategic and environmental aspects of compressed natural gas (CNG) as a viable alternative transportation fuel option in the international as well as in Pakistani context. The study, guided by three objectives, i.e. to investigate the key technical challenges associated with the CNG technology, to examine strategic framework and transitions to NGVs, and to carryout life cycle (Well-to-Wheel) assessment of NGVs. To achieve the three objectives, twelve peer-reviewed journal papers were published were categorized in three inter-related themes including:

i. Technical aspects of NGVs technology,
ii. Strategic Framework and Transitions to NGVs
iii. Life Cycle (Well-to-Wheel) Assessment (LCA) of NGVs

The first theme which is concerned with technical aspects of NGVs technology that is covered in chapter 3 of the thesis. The material and analysis presented in chapter 3 is supported with five journal papers. The first paper (paper # 2) contributes to a better understanding of techno-economic aspects of NGVs and the findings of the paper suggests that the performances of natural gas fueled engines are highly dependent on the engine design and type i.e. mono-fuel, bi-fuel or dual fuel. However, the major performance drawback with natural gas vehicles is due to 15–20% loss in brake horsepower of the engine as compared to gasoline powertrain. The low flame propagation and loss in volumetric efficiency are identified as a main attributor for the said power losses in natural gas engines. In addition the paper reveals that globally NGVs consumers can save 113% and 57% on fuel costs in contrast to fueling their vehicles with conventional gasoline and diesel fuel, respectively. Safety, from both a technological and a societal perspective is one of the major barriers to the use of natural gas as an alternative transport fuel. The 2nd paper (paper # 3) of chapter 3 systematically investigates the cause and consequences of 55 accidents related to CNG vehicles in Pakistan with objective to identify lessons that could be useful to improve the safety in CNG vehicles. The finding of this analysis suggests that the safety of vehicles fueled with CNG is highly relying on the design, installation, materials, operating conditions and maintenance, not just on the pressurized cylinder or other components in isolation. In addition, it is revealed that the main reason for CNG accidents which occurred in Pakistan were due to a lack of awareness about the rules/ regulations and driver negligence. In the 3rd paper (paper # 4) of chapter 3, the worldwide experience of NGVs with respect to their environmental competitiveness to diesel and gasoline fueled vehicles is analyzed. The finding in this analysis suggests that in contrast to gasoline/ diesel vehicles, the NGVs produces lower emission of CO_2 (20-25%), CO (50-68%), PM (10-75%) and NMHC (50-70%). In terms of NOx emissions, the analysis reveals a mix trend (lower or comparable or higher) for NGVs in contrast to its counterpart gasoline and diesel vehicles. The possible causes for this variability can be attributed to the variations in the level of vehicle maintenance and variations in the CNG composition (Shorter et al., 2005). The 4th paper (paper # 10) of chapter 3 considers the durability of natural gas fueled engine by examining the process of exhaust valve failure in natural gas engines, with objective to avoid unexpected failure of the component and increase the reliability of the engine. The finding suggests the valves fail as a result of overheating. The possible cause for overheating is mainly due to the build-up of high combustion deposit between valve face and seat. To prevent the excessive carbon build-up, the findings suggest the use of engine oil with Mg-based additives in natural gas fueled engines. The 5th paper (paper # 5) of chapter 3, provides a comprehensive review of the research progress in the use of natural gas as an alternative transportation fuel. The finding suggests that NGVs technology has been successfully adopted as an automotive fuel in various countries around the world. In addition the review suggests that there is lack of empirical work which examines the comparative maintenance cost-effectiveness of NGVs over total vehicle lifespan.

The second theme which is concerned with strategic framework and transitions to NGVs, is covered in chapter 4 of the thesis. The material and analysis presented in chapter 4 is supported with five journal papers. The first paper (paper # 7) presents a framework, which can be used by policy-makers to identify and evaluate the barriers to NGVs as well as possible solution to address these barriers. The findings suggest that the principle driving force in the successful removal of barriers to NGVs program is user economics. For example in developing countries economic factors such as fuel costs weigh more heavily in most consumers' purchase decisions than environmental attitudes. Therefore establishing retail CNG prices of 30–50% below gasoline and diesel prices are the keys for wide adoption of NGVs in these countries. In addition the vehicle refueling index –VRI (an indicator that reflect the balance between refueling stations and number of vehicles) values suggests that successful NGVs markets have the tendency to gravitate toward VRI of 1.1 in developing countries while settle to 0.2 in developed economies. The 2nd paper (paper # 8) examines the experience of existing NGVs programs in both developed and developing countries to provide insights into appropriate policy options for moving to sustainable natural gas transport system. The findings suggest that there is no universal policy for the implementation of natural gas as a transportation fuel and it is identified that a combination of the various policy measures is required to remove the existing barriers to NGVs. In addition the study shows that governments' policies need to be consistent, stable and clear to assure customers of long-term market initiatives and to influence the retail station investment decisions. Higher price differential of CNG with respect to conventional diesel/gasoline fuel and lower capital cost of a refueling stations can be the main driving force for transition to NGVs. The 3rd paper (paper # 9), aimed to develop a sustainability decision support framework to rank the strategies for the growth of NGVs program in a specific market, using Iran as a case-study country. The findings suggest that the proposed framework allows the stakeholders/decision-makers using linguistic terms to express their options and views on the sustainability of various strategies and the critical success factors for sustainable growth of natural gas as transportation fuel in Iran. The suggested technique is not limited to Iran, and it is a generic practice that can also be applied to evaluate the CNG as well as other type of alternative fuels market (e.g. hydrogen fueled vehicles) in other countries. The 4th paper (paper # 1) of chapter 4, considers the success factors, advantages and challenges for the future growth of CNG market in Pakistan by examining the approaches and outcomes of implementing NGVs in Pakistan and identifying lessons learned for the transition to natural gas transport system. The findings suggest that the significant growth in NGVs in Pakistan is due to the Government's consumer friendly policy, ample regulatory framework and the price differential between CNG and gasoline/ diesel. In addition the paper suggests that due to lack of sustainable natural gas supply plans, Pakistan's gas supplies cannot support the high demand of CNG sector. The fuel price margin and NGVs growth can be significantly affected by conventional fuel (diesel/gasoline) prices and these conventional fuel prices in turn are highly correlated to crude oil prices (Liu and Ma, 2014). Therefore the 5th paper (paper # 6) of chapter 4 presents an evaluation of factors associated with sharp decline of oil prices since 2014. The findings suggest that the 2014 plunge in oil prices is different from the previous episodes of oil price declines during the past thirty years which were caused by imbalance between supply and demand factors. The findings reveal that the demand and supply formula of oil market is not applicable to the recent plunge in oil prices. In addition the study shows that the shale oil technology will play a key role to balance the world oil supply and demand, which in turn means that current scenario of low oil prices can be maintained.

The third theme which is the life cycle (Well-to-Wheel) assessment (LCA) of NGVs, is addressed in chapter 5 and supported with two journal publications. Although natural gas can help to reduce the transport emissions due to being ~25% less carbon intensive than diesel and gasoline, there is some disagreement as to the magnitude of benefit that natural gas can deliver relative to conventional fuels i.e. diesel and gasoline. In the context of rising challenge of reducing global GHG emissions, it is important to understand the life cycle environmental potential of natural gas as transportation fuel. Therefore Chapter 5 as tandem of two papers (paper # 11 and 12) concerned with the life cycle (Well-to-Wheel) analysis of natural gas as transportation fuel considering Pakistan as case-study country. The first paper (paper # 11) of the chapter covers Well-to-Tank (WtT) energy consumption and greenhouse gas (GHG) emission analysis of 10 different petroleum and natural gas fuels pathways, i.e., gasoline, diesel, CNG and LNG. The findings suggest that petroleum fuel have WtT energy efficiency in the range of 82–86% while the WtT energy efficiency of natural gas based fuels are within 75–88%. In addition the results reveal that WtT GHG emission associated with CNG produced from indigenous natural gas sources are 16% and 21% higher than the gasoline and diesel fuel produced from ingenious crude oil, respectively. As compared to other countries, the WtT GHG emissions results of Pakistani crude oil and natural gas based fuels are 10% and 29% higher than those of European countries respectively, which is mainly due to higher methane emissions. The 2nd paper (paper # 12) focuses on the complete life cycle (Well-to-Wheel) by first considering the Tank-to-Wheel (TtW) and then integrating the Well-to-Tank (WtT) findings of the first paper (paper # 12) with the TtW results reported in 2nd paper (paper # 11) to provide the comprehensive life cycle (Well-to-Wheel) assessment for the operation of conventional and CNG passenger vehicle drivetrains specific to Pakistan. The findings suggest that on WtW basis 80 - 89% energy consumption and 73 - 86% GHG emissions for all fuel pathways comes from the TtW phase. On WtW basis natural gas based fuel pathways are 5 – 17% and 23 – 36% less efficient in terms of energy consumption, as compared to gasoline and diesel powertrain, respectively. Moreover for dedicated NGVs GHG emissions may be reduced by 20% and 12% against gasoline and diesel fuel. In addition the study reveals that large uncertainty with methane leakage can offset the GHG emissions benefits of NGVs.

6.1.1. Key Significance

Some of the key significance of published work presented in this thesis are listed below:

- The research presented in paper # 1 shows that if the NGVs program of a country is developed on the basis of political motivations rather than careful scientific evaluation of the availability of natural gas resources, it likely fails in terms of sustainability.
- The research presented in paper # 2 contributes to the literature as a first comprehensive academic work pertinent to techno-economic attributes of natural gas as transportation fuel.
- The research presented in paper # 4 contributes to the literature as a first systematic empirical research addressing the safety issues associated with the use and operation of natural gas vehicles.
- The research presented in paper # 5 contributes to the literature as a first comprehensive technical review that presents the progress in the eight different aspects of natural gas as automotive fuel.
- The research presented in paper # 7 presents a new modified the definition of optimum value of Vehicle-to-refueling-station index (VRI). Previously the optimum VRI value of 1 was suggested by Janssen et al., 2006 and Yeh et al., 2007 but according to this study the optimum VRI could go well below the value of 1 (up to 0.60) depending upon the capital and operating cost of CNG refueling stations.
- The research presented in paper # 8 contributes to the literature as a first academic work for examining the experience of existing natural gas vehicles programs in both developed and developing countries to provide insights into appropriate policy options for moving to sustainable natural gas transport system.
- The research presented in paper # 9 presents a novel MCDM technique for integrating the stakeholder visions when making decisions for the development of natural gas as transportation fuel in a specific country.

- The research presented in paper # 10 contributes to the literature as a first peer-review academic work pertinent to thermo-mechanical failure mechanism of exhaust valve from natural gas engine.
- The research presented in paper # 11 and 12 presents first comprehensive life cycle assessment of natural gas as transportation fuel in developing countries.

6.2. Future work recommendations

The outcomes of this thesis have a number of implications for further research. Therefore to extend this research, the following future works are recommended:

- There is large variation in the NOx emissions associated natural gas engines. Therefore more fundamental work is required to understand the mechanism of NOx emissions associated with the combustion of natural gas in internal combustion engines.
- The findings of paper # 4 on Table 1.1 (Khan et al., 2016a) regarding safety issues of NGVs suggest that in some NGVs related accidents, the CNG cylinder's PRD (pressure relief device) was not fully activated. A similar case of PRD failure was reported on January 26, 2016 in New Jersey, USA, where CNG cylinder of a garbage truck exploded after catching fire and blasted a hole in the front of a nearby house (Shea, 2016). Therefore further research is needed which can help determine the root cause of the PRD not completely activated.
- The suggested Well-to-Wheel emissions finding in paper # 11 and # 12 is based on simulated operation under test conditions and unable to consider real-world conditions in actual operations of the case-study powertrains especially the drive cycles (e.g., speed, idling, road grade) (Reyna et al., 2015) and payload profiles (Xu et al., 2013) as such information is limited in Pakistan. Measurements of these types of emissions in real world operation is a key area for future research.
- The findings of paper # 12 suggest that methane slip from natural gas engines is an important factor limiting their GHG emissions potential. There is ongoing research to reduce the methane slip NGVs through various approaches and this is likely to be a persisting challenge that will benefit from further attention. However, there is likely a trade-off between NOx emissions and methane slip (Prehn et al., 2018) with engines that provide

the lowest methane slip also providing the highest NOx emissions. So there will be a need for complimentary research into after-treatment technologies and the optimization of these two aspects of natural gas engine emissions.

- It is required to conduct the comparison of social costs across all of the case-study powertrains and study whether switching to natural gas as transportation fuel reduces the social costs compared to gasoline and diesel fuel. The social costs may take into consideration the upfront vehicle price, available incentives that offset the vehicle price, lifetime maintenance costs, lifetime fuel costs and the social costs of emissions to the atmosphere.

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Annexures

Annexure-A

Khan, M.I. and Yasmin, T., 2014. Development of natural gas as a vehicular fuel in Pakistan: issues and prospects. Journal of natural gas science and engineering, 17, pp.99-109.

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Development of natural gas as a vehicular fuel in Pakistan: Issues and prospects

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ABSTRACT

In a step towards adopting environment friendly fuel and to save foreign exchange, Compressed Natural Gas (CNG) was introduced by the Government of Pakistan in the country in 1992. Due to available price differential between CNG and gasoline/diesel and investor friendly policy and regulatory framework, CNG sector has shown tremendous growth over the last ten year in the country. This growing demand of natural gas by CNG sector, results in gas shortages in the country. This paper describes the key steps in the development of CNG as transportation fuel in Pakistan. The present scenario of the CNG industry including the natural gas vehicles (NGVs) population growth and the expansion of CNG refilling stations are discussed. Various aspects of the CNG program in Pakistan, for example environmental benefits, economic benefits and problems associated with CNG industry of Pakistan are illustrated.

1. Introduction

The word is turning to replace gasoline and petroleum based energy, which is showing a rising trend in price. Around the world a widespread research is carried out to investigate that CNG is good for the customer and kind to the environment, while making the country into more fuel sovereign state. A growing number of countries around the world are jumping on the moving train to make use of CNG, because of various advantages. The entire credit for this goes to New Zealand, which in 1980s launched CNG programs on a commercial scale successfully. It seen that CNG is the answer to the world, in the hunt for alternative transportation fuel. Today CNG programs are being pursued in more than 86 countries and Pakistan stands 2nd in the world tally in terms of NGVs (1st Iran) & fillings stations (1st China) (Statistics and Europe, 2013).

2. Background CNG program in Pakistan

The foundation-stone of CNG program in Pakistan was laid down by HDIP (Hydrocarbon Development Institute of Pakistan) through the establishment of CNG refilling stations at Karachi in 1982. In 1992, Ministry of Petroleum and Natural Resources of Pakistan, announced the CNG Rules of 1992, which commercialized CNG as a transportation fuel in the country. The program really picked up in 1998 when the government declared a two year goal of establishing 150 CNG stations and conversion of 100,000 vehicles.

Keeping in view the lack of domestic fuels, a large space always existed in the country for the development of alternative transportation fuels, particularly natural gas, which is locally available at a low cost, while a widespread infrastructure for transmission and distribution of natural gas is already in position.

3. Statistics of Pakistan's CNG industry

Due to Government's consumer friendly policy, ample regulatory framework and extensive efforts, CNG industry has developed significantly at an unprecedented rate of around 52.5% per annum during the last few years. Currently the country has 6.167 million total number of register vehicles (Pakistan National, 2010), out of which there are 3,100,167 (89%) vehicle has been running on CNG while the rest, which includes buses, trucks, and two wheelers, three wheelers etc, are using gasoline and diesel. Table 1 depicts the statistical highlight of natural gas vehicles – NGVs in Pakistan.

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Table: 1
Statistics of Pakistan's CNG industry (Statistics and Europe, 2013).

Total NGV population (other than ships, trains and aircraft)							CNG stations		Date
Total NGVs	LD + MD + HD Vehicles	LD Vehicles	MD + HD Buses	Other	% of total vehicles in the country	% of total NGVs worldwide	Total	% of total CNG stations worldwide	
3,100,167	2,920,167	2,919,500	667	180,000	89.14%	19.12%	3330	15.84%	March, 2012

4. Prevailing status of CNG in Pakistan

Because of higher priority and the insatiable demand for natural gas by power plants and industry, the government has to ration natural gas for CNG sector. It often announces “gas holidays” where gas supply to CNG stations is cut off for several days a week, conducing to widespread dissatisfaction among CNG consumers. Owing to these gas shortage problems, the government is not in favor of further expansion of CNG sector in the country. The officials are struggling with the difficult task of trying to turn back the strategy and to ablactate vehicles back onto gasoline to divert the natural gas to industry and power plants. Recently the government, without consulting the stake holders, imposed ban on import of CNG Kits and CNG Cylinders and has restricted the OEM companies i.e. Pak Suzuki Motor Company, Indus Motors Company (Toyota) and also after-market installers to stop conversion of vehicles to CNG.

To rationalize the gas consumption, a load plan in October 2010 has been implemented. Under the plan, gas feeding to the CNG stations was curtailed to five days a week in certain regions of the country. The main reason behind failure of gas energy plans and policies in Pakistan is political disability, as a result of which policies of previous governments have been destabilized by preceding governments.

5. Growth of CNG in the country

The CNG industry in Pakistan has witnessed a tremendous growth in the last decade, by virtue of friendly government policies and the key role played by CNG station/vehicle owners. At present, it is stands 1st in the world. Figs. 1 and 2 reflect the continuous increase in the number CNG stations and CNG vehicles respectively. A significant increase has also been seen in the consumption of natural gas by CNG sector as shown Fig. 3. Over the past ten years (2001–2010) there is more than 11, 000 percent raise in gas consumption by this sector. Currently CNG industry consumes 325 MMSCFD (million standard cubic feet per day) natural gas (9% of country gas production) (Pakistan Energy, 2013).

6. Government policy & support

Pakistan has sought ways to raise awareness, investment, technology and institutional framework, while pursuing fast track development of the CNG industry. Government's interest to boost national economy by reducing oil import bill and improving the environment has led to the provision of incentives for investors in CNG sector. Some of them are highlighted below:

- Exemption from import duty and GST for CNG station and vehicle conversion equipment for a period of five years
- Permit import of used and reconditioned CNG compressor.
- Loans on soft terms to setup a CNG station
- Strong commitment by the government to promote the use of CNG
- Liberal procedures for issuance of license for setup a CNG stations.
- Deregulated market price for CNG consumers
- Natural gas tariff for CNG coupled to gasoline
- Gas connection priority to CNG stations

7. Natural gas scenario in Pakistan

Pakistan is an energy deficit country. The country primary energy supply during the financial year 2011–12 was recorded as 64.7 MTOE (million tons of oil equivalent) (Pakistan Energy, 2013) and it is majorly depends upon imported petroleum products, as a result of which the country's annual oil import crossed the limit of

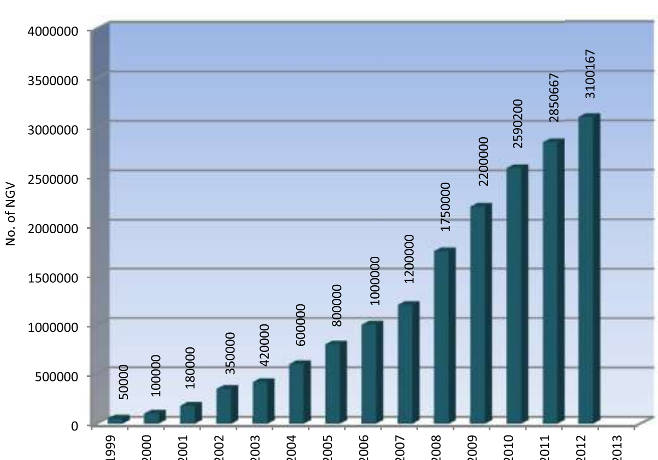

Fig. 1. CNG vehicle growth in Pakistan.

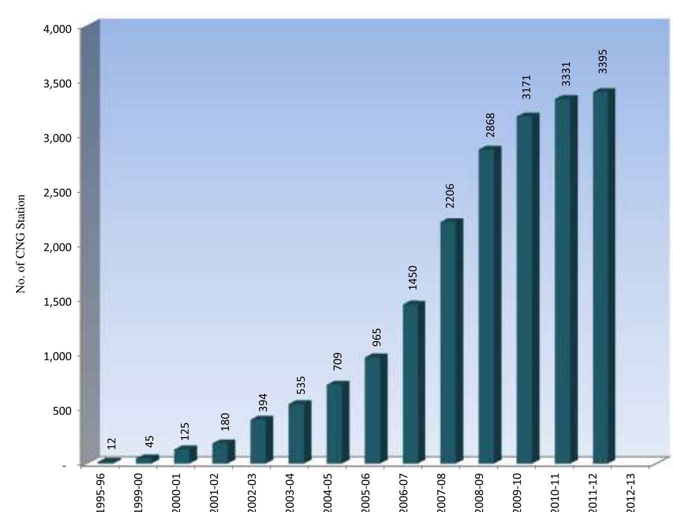

Fig. 2. Growth of CNG filling Station in Pakistan.

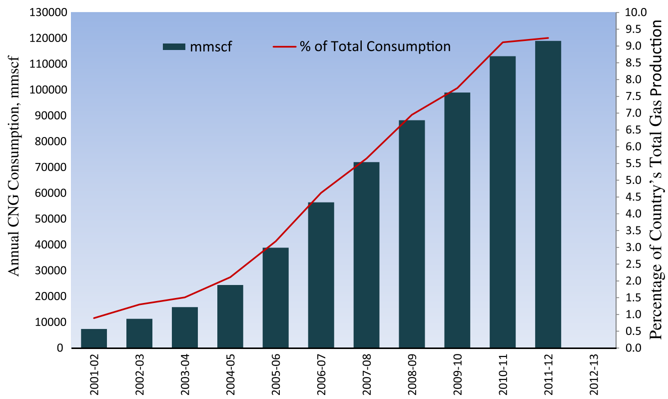

Fig. 3. Natural gas consumption by transport sector.

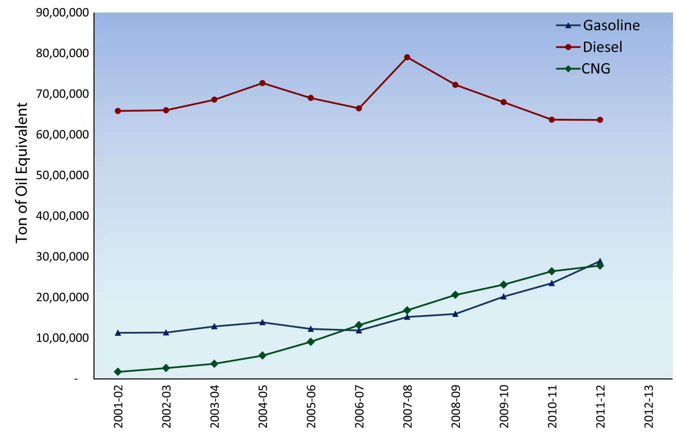

Fig. 5. Fuel consumption by transport sector.

fourteen billion US dolor, which is a big load on economy. Total energy consumption of the country in fiscal year 2011–12 remained 40.03 MTOE (Pakistan Energy, 2013). The contribution of natural gas was remained highest equal to 43.3% of the total energy consumption of the country, followed by oil (29%) (Fig. 4).

In Pakistan oil and gas are the two sources of energy used as transportation fuel. Transport is the largest consumer of oil in the country as more than 50% of oil is consumed by this sector (Habib-ur-Rehman et al., 2009-10). However, over the past 10 years there has been loss of more than 20% in the consumption of oil through the transport sector. This decrease is due to the growing trend towards the use of compressed natural gas as transportation fuel (Fig. 5).

Pakistan has a good potential for the production of natural gas. Current recoverable reserves of natural gas in the country are 28.9 TCF (trillion cubic feet) (Pakistan Energy, 2013). The daily production of natural gas during the fiscal year 2011–2012 was remained 4002 MMSCFD, a bulk of which is utilized as fuel for power generation (27.2%), followed by industrial sector (23.5%). To support its CNG sector, the country has a widespread infrastructure of natural gas distribution pipeline network spreading in major part of the country (Fig. 6). In recent years a phenomenal growth has been witnessed in the transmission and distribution networks of natural gas pipeline due to rapid increase of natural gas as a transportation fuel.

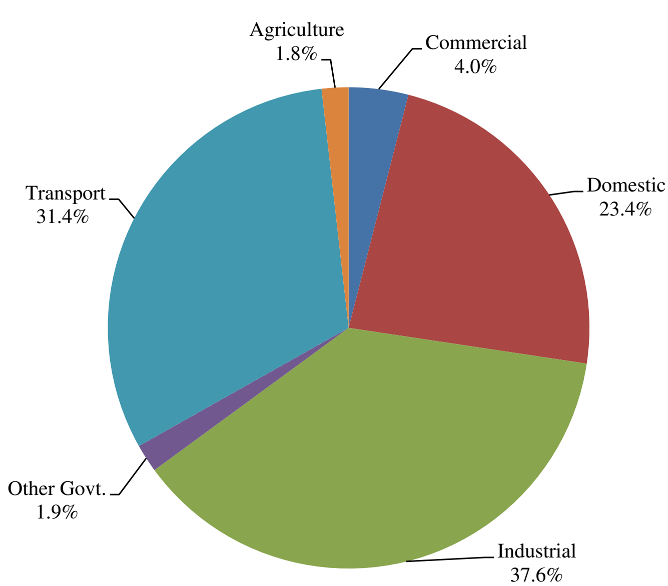

Fig. 4. Energy Consumption by Sector (Excluding fuel consumed in thermal power generation).

8. Supply and demand gap

The annual growth rate for the demand of natural gas in the country is expected at an average rate of 2% from the year 2012. Fig 7 illustrates the future of gas demand and supply projections in the country. Keeping in view the current supply projections, indigenous gas production is expected to reach its peak value of 3680 MMSCFD in 2014 and will decline thereafter. With passage of time natural depletion of gas reservoirs will make sure that committed supplies fall well short of demand, which is expected to reach 5980 MMSCFD in year 2016. Moreover, since the local production of natural gas will no longer be ample to meet growing demands, dependence on imports will raise.

To meet the growing demand of CNG by transport sector, the government is promulgating a new strategy to import natural gas from neighboring countries. The Turkmenistan–Afghanistan–Pakistan–India (TAPI) and Iran–Pakistan (IP) gas pipeline projects are the key elements of this strategy. The Iran–Pakistan (IP) gas pipeline project is projected to bring natural gas to Pakistan at the end of 2014. In this context, an agreement has already been signed between the two countries. The volume of gas supply is expected to be 7.52 BSCFD (billion standard cubic feet per day) for the first year and 13.98 BSCFD for the second year and 21.5 BSCFD from the third year onward until the expiry of IP GSPA (Iran Pakistan gas sales purchase agreement), 25 years from the effective date. If these projects to import natural gas have not completed in time, gas shortages could worsen considerably. This will drastically affect the country's CNG industry.

9. Economic benefits

The growth of CNG vehicles is mainly due to the cost benefits of CNG over gasoline/diesel fuel. In Pakistan CNG is much cheaper compared to petrol and diesel. The cost for the operation of CNG vehicles vis-a-vis its operation on gasoline/diesel has been carried out at the current fuel prices in the country. The results are reproduced in the form of a bar graph as shown in Fig. 8. The comparison is illustrated using the following calculations:

Current Price of CNG = Rs. 65/kg
Current Price of Gasoline = Rs. 105/Lit
Current Price of Diesel = Rs. 104/Lit

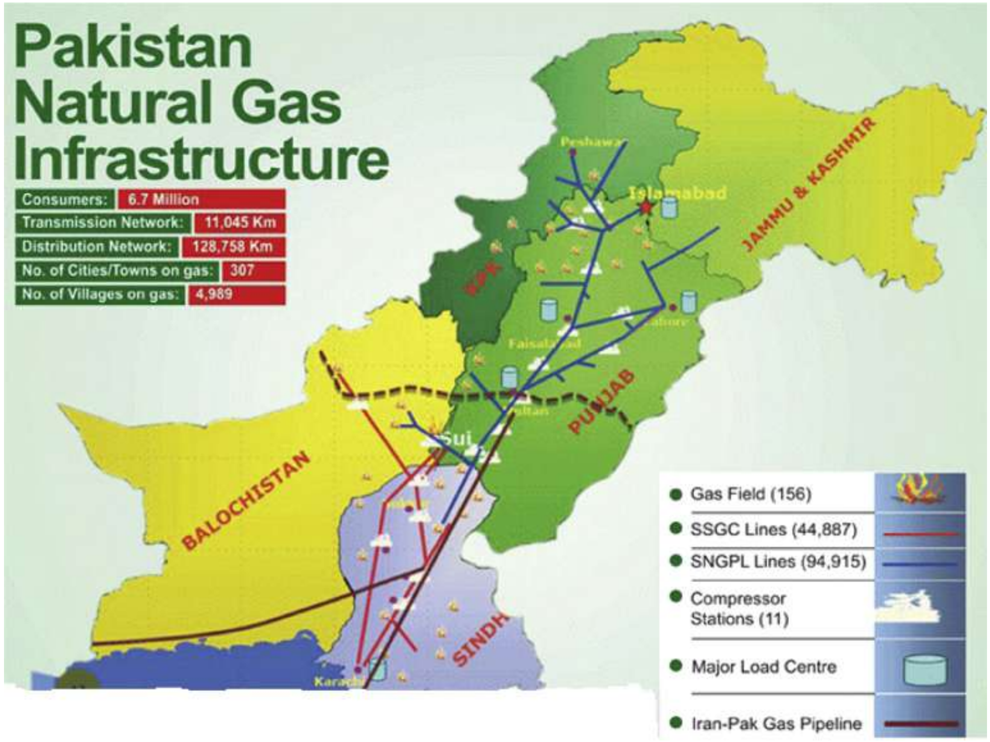

Fig. 6. Pakistan natural gas infrastructure (Petroleum Exploration, 2012).

Now on the basis of energy equivalent
1 kg of CNG = 1.4 L of Gasoline And on the basis of engine compression ratio
1 L of Diesel = 1.4 L of Gasoline

Consider the case of Honda Civic 1.8 L Car in Pakistan, in general this car with a fuel consumption rate of 17.5 km per liter of gasoline on the highway. If the said car traveled a distance of 1000 km, it will consume 57 L of gasoline or 41 kg of CNG. Therefore keeping in view the current market prices, CNG allows significant fuel savings of about 50% compared to gasoline or diesel. Fig. 9 shows the retail fuel price advantage of CNG over gasoline/diesel for the last 12 years in the country.

In addition, the CNG has substituting at least 6.2 billion gallons of gasoline each year and save foreign exchange amounting to billions of dollars. The CNG industry pays 24% GST (general sales tax) and 4% withholding tax to the government. The CNG sector of the country has so far attracted more than Rs. 89 billion investment (Annual Report, 2011-12). The activities in this industry have created more than 121,000 cumulative (direct and indirect) job opportunities. Figs. 10 and 11 illustrate the investment trend and employment opportunities produced by CNG sector respectively.

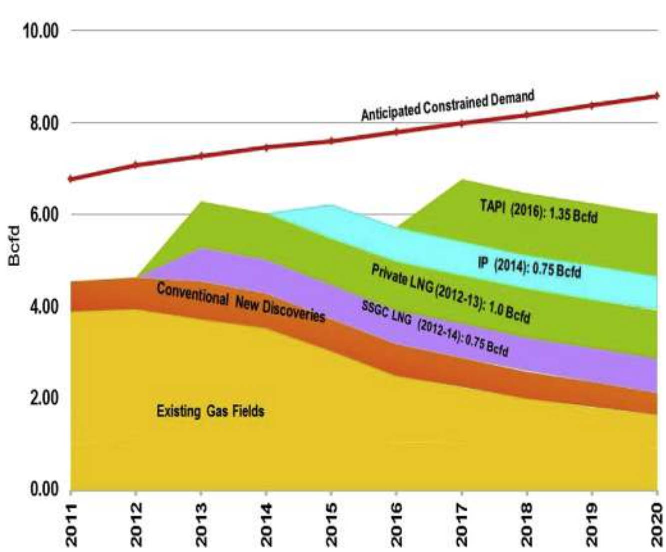

Fig. 7. Gas demand & supply projections (Inter State Gas Systems, 2013).

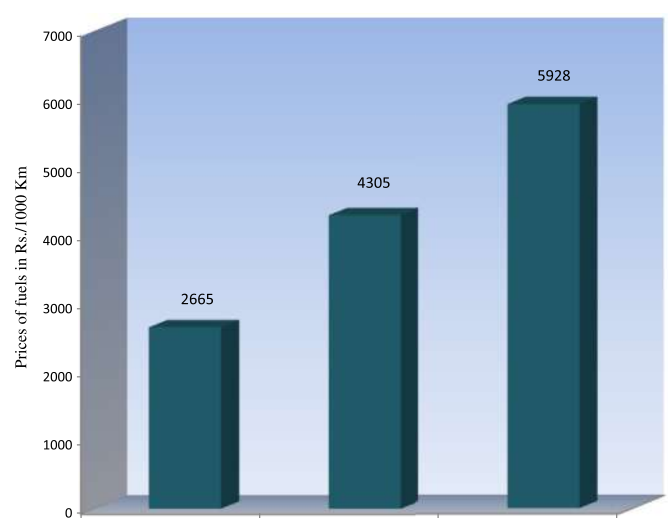

Fig. 8. Cost comparison of CNG vs other fuel.

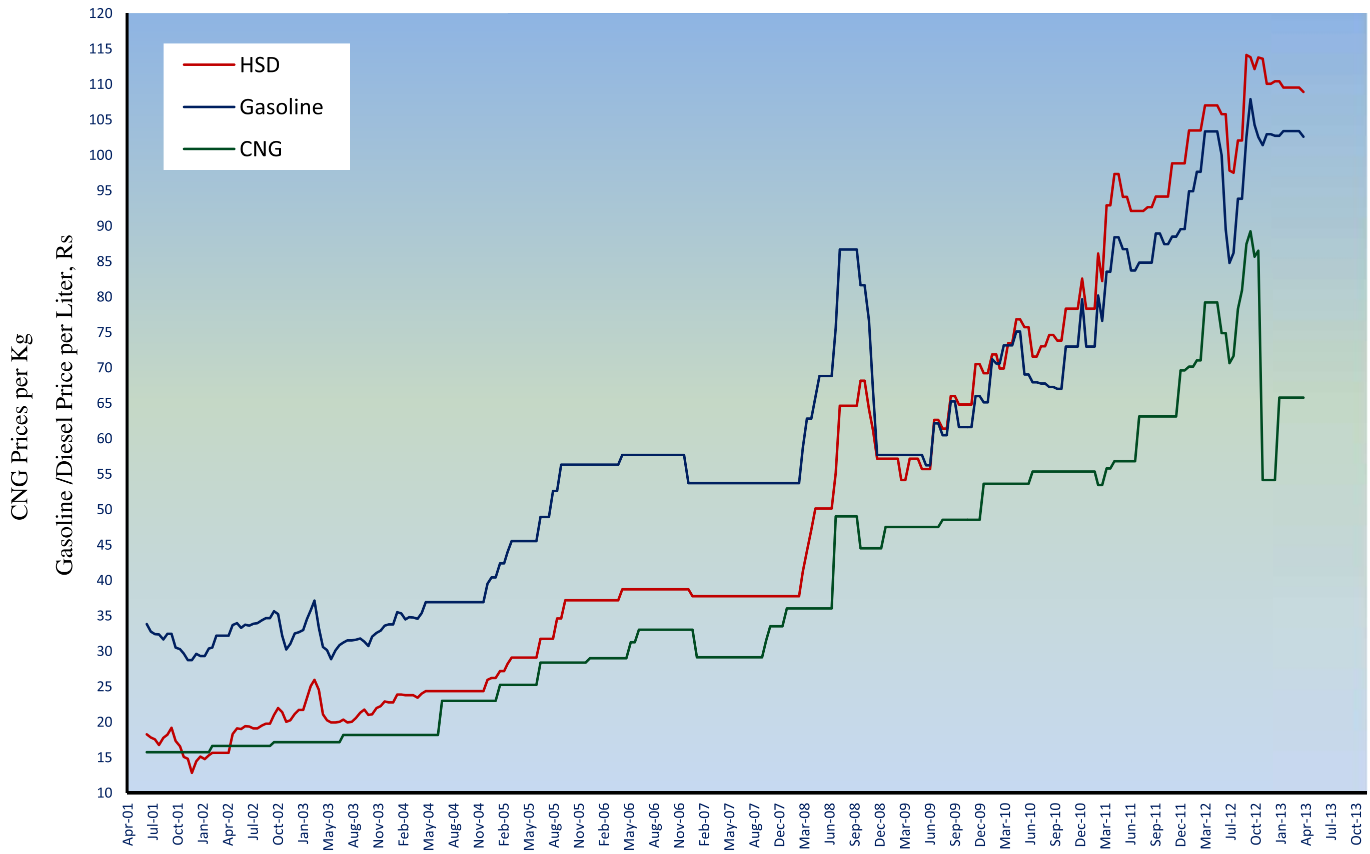

Fig. 9. Pakistan retail fuel prices.

10. CNG technology in Pakistan

In Pakistan almost the entire fleet of NGVs is usually bi-fuel vehicle, burning one fuel at time. Their engine is a standard gasoline Internal Combustion Engine. For converting the gasoline engine into CNG engine, a CNG conversion kit and a cylinder is required. CNG conversion kit is basically a set of components and tools that are installed in a vehicle so it can operate using both gasoline and CNG. The driver can select what fuel to burn by simply flipping a switch on the dashboard. CNG conversion kits usually come with parts such as regulator, high pressure tubing and fittings, pressure gauge, filling nozzle, hoses, refueling valve, power adjuster, closed loop fitting system, emulator, timing advance processor, fuel change over switch as well as the necessary wiring, straps and screws.

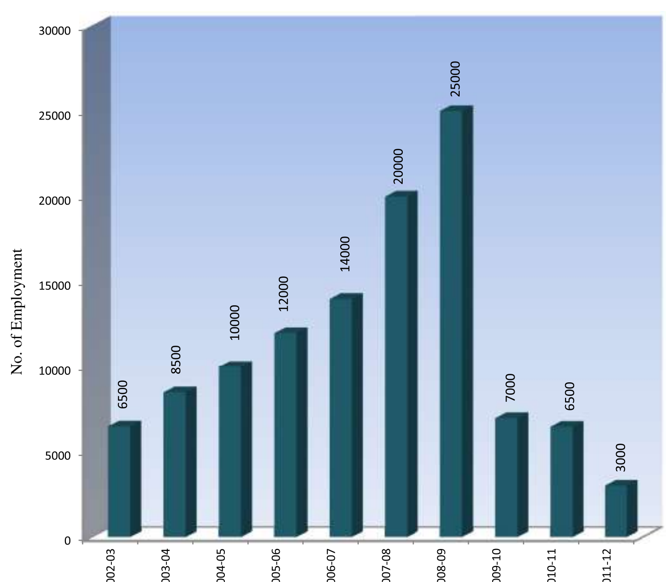

Fig. 10. Employment in CNG sector.

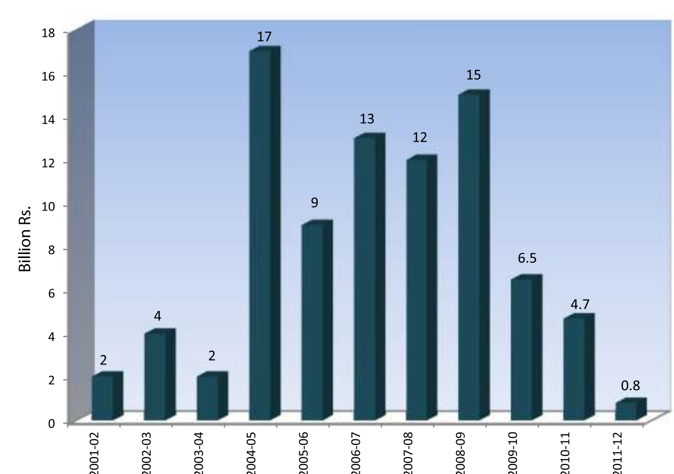

Fig. 11. Investment in CNG sector.

In Pakistan there are 9 approved brands of CNG conversion kit and 11approved brands of CNG cylinder, which has generally been used for converting gasoline vehicle to natural gas vehicles. Of the 9 approved brands of CNG conversion kits, five has been manufactured locally. Landi Renzo, one of the renowned Italian CNG kit manufacturers has setup a plant at Karachi with complete technology transfer to Pakistan. Over 90 percent market share of CNG kits in Pakistan has captured by local companies. These local companies has a broad based engineering design, development, testing and hi-tech manufacturing setup that are geared towards the production and constant improvement of CNG kits.

The country has now started regular export of CNG kits to China, Brazil, Far Eastern and European countries. The CNG cylinders are usually imported from India. There is only one local company engaged in the manufacturing of CNG cylinder. To setup a CNG refilling station one needs CNG compressor and dispenser. CNG compressors are imported from UK, USA, Canada, Germany, China and Italy while major share of dispenser are produced locally by M/s Tesla Tech.

11. Environmental aspect of CNG program

Due to rapid industrial growth, urbanization and hence increase in traffic volume over the last few decades under developed countries like Pakistan have undergone substantial increases in terms of emission sources of air pollutants (Majid et al., 2012). In Pakistan, as in many other countries, traffic is a major cause of high levels of pollution in the cities (Ali and Athar, 2008). There are no systematic obligations for controlling the vehicle emissions in Pakistan, which caused more than 90% of the ambient pollution (Faruqee, 1996). Pakistan's National Conservation Strategy Report states that the average Pakistani automobile, releases 20 times more hydrocarbons, 25 times more carbon monoxide and 3.5 time more NO_x in grams per kilometer than the average vehicles in the United States (Pakistan Strategic, 2006). The report states that urban air pollution cause around 22,700 premature deaths per year in the country (Pakistan Strategic, 2006). Most of the Pakistani cities are reeling under critical levels of NO_x and particulate matter pollution. There are serious public anxiety about health effects of diesel associated fine particulate matter, and other air pollutants. These worries are supported by the dissemination of studies in India and epidemiological studies conducted in various other countries that have highlighted variety of health risks associated with particulate matter in vulnerable populations, including premature death, hospital admissions, respiratory diseases and changes in pulmonary function.

The emission of air pollutants is directly related to fuel consumption. Consumption of petroleum products in Pakistan is growing at an annual rate of about 6%, almost half of them consumed in the transport sector. The major agents of the vehicle emission in Pakistan are: CO_2, CO, NO_x and PM.

11.1. Carbon dioxide CO_2

Carbon Dioxide – CO_2 is the major source of emission associated to transport, because it is the natural outcome of combustion of carbon based fuels such as diesel and gasoline (both of which have high carbon contents compared to CNG). In Pakistan transport sector makes up 70% of CO_2 emissions (IEA Statistics, 2012; Imtiaz et al., 2008). CNG has the lowest carbon-to-hydrogen ratio than either gasoline or diesel fuel (McTaggart et al., 2008). This led to the lower emission of CO_2 for the CNG than the gasoline or diesel fuel (McTaggart et al., 2008). Additionally, the emissions of CO_2 from a CNG engine can be decreased by more than 20% compared to that of a petrol engine with the same load due to the high hydrogen content of natural gas fuel (Kato et al., 2001; Weaver, 1989).

The CO_2 emissions of a CNG vehicle can even be lower than that of a diesel vehicle with the same air -fuel ratio and nearly the same thermal efficiency under very lean conditions (Tilagone et al., 1996). The conclusion of recent studies, like those conducted by California Air Resources Board (CARB), is that CNG can reduce CO_2 emissions by 20%–30% compared to diesel and gasoline.

11.2. Carbon monoxide – CO

One of the other hazardous vehicle emissions is carbon monoxide – CO. In Pakistan the road traffic contributes 70% to the national CO-emission and totally dominates the CO-pollution in most of the cities (IEA Statistics, 2012). Carbon monoxide is produced by incomplete combustion of carbon-based fuels. Incomplete combustion takes place when there is not enough oxygen available for the fuel to burn completely or when burning is extinguished near the cold surface of combustion cylinder.

Carbon monoxide is a toxic gas, which causes nausea, headache, fatigue, breathlessness and in high concentrations it may cause death. It is responsible for more than 50% of all poisoning deaths reported worldwide each year (Raub et al., 2000). Due to excellent lean flammability limit of CNG, it produces lean burning operation which conduces to the reduction of carbon monoxide and NO_x production in exhaust emission (Nine et al., 1997). As per NGV America, CNG vehicle can reduce the production of CO in the exhaust emissions by 70 percent (NGV, 2013).

11.3. Nitrogen oxides – NO_x

NO_x are by-products of all carbon based fuel combustion processes and national transport sector contributes about 35% of total NO_x emissions (Ali and Athar, 2008). In the respiratory system NO_2 is transformed into secondary pollutant such as nitrates and nitric acid (HNO_3) which act as respiratory irritants. Exposures to NO_x for longer duration may affect the lungs structure, lungs immune system, lungs metabolism, and impair the lungs function. As combustion of CNG takes place at a lower flame temperature than gasoline/diesel fuel, which results in low NO_x emissions (Tilagone et al., 1996).

11.4. Hazardous additives in liquid hydrocarbon fuel

In Pakistan the other major hazardous vehicle emission is caused by the high concentration of sulfur in High Speed Diesel (HSD). The country maximum allowable value of Sulfur in High Speed Diesel – HSD is 1 percent (10,000 ppm), while the neighbor countries China and India have set the limit of 50 ppm for the same. The sulfur content of diesel fuel has direct correlation with the production of particulate matter-PM in combustion. Reducing sulfur content of fuels will lower the concentration of sulfur dioxide (SO_2) and sulfate PM in exhaust emission (Saiyasitpanich et al., 2005; Bielaczyc et al., 2002) As CNG does not consist of any sulfur content thus lower the emission of sulfate PM from all vehicles, and decreases maintenance costs, as high sulfur levels cause corrosion of fuel injector and piston rings, oil acidification and overall engine wear.

Unlike gasoline or diesel, CNG is directly utilized in vehicle without any refinery processing i.e. no chemical agents are added to CNG fuel. While many hazardous additives such as olefins and aromatic compounds are added to gasoline to improve its octane number. These olefins and aromatic additives affects the performance of the engine and by lowering their concentration will result to lower octane number. These octane enhancing additives are not environmentally friendly because aromatics produce more smoke and smog and increase the NO_x emission. Maximum allowable European requirements for olefins and aromatics are 18 %v/v and 42% v/v respectively. Once again the quality of Pakistani gasoline is very poor as compared to European Union standards for example currently there are no high limits for the concentration of olefins and aromatics for gasoline imported to or produced in Pakistan (Yasin et al., 2008).

11.5. Particulate matter –PM

In order to avoid more costly methods of boosting octane number of gasoline, petroleum refiners in Pakistan have ads tetraethyl lead – TEL to gasoline blends. However, the costs to society in form of adverse health effects from lead are comprehensive and well-documented. These include but not limited to immune deficiency, kidney function impairment, *coronary artery disease*, premature death, reproductive and developmental problems in children. Owning to this poor quality of gasoline and HSD, road traffic has been identified as major source of lead and nitrous oxide, and an important contributor of particulate matter (PM-10), carbon monoxide – CO and sulfur dioxide – SO_2 in Pakistan (Brandon, 2010).

In a recent study by Alam et al. (Majid et al., 2012) using an optical particle counter documented 24 h average PM10 concentrations of 461 $\mu g/m^3$, 198 $\mu g/m^3$, 448 $\mu g/m^3$, and 540 $\mu g/m^3$ for Karachi, Lahore, Rawalpindi and Peshawar respectively which is much higher than comparable 150 ppm WHO standards. *Exposure to traffic*-related particulate matter in most of the urban area of Pakistan has been shown to increase the risk of various health problems. CNG vehicle releases very small amounts of particulate matter because CNG does not contain aromatic compounds such as benzene (Cho et al., 2007).

Natural gas majorly comprises of methane which does not possess carbon–carbon molecular bonding and as result combustion of natural gas leads to a significantly lower possibility of benzene rings formation, which subsequently conduce to decrease in formation of polycyclic aromatic hydrocarbons (PAHs) with various carcinogenic potencies (Warnatz et al., 1999). Therefore CNG eliminates the risk to the health of consumers who may receive direct exposure of the carcinogenic substance.

The rising concern about the potential health impacts of traditional Pakistani gasoline & HSD exhaust emissions, have made CNG a very appealing alternative fuel for road transport with advantages of being environmentally friendly fuel. Although specific studies have not been carried out to assess the environmental & health benefits of the CNG program in Pakistani cities, however it is assumed based on the global research findings and experiences that in contrast to the gasoline/diesel, the natural gas vehicles offer greater advantage of reducing exhaust emissions due to the low carbon content. For example, the U.S. Environmental Protection Agency calculated the environment friendly potential of CNG vehicles vis-à-vis gasoline fueled vehicles and summarized the results as following (Clean Alternative Fuels, 2012):

- Reduces CO exhaust emissions by 90%–97%
- Reduces NO_x exhaust emissions by 35%–60%
- Reduces CO2 exhaust emissions by 25%
- Significantly reduces non-methane hydrocarbon exhaust emissions by 50%–75%
- Releases minute or no PM
- Eradicate evaporative exhaust emissions
- Releases less toxic and carcinogenic pollutants

NGV America, Encana estimate and Environmental Protection Agency conducted a comparative analysis of CNG vs Diesel vehicle emissions as shown in Fig. 12

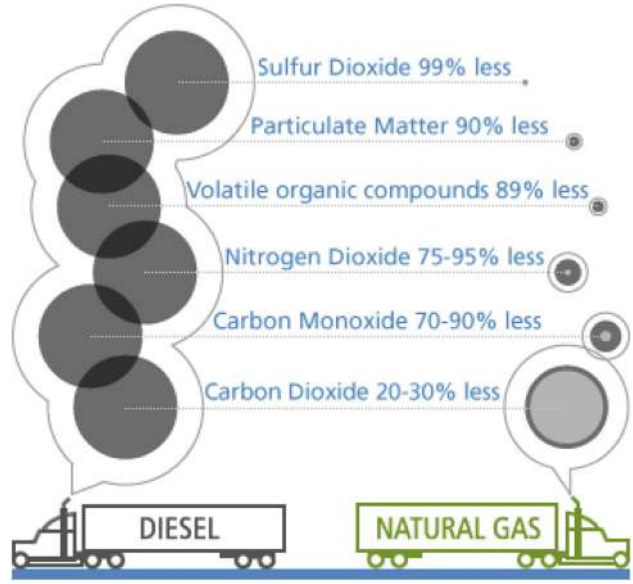

Fig. 12. CNG vs Diesel vehicle emissions (Natural Gas and Transport, 2012).

Analysis of ambient pollutant levels before and after the execution of CNG program in the country shows significant reductions in PM, CO, CO_2, TSP, NO_x & SO_2.

On general for over 3.2 NGVs in the country, there is corresponding decline in the transport emission as highlighted in Table 2 (RazaNasreen, 2008).

Few years ago there was no national Auto Fuel Policy in Pakistan. To control vehicular pollution resulting from the dramatic growth in vehicular traffic in the country, Pakistan Environmental Protection Agency (Pak-EPA) launched National Environmental Quality Standards (NEQS) for exhaust emissions of vehicles in 2009. Table 2 depicts the emission limits for passenger car according to this policy. As can be seen the limits are very similar to Euro II emission for same category vehicles. The implementation of this policy will further boost the growth of CNG program in the country.

12. Problems

Besides several advantages of CNG, there are some negative effects which CNG introduce in the energy sector of Pakistan.

1. Pakistan present gas consumption growth rate shows that our gas needs will increase from 5400 mmscfd in 2012–8400 mmscfd in 2020.
2. Due to the rapid replacement of diesel and gasoline vehicle with CNG powered vehicles, the prices of natural gas are rising up very sharply. As evident from Fig. 9, the prices of CNG raised nearly 8 times in the last 13 years due to which domestic natural gas prices are also raised very sharply and this increasing share of transport in the gas consumption has made it a contender for

Table 2
Decline in the transport emission due to CNG program.

S. no.	Emissions	Kg/Km
01	Carbon dioxide – CO_2	355
02	Carbon monoxide – CO	7680
03	Oxides of Nitrogen – NO_x	6080
04	Hydrocarbons – HC	896
05	Particulate matter – PM	7616

Fig. 13. Long queues of vehicles waiting for filling of CNG at refilling station.

the domestic/household sector. The questions such as either to supply natural gas for 'cooking meal for poor on costly fuel' or 'fueling vehicles of the wealthy people on inexpensive fuel' are becoming increasingly prominent in the country.

3. Due to gas curtailment to CNG sector, CNG station are now open only four days a week, Owing to this, whenever CNG supplies resumed motorists have to wait for hours in long queues to get their tanks filled (Fig. 13), clogging traffic and car drivers waiting for CNG filling cannot serve passengers. Many taxi drivers are reluctant to use petrol; those who do charge higher fares than their CNG-burning counterparts.
4. Increasing CNG cylinder accidents are a major threat to life in Pakistan. Although CNG is much safer fuel as compare to gasoline & diesel, but owning to low quality CNG system material e.g. CNG cylinder, CNG design & installation, maintenance system etc. and lack of strict government CNG vehicle safety regulations, every year several CNG vehicles accidents took place in the country. Table 3 summarizes the major CNG accidents happened in the country during the period 2003–2012. Table 4

Fig. 14 highlight some of the above mentioned CNG vehicles accidents. Analyzing the causes responsible for the above reflected CNG vehicle accidents, following technical deficiencies can be derived.

- Leakage of gas from high pressure piping and cylinder valve due to various reasons.
- The use of non-certified gas cylinder.
- Pulling out of high pressure gas pipes from fittings.
- Bursting of unapproved cylinders, welded cylinders and the cylinder not made for CNG.
- Short circuit in electrical wiring creating sparks.
- Bursting of unapproved valve.
- Generally, the conversions were found to have much lower quality than the OEM vehicles.
- Clamping of gas pipes was not sufficient in several locations

In order to prevent CNG-related accidents, ministry of petroleum has formed a task force to draft a law in consultation with stake holders. Following measures are being taken under task force to make safe usage of CNG:

1. More than 100 workshops all over the country duly approved by Chief Inspector of Explosives (CIE) and certified by Hydrocarbon Development Institute of Pakistan (HDIP), have started certifying vehicles, in this campaign all un-approved CNG equipment including unapproved CNG Cylinders shall be replaced.
2. HDIP and CIE being the statutory bodies for the purpose are developing detailed criteria for installation of CNG system in the vehicles, especially Public Service Vehicles.
3. Allowing only approved brands CNG cylinders manufactured as per NZS 5454-1989 standard and the installed CNG cylinder shall be pressure tested after every five year.
4. Un-certified Vehicles shall not be given fitness certificate/route permits by relevant transport authorities.
5. Uncertified vehicles shall not be allowed to be filled by CNG Stations.
6. Massive media campaign is also launched for awareness of safety aspects associated with usage of CNG.

13. Conclusion

From the above details we may draw conclusions as follows:

- Natural gas is clearly a powerful weapon for Pakistan in the battle to replace oil in the transportation sector, to reduce air pollution and to address the challenge posed by climate change.
- To quantify the environmental benefit of the country CNG program, there is a need for qualitative and quantitative assessment of ambient air of quality in major cities of Pakistan.
- CNG is going to witness a phenomenal growth with growth of transmission pipeline network and implementation of city gas distribution network in various cities of the country. In Pakistan, from the vehicle owner's prospective the attraction for CNG is not its environment impact, but its cost viz-a-viz petrol and diesel. It is this differential in the operating cost of a vehicle that is the driving force to opt for CNG.
- The country has extremely efficient gas transmission and distribution networks for utilization of natural gas transportation fuel. However, in order to meet the shortfall of gas for CNG industry, it is essential that natural gas must be imported on fast-track basis either through Turkmenistan-Afghanistan-Pakistan (TAP) or Iran–Pakistan gas pipeline project or LNG. There is a vital need for improvement in exploration activities and to increase domestic gas production.
- Discontinuing the use of CNG as a transportation fuel will add to the economic woes of the government that will have to spend 5 - 6 billion dollars more to import additional quantities of petrol and diesel.
- The decision by the government to curtail the gas supply to CNG sector will adversely affect hundreds of thousands of workers

Table 3
NEQS vehicles emission standard, 2009, (g/Km).

Type of vehicle	Category	Tiers	Fuel	CO	HC + NO_x	PM	Applicability
Passenger Cars	RW < 2500 Kg	Pak-II	Diesel	1	0.7	0.08	1st July, 2012
			Gasoline	2.2	0.5	–	1st July, 2009 (new car)
							1st July, 2012 (older than 2009 car)
Vs							
Passenger Cars		Euro II	Diesel	1	0.6	1	1996
			Gasoline	2.2	0.5	–	

Table 4
Summary of major CNG vehicles Accidents in Pakistan.

S/N	Date	Accident description	Place	Vehicle	Deaths	Injured	Causes
1	30-Mar-08	Explosion of CNG cylinder	Attock	Pick-up	2	3	Explosion took place during refilling at CNG station due to substandard cylinder.
2	6-Oct-08	Explosion of CNG cylinder	Peshawar	Car	2	4	Explosion took place during refilling at CNG station due to substandard cylinder.
3	7-Jun-09	Explosion of CNG cylinder	Rawalpindi	Car	2	4	Explosion took place during refilling at CNG station due to substandard cylinder.
4	14-Dec-09	Explosion of CNG cylinder	Mirpurkhas	Car	4	4	Explosion took place during refilling at CNG station due to substandard cylinder.
5	18-Feb-10	Explosion of CNG cylinder	Lodhran	Van	6	15	Gas cylinder installed in the van had crossed the standard age and needed to be checked
6	21-Oct-10	Explosion of CNG cylinder	Swabi	Car	2	2	Explosion took place during refilling at CNG station due to substandard cylinder.
7	5-Jan-11	Explosion of CNG cylinder	Lahore	Car	–	4	The CNG cylinder exploded when the cylinder being filled at local CNG gas station
8	12-Jul-11	Explosion of CNG cylinder	Near Islamabad	Mini-Bus	9	3	Gas leakage from any point of CNG piping system and caught fire possibly of short circuit
9	3-Sep-11	Explosion of CNG cylinder	Near Lodhran	Van	4	21	Due to low quality cylinder.
10	1-Nov-11	Explosion of CNG cylinder	Khairpur	Van	4	8	Gas leaked from the CNG cylinder and caught fire followed by a blast
11	29-Nov-11	Fire in Vehicle	Islamabad, Golra Sharif	Van	12	7	In an effort to save an oncoming pedestrian, the vehicle hit the median on the GT Road. The vehicle caught fire following the accident, after gas leaked from its three CNG cylinders
12	29-Nov-11	Explosion of a CNG cylinder due to collision of a Passenger	Near Taxila	Van	14	7	The van crashed into a tree after one of its tires burst
13	3-Dec-11	Explosion of CNG cylinder	Multan	Car	2	1	Explosion took place during refilling at CNG station due to substandard cylinder.
14	7-Dec-11	Explosion of a CNG cylinder due to leakage	Near Hyderabad	Van	11	11	Van caught fire because of a CNG leakage.
15	10-Dec-11	Explosion of a CNG cylinder due to collision of a Passenger	Near Vehari	Mini Bus	17	10	The tragedy took place after the Hiace driver, while attempting to overtake another wagon, lost control of his vehicle and hit a Tractor trolly laden with large cans of oil and ghee.
16	13-Dec-11	Explosion of CNG cylinder	Gujranwala	Mini Bus	1	4	Explosion took place during refilling at CNG station.
17	17-Dec-11	Explosion of CNG cylinder	Peshawar	Car	–	6	Explosion took place during refilling at CNG station due to substandard cylinder.
18	18-Dec-11	Explosion of CNG cylinder	Near Khurinwala	Van	5	14	Unknown Causes.
19	21-Dec-11	Explosion of CNG cylinder	Gujranwala GT road Eminabad	Van	6	15	Vehicle rammed into a road's demarcation wall while saving a cyclist and caught fire when its CNG cylinder exploded.
20	21-Dec-11	Explosion of CNG cylinder	Khairpur, Setharja	Van	13	12	Cylinder suddenly blasted.
21	23-Dec-11	Explosion of CNG cylinder	Noshehra, Pabbi	Pick up	1	3	Explosion took place during refilling at CNG station due to substandard cylinder.
22	24-Dec-11	Explosion of CNG cylinder	Rawalpindi	Mini-Van	–	–	Unknown Causes.
23	24-Dec-11	Fire explosion have resulted from gas accumulation due to leakage.	Rawalpindi	Van	–	–	As soon as smoke started coming out of the, the driver asked the passengers to run for their lives and after some minutes the CNG cylinder exploded resulting in complete destruction of the vehicle.
24	27-Dec-11	Explosion of CNG cylinder result in fire	Islamabad	Car	–	–	Unknown Causes.
25	29-Dec-11	Explosion of CNG cylinder	Peshawar	Car	–	3	Explosion took place during refilling at CNG station due to substandard cylinder.
26	18-Feb-12	Explosion of CNG cylinder	Muzafargar	Car	4		The vehicle collided with a bridge which results in the explosion of CNG cylinder.
27	2-May-12	Explosion of CNG cylinder	Sheikhpura	Mini Van	6	4	Gas leakage from any point of CNG piping system and caught fire possibly of short circuit.
28	16-Jun-12	Explosion of CNG cylinder	Narowal	Van	2		Unknown Causes.
29	18-Aug-12	Explosion of CNG cylinder	Mansehra	Car	–	5	Explosion took place during refilling at CNG station.
30	7-Oct-12	Explosion of CNG cylinder result in fire	Near Khairpur	Car & Bus	7	22	The bus collided with a car near Khairpur. The CNG tank of the car exploded and fire engulfed the bus.
31	18-Nov-12	CNG cylinder explosion	Karachi	Mini-Bus	2	4	Explosion took place during refilling at CNG station due to substandard cylinder.
32	26-Nov-12	Explosion of a CNG cylinder due to leakage	Multan road near Manga Mandi	Van	7	4	Fire was blow up due to lightening of cigarette.
33	26-Nov-12	CNG cylinder explosion	Mardan	Riksha	–	4	Explosion took place during refilling at CNG station due to substandard cylinder.
34	11-Dec-12	Explosion of CNG cylinder	Karachi	Car	–	3	Unknown Causes.
35	25-May-13	Explosion of CNG cylinder	Gujarat	Van	18	7	As soon as the driver switched the fuel from gas to petrol, the vehicle caught fire
36	9-Jan-13	Explosion of CNG cylinder	Faisalabad	Van	1	4	The van was on its way when its cylinder exploded.
37	31-Mar-13	Explosion of CNG cylinder	Mandi Jabharan	Van	3	16	The vehicle caught fire due spark produced by short circuit near petrol fuel line which is subsequently spread toward CNG cylinder.

(*continued on next page*)

Table 4 (*continued*)

S/N	Date	Accident description	Place	Vehicle	Deaths	Injured	Causes
38	20-Jan-13	Explosion of CNG cylinder	Nowshera	Car	1	3	Explosion took place during refilling at CNG station due to substandard cylinder.
39	12-May-13	Explosion of CNG cylinder	Bannu-Mirali Road, North Waziristan	Van	15	3	Unknown causes
40	30-July-13	Explosion of CNG cylinder	Karak	Van	17	1	As a result of the collision between Passenger van and truck, the CNG cylinder of van exploded, causing a huge fire that killed all the passengers except one.

Fig. 14. Pictorial view of some of the mentioned accidents.

directly and indirectly. Considering the huge investment that has been made in the CNG sector both by investors and the consumer, it would be unwise to ban the fuel's usage for private consumers completely. Instead, the government should work towards importing affordable natural gas together with the use of indigenous gas sources.

- The pricing of all fuels needs to be rationalized and brought at par in order to create a level playing field and to ensure there is not over-consumption of a particular fuel.

Competing interests

The authors declare that they have no competing interests.

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Abbreviations used

BSCFD	Billion Standard Cubic Feet per Day
CARB	California Air Resources Board
CIE	Chief Inspector of Explosives
CNG	Compressed Natural Gas
GHG	Green House Gas
GOP	Government of Pakistan
GSPA	Gas Sale Purchase Agreement
GST	General Sale Tax
HDIP	Hydrocarbon Development Institute of Pakistan
HSD	High Speed Diesel
IP	Iran Pakistan
LNG	Liquefied Natural Gas
MMSCFD	Million Standard Cubic Feet per Day
MTOE	Million Tons of Oil Equivalent
NEQS	National Environmental Quality Standards
NGVs	Natural Gas Vehicles
OEM	Original Equipment Manufacturer
Pak-EPA	Pakistan Environmental Protection Agency
PM	Particulate Matter
ppm	Parts per Million
Rs	Rupees
TAPI	Turkmenistan-Afghanistan-Pakistan-India
TCF	Trillion Cubic Feet
TEL	Tetraethyl Lead
TSP	Total Suspended Particle
WHO	World Health Organization

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Annexure-B

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Technical overview of compressed natural gas (CNG) as a transportation fuel

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ABSTRACT

Increasing urbanization and industrialization have led to a phenomenal growth in transportation demand worldwide, coupled with a concentration of vehicles in metropolitan cities. With regard to increasingly stringent emission legislation natural gas is gaining interest as a transportation fuel with worldwide over 19 million natural gas vehicles in operation. This paper presents the worldwide background, prospects and challenges of natural gas fuel and natural gas fueled vehicles along with environmental and economic aspects of compressed natural gas as a transformation fuel. Technical aspects of compressed natural gas properties, storage, safety problems and its effect on engine performance, efficiency, emissions and barriers to natural gas vehicles adaptation are discussed in detail. The main indicators selected for the comparative assessment of natural gas as vehicular fuel are: economic, emission performance and safety aspect. The results showed that CNG has several advantages over both diesel and gasoline fuel, including considerable emission and cost reductions.

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1. Introduction

In the world today a total of 12,730 Mtoe of energy is consumed, of which 7205 Mtoe are oil and natural gas (Fig. 1). Transport sector with over one billion light-duty motor vehicles in operation is a major consumer of oil worldwide [1–4], increasing from 45.5% in 1973 to 59% in 2011 mainly in the form of gasoline and diesel [5]. It is well known that oil reserves are being depleted at an alarming rate. In addition, the burning of these conventional fuels by transport sector contributes greatly to atmospheric pollution that threatens the very survival of life on this planet [1,6,7]. The function of current IC engines needs to be reviewed today, in the perspective of these two main crises. The energy crisis and serious environmental pollution around the world have triggered the development of low emission and high fuel efficient vehicle to become major research objective [8]. Various alternative fuels have been introduced into the transport sector e.g. LPG, propane, bio-diesel, hydrogen, fuel cells. Out of these available alternate fuels compressed natural gas (CNG) is the one which is meeting the maximum needs of countries worldwide, who want to switch over to alternate fuels [9–12]. CNG has been considered as one the best solutions for fossil fuel substitution because of its inherent clean nature of combustion [13–15]. It has now been recognized worldwide as environment-friendly fuel [16,17]. Following are the main features which conduced to an increased interest to use natural gas as a transportation fuel:

i. Wide availability
ii. Eco friendly
iii. Conventional SI and CI engines compatibility
iv. Low operational cost.

The article presents an extensive review of the CNG fuel properties, storage, safety problems and its effect on engine performance, efficiency, emissions and barriers to NGVs adaptation. A comparative study of literature on CNG versus diesel and gasoline fuel and their impact on the environment has been attempted here.

2. CNG as fuel

The natural gas used in natural gas vehicles is the same natural gas that is used in domestic sector for cooking and heats. CNG is produced by compressing the conventional natural gas (which is mainly composed of methane –CH_4) to less than 1% of the volume it occupies at standard atmospheric pressure. It is stored and distributed in a rigid container at a pressure of 200–248 bar (2900–3600 psi), usually in cylindrical shapes metallic cylinder. Table 1 represents the comparison between the physiochemical properties of CNG to that of diesel and gasoline.

3. World NGV market

Worldwide quantities of natural gas vehicles are increasing so speedily that the statistics lag behind and no consistent sources of information are available. However, as per the recent authentic sources, the world leader in NGVs (for the moment) is Iran, with 4.07 million NGVs [18]. Following closely behind Iran is China, with 3.99 million NGVs. Fig. 2 shows that in the last ten years, worldwide the NGVs population has escalated speedily at an annual rate of 24% with the biggest contribution coming from the Asia-Pacific and Latin America regions (Fig. 3). This trend is projected to continue with average annual growth rate of 3.7% upto 2030, with major fraction of growth contributing by non-OECD countries.

Today there are over 18 million natural gas vehicles distributed through more than 86 countries of the world with major concentrations in Iran, China, Pakistan, Argentina, India, Brazil, Italy and Colombia [18]. The majority (93%) of CNG vehicles are light duty car and commercial vehicles. Besides these there are more than 26,677 CNG refueling stations throughout the world. Fig. 4 shows the top 10 countries of world with highest number of NGVs.

4. Historical background of CNG

The use of CNG as a vehicular fuel discovered back in early 1930 in Italy [19], but the first retro which experienced any considerable activity started in the 1970s, when natural gas was witnessed as a promising fuel aftermath of the oil crisis. When the oil prices rose during late 1970s and early 1980s, the market for CNG vehicles became more attractive. However, the subsequent period up to

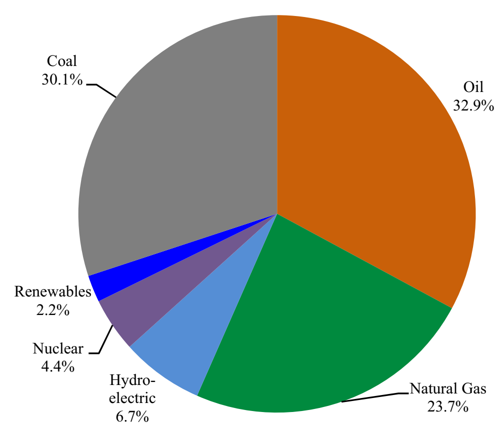

Fig. 1. World primary energy consumption.

Table 1
Physiochemical properties of CNG vs gasoline and diesel.

Properties	CNG	Gasoline	Diesel
Octane/cetane number	120–130	85–95	45–55
Molar mass (kg/mol)	17.3	109	204
Stoichemetric $(A/F)_s$ mass	17.2	14.7	14.6
Stoichemetric mixture density (kg/m^3)	1.25	1.42	1.46
L.H.V. (MJ/kg)	47.5	43.5	42.7
L.H.V. of stoichemetric mixture (MJ/kg)	2.62	2.85	2.75
Combustion Energy (MJ/m^3)	24.6	42.7	36
Flammability limit in air (vol% in air)	4.3–15.2	1.4–7.6	1–6
Flame propagation speed (m/s)	0.41	0.5	–
Adiabatic Flame Temp. (°C)	1890	2150	2054
Auto-ignition Temp. (°C)	540	258	316
Wobbe Index (MJ/m^3)	51–58	–	–

2000, has made it challenging for CNG to strive as vehicular fuel. But after 2000s, the oil prices rose once again very sharply and owing to this CNG vehicles got an opportunity to prove itself as a cheap and cleanest fuel. Since that time, Natural gas vehicles have entered and left the transportation market of several countries/regions at different times, with the advancement of technology.

The Origen of NGVs with dedicated CNG engines routes to Italy. The first natural gas vehicle using pressurized gas container was observed in Italy 1936 as shown in Fig. 5 [20], but the first promising period that observed any considerable activity dated to 1970, when CNG was recognized as cheap and stable fuel after the oil crisis.

5. Demand for natural gas as a transportation fuel

Natural gas is becoming one of the most important resources of energy and currently shares 23% of world primary consumption [21]. As reported by Cedigaz [22], the world's proved natural gas reserves are 7080.3 TCF as of January 1, 2014, which correlates to over 60-year supply at current annual consumption levels of 118.20 TCF [23]. Fig. 6 illustrates the global primary energy demand by fuel type from 1980 to 2035. It can be observed that natural gas will surpass coal before 2030 and will cover a 25% total energy demand in 2035. An IEO2014 projection of future energy demands shows that natural gas is the fastest-growing primary energy source in the future and its consumption is forecasted to be double between 2020 and 2040 [24]. The report projected that growing production of natural gas from tight shale reservoirs will keep the prices of natural gas to customers under the price level of 2005–2008 through 2038. This has led to a growing interest to use natural gas as a transportation fuel. The current annual consumption of natural gas as transportation fuel is 1.205 TCF, only accounts for 1.01% of total global demand for natural gas.

6. Types of NGVs

In terms of fuel supply, there are three types of NGVs:

i. Dedicated CNG engine
ii. Bi-fuel retrofitted gasoline engine
iii. Dual-fuel diesel engine.

6.1. Dedicated CNG vehicle

Dedicated CNG vehicles have SI engines that are operated only on natural gas. The compression ratio of these engine are

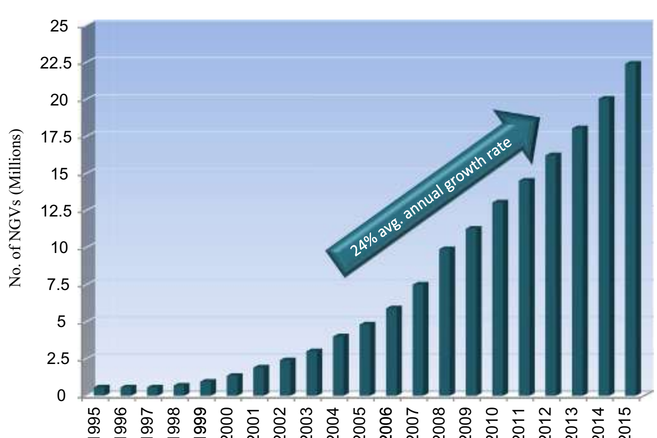

Fig. 2. Worldwide NGVs growth.

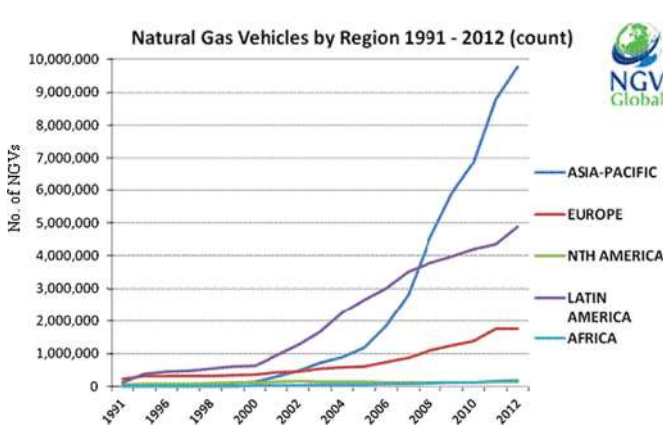

Fig. 3. Worldwide NGVs growth by region.

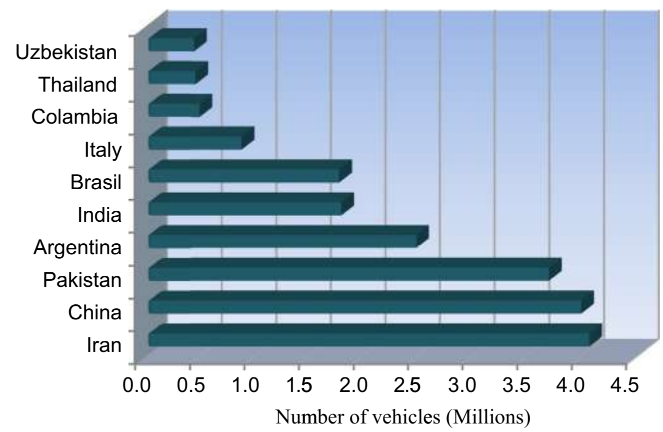

Fig. 4. NGVs adoption by country (number of vehicles in millions).

Fig. 5. Natural gas inter-urban with 40 seats on FIAT chassis 635 RL of 1936.

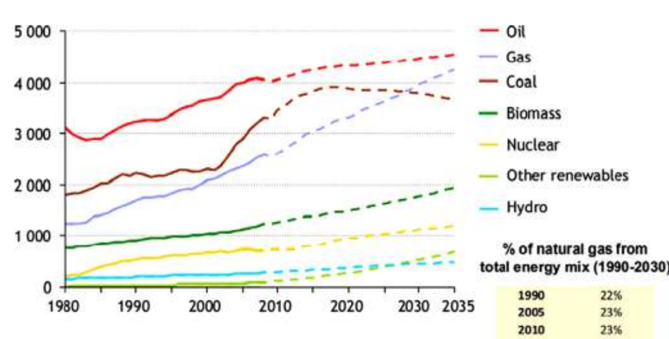

Fig. 6. World primary energy demand by fuel [23].

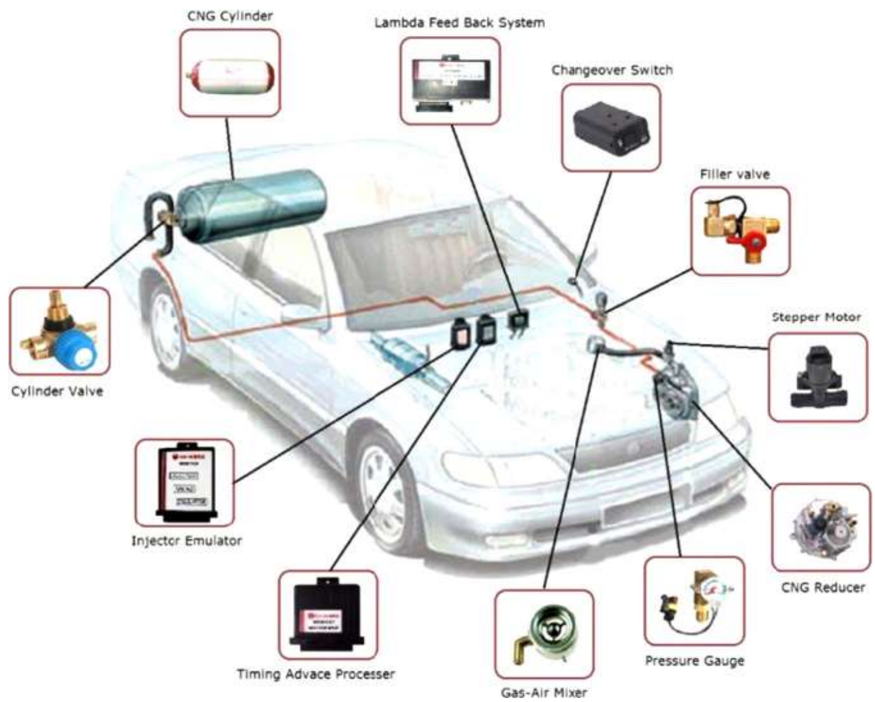

Fig. 7. Schematic of retrofitted bi-fuel vehicle.

optimized to utilize the advantage of high octane number of natural gas and are designed keeping the combustion properties of natural gas, so that the vehicle produce very less emission pollutant.

6.2. Bi-fuel

Bi-fuel vehicle can run on either natural gas or gasoline. The engine type they used is a regular gasoline IC engine. The driver can select what fuel to burn by simply flipping a switch on the dashboard. Any existing gasoline vehicle can be converted to a bi-fuel vehicle. Most of the CNG vehicles operated today are retrofitted from the gasoline engine [25]. In Pakistan, the 2nd largest consumer of CNG almost the entire NGV fleet comes under bi-fuel vehicle category [26].

The combustion properties of natural gas are significantly different from regular fuel i.e. diesel and gasoline. As compared to diesel and gasoline CNG has a longer ignition delay time due to low flame propagation speed. Thus using the same gasoline fuelled engine for CNG, the combustion duration becomes relatively longer and it requires more advance spark timing. Hence, retrofitting is necessary for conventional gasoline fueled engine to run with CNG. The bi-fuel engines are generally optimized for natural gas, with the ignition timing rather advanced to accommodate the slower burning rate of methane. Fig. 7 depicts a schematic of conventional retrofitted bi-fuel CNG vehicle.

6.3. Dual-fuel vehicle

Dual-fuel vehicle are based on CI engine technology. They run either on diesel only or utilize a mixture of natural gas and diesel, with the natural gas/air mixture ignited by a diesel “pilot”. During the idle condition these engines tend to operate only on diesel. As the vehicle starts to pick the load, the natural gas substitutes the diesel fuel up to 60–90%. However, like bi-fuel vehicle direct conversion is not possible due to the very low cetane number of natural gas as a result of its very high auto ignition temperature which necessitates either conversion to spark-ignition or adoption of a dual-fuel system. Due to high ignition temperature of natural gas, it needs very high compression ratio for auto ignition i.e. about 38:1. Owing to this, it should be ignited with another fuel (diesel)—pilot injection. The diesel fuel is introduced directly into combustion chamber, while gas is injected into air intake by carburetion. The gaseous fuel is then compressed in the compression stroke of the engine. Diesel fuel is then injected near the end of compression stroke. With a short ignition delay the combustion of diesel fuel happens first, resulting in the ignition the natural gas and instigation of flame propagation. An important factor for the dual fuel operation is the replacement rate, which is defined as the portion of energy content of the fuel which is supplied by natural gas. The replacement rates vary depending on the engine load. A maximum replacement rate up to 90% can be obtained with the currently available dual-fuel engines. Substitution rate affect both engine performance and emission. Egúsquiza et al. [27] found that brake specific fuel consumption increased as the percentage of substitution increased. They also observed that at higher loads and with the increase of substitution ratio, the hydrocarbons concentrations showed a tendency to increase while CO concentration first increased upto substitution rate of 70% and then decreased. NO_x were the only emission factor which showed decreasing trend with the corresponding increase in substitution ratio.

Duel-fuel vehicle provides 30–40% higher engine efficiency which subsequently reduces the fuel consumption by 25% [28]. In both cases, there is an incremental cost relative to conventional diesel and gasoline vehicles and this extra cost to be reimbursed by the saving in operating cost due to fuel cost [29].

7. Commercial status of CNG technology

The technology of CNG engine development and engine conversion is well established and suitable conversion equipment is readily available. Worldwide various manufacturers offer natural-gas engines either as dedicated (mono-fuel) Otto-cycle engines or as duel fuel diesel-cycle engines. In the USA, Cummins Westport Inc. is a leading supplier of high-performance CNG engines for the automotive market. It designs, engineers, and markets 6 to 12 l (195–400 hp) dedicated CNG SI engines for commercial transportation applications such as truck and buses. The Cummins

Westport ISX12 G (298 kW) is a CNG engine suitable for various types of heavy duty vehicles including waste collection trucks and transit buses. The ISX12 G is a stoichiometric CNG engine that employs proven Stoichiometric Cooled Exhaust Gas Recirculation (SEGR) combustion technology, turbocharging and aftertreatment through a TWC to achieve U.S. 2014 EPA emission standards.

IVECO is the European leader in the production and sales of CNG engines and vehicles. Since 1994 IVECO is offering a wide range of NGVs and one of leading researcher and manufacturer of natural gas vehicles and engines in Europe, with thousands of vehicle in operation with both public and private authorities. IVECO is currently offering three main types of CNG engines i.e. IVECO Sofim 3 l (100 kW), IVECO Tector 6 l (kW) and IVECO Cursor 8 l (200 kW). All IVECO natural gas engines use a dedicated CNG SI engine operating on stoichmetric combustion cuopled with TWC.

Volvo, Sweden is the third largest manufacturer of CNG buses in Europe. They offer both dual fuel and dedicated CNG engine since 1992. The Volvo FM Methane-Diesel D13C-Gas engine is a 13-l (460 hp) dual fuel engine, with a compression ratio of 17.8:1 and powered by up to 75% natural gas or bio-methane. The engine technology is based on a conventional diesel engine equipped with a gas injector. Under the dedicated CNG engines category they offer, G9A which is a 9.4-l six-cylinder (260 or 300 hp) gas engine with compression ratio of 10.25:1. The engine easily meets the EU's requirements for exhaust emissions according to Euro 5 and EEV.

Since 2006 Mercedes-Benz is manufacturing M 447 hLAG (185 kW) dedicated CNG engine used in the Mercedes-Benz Citaro urban buses rated as a Euro4/EEV vehicle. Recently they introduced a M-936G six-cylinder (302 hp) deicated CNG engine. Similarly to a modern gasoline engine, the new dedicated CNG engine M-936G operate with a stoichiometric combustion ratio of lambda = 1, i.e. it employs neither excess air nor a rich mixture. This result in particularly clean combustion coupled with high output power and low exhaust emissions. The engine complies with emission standards of Euro VI.

TEDOM, a leading bus manufacturer from the Czech Republic, offers dedicated CNG fueled buses comply with Euro 5 EEV levels of emission standards. TEDOM produces turbo or naturally aspirated 12 l, 6-cylinder CNG combustion engines Equipped with OBD-II (On-board diagnostics) technology. The engines are manufactured in vertical or horizontal layout with horse-power range 241–348 HP and compression ratio range of 11:0 to 13:1.

Most available light duty NGVs are based on bi-fuel CNG technology. There are few manufacturer who are producing dedicated light duty NGVs e.g. Car, Van etc. A listing of the light duty natural gas vehicles available worldwide is provided in Table 2.

Table 2
Light duty dedicated NGVs manufacturer.

S.N.	Manufacturer	Model	Engine Dis.
1	Opel (Germany)	Combo CNG	1368
2	Opel (Germany)	Zafira Tourer	1578
3	Volkswagen (Germany)	Touran EcoFuel	1984
4	Honda (USA)	Civic GX	1798
5	General Motor (USA)	GMC Savana Cargo Van	4700
6	FIAT (Brazil)	Siena 1.4	1368

8. Technical aspect of CNG engine

Thermal efficiency of the engines is function of various parameters but perhaps most important is the compression ratio of the engine. Higher the compression ratio higher would be theoretical and also actual efficiency. The octane number of natural gas is ranging from 120 to 130, which means that the engine could function at compression ratio up to 16:1, without knocking. The high octane value allowing a dedicated CNG engine to use higher compression ratio to enhance engine thermal efficiency of about 10% above than that of gasoline engine [30]. Therefore, the dedicated CNG engines may have the efficiency up to 35% in contrast to 25% for that of gasoline engine. Incidentally retrofit gasoline engines will not have the advantage of a high octane value of CNG as the compression ratio will be set to the level required for gasoline. The benefit of high efficiency quoted above can be achieved in dedicated CNG engines. Following are the major attributes connected with CNG engines:

8.1. *Mixing advantage*

The molar mass of gasoline (114.23 g/mol) is much higher than natural gas (16 g/mol). Being light weight fuel, natural gas can produce much better homogeneous air–fuel mixture [31]. On the other hand, liquid fuel needs time for complete atomization and vaporization to form a homogeneous air–fuel mixture [25]. CNG being a gaseous fuel at normal atmospheric conditions has the inherent advantage of high level of miscibility and diffusion with gaseous air, which is essential for good combustion [32].

8.2. *Maintenance advantage*

NGVs have lower maintenance cost as compared to conventional fueled vehicle. Chandler et al. [17] conducted 12 months comparative analysis between CNG and diesel transit buses operated by Washington metropolitan area transit authority. They found that the maintenance cost of CNG powered buses were 12% lower than diesel fueled buses. CNG does not contaminate or dilute engine oil, which subsequently enhance the useful life of lubricant. CNG comes into the engine in gaseous form, unlike gasoline which enters the engine as spray or mist and washes down the lubricating oil from the piston rings region which subsequently enhances the wear and tear of the engine. Therefore, CNG cuts the maintenance costs and prolongs engine useful life. But as compared to diesel and gasoline engines, CNG engines require low sulfated ash oil. Sulfated ash is a characteristic of natural gas engine oils that gives an indication of the oil's ability to neutralize acids from the combustion process. Because of its gaseous nature, CNG is dry and provide absolutely no lubricant value conduce to sulfated ash deposits on exhaust valves that contain metal sulfates, including barium, calcium, magnesium, zinc, potassium, sodium and tin. Large quantities of this remnant can result in reduced heat transfer, detonation, valve burning and ring sticking or breaking.

The absence of lead concentration in CNG contributes to avoid lead fouling of spark plugs, thus extending the life of piston rings and plugs [33]. Interval between tune-ups for natural gas vehicles extended upto 30,000 km. Similarly interval between oil changes for natural gas vehicles can be extended from 5000 to 10,000 additional km depending on how the vehicle is used.

8.3. *Brake specific fuel consumption:*

Brake specific fuel consumption (BSFC) is very important characteristic for comparing the performance of IC engines fueled with different fuels. Various studies confirmed that BSFC of CNG fueled engines was 12% to 20% lower than that of gasoline throughout the speed range [14,34–39]. This can be attributed to the following two factors:

i. Higher heating value of the CNG (47.5 MJ/kg) as compared to that of gasoline (43.5 MJ/kg)
ii. Lean and slow burning of CNG as compared to gasoline

Owing to this low BSFC and higher CNG calorific value, natural gas engines shows 5–12% higher brake thermal efficiency (BTE) in contrast to gasoline engine [25,36–38]. Similarly Singh et al. [40] investigated the BSFC & BTE of duel fuel engine (60% CNG+40% Diesel) and observed that on average BSFC of dual-fuel mode is less than pure diesel mode by 60% and BTE of dual fuel mode is more than neat diesel mode by11%.

8.4. Engine performance shortcomings

The performance of CNG fueled engine highly depended on the engine design and type i.e. dedicated CNG or not. However, the major problem that all investigators and manufacturers are facing today is the brake power loss in the CNG engine. Several attributes of CNG fuel that affect the engine power are low flame propagation speed, lost in volumetric efficiency and absence of fuel evaporation [41].

8.4.1. Low flame speed

Several experimental studies have reported that the flame propagation speed of natural gas is lower in contrast to conventional fuels, such as gasoline and diesel [42–45]. This lower flame propagation speed conduce to prolongation in total combustion duration compared with gasoline/diesel and allows exit of a greater amount of unburned natural gas through the exhaust [32]. Due to this low speed of the flame, when the when the engine fueled by CNG engine operates closely to the lean limit, problem of misfiring happens. As methane (CH_4) is the main component in natural gas and among hydrocarbons, methane has the slowest flame speed [46]. This increases the energy losses due to heat transfer which subsequently reduces the engine power output from 5 to 10% [47].

One effective method to address the problem of slow flame propagation speed of natural gas is to mix the CNG with the fuel having fast burning speed e.g. hydrogen. Hydrogen is considered as the best additive for CNG due to its fast flame propagation speed (265–325 cm/s), much better lean-burn ability and small quenching distance. This combination is projected to boost the lean-burn features of CNG engines [47–49].

8.4.2. Volumetric efficiency

One of the other major problems with the CNG engine is the gaseous nature of the CNG fuel which causes the reduction in volumetric efficiency up to 10% by displacing the air available for proper combustion [38,45,50–57]. The maximum potential power therefore will reduce by up to 10% compared to a gasoline engine under similar condition. This decrease is due to the larger volume of inlet air occupied by CNG. Using ideal gas state equation it can be easily shown that the volume occupied by natural gas is larger than that by gasoline in a stoichiometric air–fuel mixture. In case of gasoline/diesel engine, by the time the air–fuel mixture enters the cylinder the liquid particles become almost completely vaporized this increases the inlet pressure of the cycle, while in case of CNG, the fuel supplied is gaseous; hence, such increase in inlet pressure is not present [29]. There are several ways to improve the volumetric efficiency of CNG engines such as increasing the number of intake valves per cylinder, valve timing and lifting optimization [12], using turbocharged CNG engine [52,53] and designing a modified intake manifold; however these all affect cost and reliability.

8.4.3. Lower power output

Owing to the above two factors i.e. flame speed and volumetric efficiency, the conventional CNG engine yields less brake power than that of gasoline. Several experimental studies have shown that gasoline vehicles retrofitted to CNG are subjected to a 15% to 20% loss in total brake horse power while running on natural gas [14,35–41,45,47,54,58–61]. Many experimental works have been done on the performance analysis of CNG fuelled engines. Aslam et al. [14] investigated the performance of 1468 cm^3 Proton Magma12-Valve, 4 Cylinder, engine having compression ratio 9.2:1. The tested engine was a CNG converted gasoline engine equipped with bi-fuel system. They found that an average CNG yielded 16% less brake power to that gasoline. Al-Baghdadi et al. [62] exercised the emissions and performance of a retrofitted bi-fuel gasoline/CNG engine. As per their finding, the exhaust emissions and brake power of CNG were very low compared to gasoline fuel. Their investigation revealed that the brake power of CNG fuelled engine is lower than that of gasoline engine. Ramjee et al. [34] carried out experimental work on a single cylinder 4-stroke Bi-fuel engine to measure the performance of the test engine. They observed that the volumetric efficiency and brake power of CNG fueled engine was low than that of gasoline engine. Ehsan [32] studied the effect of variation of spark advance on the performance of a typical bi-fuel 4-cylinder, 1600 cm^3 carburetor car engine. According to his results, maximum engine power produced when running on natural gas was 5–10% lower compared to when running on gasoline. Geok et al. [45] endeavored to compare the performance and exhaust emission of a 4 cylinder, 1468 cm^3, retrofitted gasoline/CNG engine (Mitsubishi 4G15) under various steady state operations. They observed that on average, CNG operation resulted in 22% less BSFC and 13% higher FCE compared to gasoline. The investigation on the comparative performance analysis of CNG and gasoline in a retrofitted 4-cylinder, SI car engine has been performed by Jahirul et al. [25]. The experimental results showed that CNG produces lower brake power than the gasoline throughout the speed range. Gupta et al. [63] investigated the performances and emissions of a spark ignited engine fuelled with gasoline and compressed natural gas. Results revealed that for naturally aspirated engine with stoichiometric fueling, 10–15% less power can expected for CNG over gasoline fuel.

Shamekhi et al. [38] experimentally investigated the performance and exhaust emissions of a Mazda B2000i bi-fuel SI engine for both natural gas and gasoline fuels over a wide range of engine operating conditions. Their investigation revealed that the brake power and volumetric efficiency of CNG fuelled engine is 11 to 14% lower than that of gasoline engine. The investigation also revealed that on average, CNG operation resulted in 20% less BSFC and 18% higher thermal efficiency compared to gasoline.

Firouzgan et al. [64] evaluated two generations of gas fueling systems including mixer type and Sequential system type in a bi-fuel (gasoline/CNG) engine. He measured various parameters including performance, emissions and fuel consumption of bi-fuel engine. He reported that the sequential gas fueling system is better than the mixer type. The power loss in mixer type is 1.78% higher than that of the other one.

Ebrahimi et al. [65] made experimental investigation to observe the effects of natural gas fuel on the engine performance of a bi-fuel engine in comparison to gasoline fuel. They conducted experiments with the spark timing adjusted to maximum brake torque (MBT) timing with wide open throttle (WOT) condition at different engine speeds and equivalence ratios for gasoline and natural gas operations. It was concluded that natural gas operation causes an increase of about 6.2% in BSFC, 22% in water temperature difference between outlet and inlet of the engine, 2.3% in brake thermal efficiency (BTE) and a decrease of around 20.1% in maximum brake torque (MBT), 6.8% in exhaust gas temperature and 19% in lubricating oil temperature when compared to gasoline. This engine deficiency can be recovered through optimization and design modifications in fuel injection system providing complete combustion of natural gas in the engine cylinder.

To enhance the performance of the CNG engine, alternative methods of fuel injection such as direct injection and port injection of CNG into the combustion chamber are being considered as an option to make CNG a more promising transportation fuel [43]. Direct injection can enhance the absolute heating value of the cylinder charge and improve the turbulence intensity for better mixing before ignition [66,67]. Combustion efficiency is increased which produces improved power and torque, reduces pumping and heat losses and allows better control of the *A*/*F* ratio [68,69]. However, the development of a direct injection engine is expensive and technically tough. This is due to the requirement of advance cylinder head to adapt with direct fuel injector and also the involvement of the detailed calibration of the engine's control system [70].

9. Environmental aspect

The emission performance of transport system is a vital area and one faces a wide range of analytical challenges. Natural gas as transportation fuel becomes the subject of interest nowadays, as the combustion of conventional fuel i.e. diesel and gasoline results in the harmful emissions that threaten the very survival of life on this planet [33].

The use of natural gas as a transportation fuel is associated with a number of potential benefits to the environment, particularly air emissions and noise. On a "well-to-wheels" basis, CNG is one of the cleanest burning alternative vehicular fuels available in the market today [71]. Emissions from properly functioning CNG vehicles (NGVs) are generally considered to be lower than emissions from gasoline operating vehicles [72]. A number of international studies demonstrate that CNG can reduce emissions in transport. In Delhi (Indian capital and world 2nd most densely populated city), the entire public road transport was switched over to CNG fueled vehicle from diesel and gasoline in 2002 after the verdict of Indian Supreme Court. Today Delhi has the world largest CNG-fuelled public transport system. The comparison between the levels of environmental pollutants in pre and post years of NGVs implementation in Delhi showed considerable reduction in total suspended particles (14%), CO (10%), SO_2 (22%) and NO_x (6%) [73]. Dondero et al. [74] carried out a research in Brazil as one of the pioneers in development of CNG retrofitted vehicles. They concluded that compared to gasoline powered vehicles, utilization of third generation conversion kits in CNG retrofitted vehicles will result in reduction of CO emissions equal to 53%, non-methane hydrocarbon (NMHC) emissions equal to 66% and CO_2 emissions equal to 20%.

A growing concern with the transportation sector is the impact of Carbon Dioxide (CO_2) emissions can have on the global climate change. CO_2 emissions from the combustion of fuel largely depend upon the hydrogen-to-carbon ratio (H/C) of a fuel. Higher the hydrogen-to-carbon ratio (H/C) of a fuel, the amount of CO and CO_2 will be lower. CNG has the highest hydrogen-to-carbon ratio (H/C) (almost 4:1) than either gasoline (2.3:1) or diesel fuel (1.95:1). This caused the lower CO_2 emission for the CNG than that of gasoline or diesel fuel [75]. From the chemical equilibrium of combustion of CNG fuel, CO_2 emissions from a natural gas engine can be decreased by more than 20% in contrast to a gasoline engine operating with the same condition [76]. The CO_2 levels of a CNG vehicle may also be lower than a comparable diesel vehicle at the same *A*/*F* ratio, while maintaining almost the same thermal efficiency at very lean conditions [52]. As a rule of thumb based on fuel efficiency experienced by Chive Fuels, UK; CNG saves 2.65 kg CO_2 emission for every gallon of diesel replaced by CNG in a dual fuel engine. Based on a well-to-wheel, natural gas vehicles produce 29% less greenhouse gases than comparable gasoline vehicles and 22% less than diesel vehicles [77]. The CARB (California Air Resources Board) has conducted a thorough analysis on this matter. It determines that combustion of CNG yields about 68 g of equivalent CO_2 emissions per MJ of heat release (this includes all methane emissions), and combustion of conventional diesel and gasoline release about 95 g of equivalent CO_2 emissions per MJ.

Another major vehicle emission is carbon monoxide—CO which is formed by incomplete combustion. Besides having highest hydrogen-to carbon ratio, natural gas engines have two additional important characteristics: (a) low heating value compare to gasoline and (b) low flame propagation speed as compare to other fuels. These two factors reduced the maximum temperature inside the combustion chamber, and therefore, reducing dissociation from CO_2 to CO. Due to excellent lean flammability limit of CNG, it produces lean burning operation which conduces to the reduction of carbon monoxide and NO_x production in exhaust emission [78]. Various studies have been conducted which confirm that the CO emission of the CNG engine was significantly lower than that of the gasoline and diesel vehicle at various load conditions.

Vehicle exhaust emissions also consist of oxides of nitrogen—NO_x, which are by-products of all carbon-based fuel combustion processes and global transport sector contributes about half of the total NO_x emissions. There are lot of adverse health effects associated with NO_x emission such as an increase in total mortality, cardiovascular deaths, and infant mortality [79]. Hu et al. [80] theoretically proved that NO_x formation depends directly on two factors: the concentration of reactants, and temperature. Concentration of NO_x emission is strongly related to the air–fuel ratio and combustion temperature [81]. Lean air–fuel mixture and high combustion temperature are the favorable conditions for NO formation [82]. Lean-burn combustion use a lot of excess air, usually up to twice the amount needed for complete fuel combustion while on other hand rich-burn engines operate at an almost stoichiometric air/fuel ratio (AFR), which is exactly enough air to burn all of the fuel. This excess air effectively cools down the peak combustion temperatures in the cylinder; that reduces the NO_x production. As CNG burns at a lower adiabatic flame temperature than gasoline or diesel, which results in low NO_x emissions [52,83,84]. Studies [85–89] have shown that NO_x reductions of 50–80% are possible when heavy-duty vehicles are operated on natural gas instead of diesel fuel.

One of the main harmful exhaust emissions produced by internal combustion engines is particulate matter—PM. PM especially in view of the severe health effects that have been linked with fine particles becomes a serious environmental concern in urban areas. CNG is a potentially advantageous fuel because PM emissions are significantly reduced with natural gas fuels, since natural gas does not contain aromatic and polyaromatic compounds and contains less dissolved sulfur compounds than petroleum fuels [25,90–92]. Thus, the contribution of NGVs to smog formation can be less than that of comparable gasoline- and diesel-powered vehicles. Results of various studies based on real world data [85–90,93–104], which confirm the potential reduction of particulate matter emission of CNG fuel. Operating CNG buses to substitute existing diesel buses in the city of Santiago cuts annual particulate emission in 229 t/year, conducing to an annual reduction in PM2.5 of 0.33 μg/m^3. These reductions lead to health benefits of 9130 USD/year for each diesel bus substituted by CNG bus [99]. On average the total PM emissions of CNG powered vehicles are significantly lower, i.e. only 7–9% of the emissions of diesel powered vehicles [85,102–104].

Another potential benefit of CNG is to reduce non-methane hydro carbon (NMHC) emissions. CNG majorly comprises of methane and since methane has not carbon–carbon molecular bonds, combustion of CNG results in a significantly lower probability of benzene emission, which by other way means a decline in formation of carcinogenic PAHs (polycyclic aromatic hydrocarbons) and soot [105]. CNG contains less aromatic content and has a higher hydrogen/carbon ratio, both of which are responsible for the reduction of volatile organic compounds (VOCs) species in case of CNG fuelled vehicle.

Although ambient air improvement is certainly one of the prime objective for the authorities promoting natural gas vehicles, some results of emission studies have been unsatisfactory or even worse than those of gasoline fuelled vehicles, because of improper retro-fitting, maintenance, and system integration of CNG vehicles [74,106–108] are often "tuned" to non-stoichiometric air/fuel ratios.

10. Life cycle emissions of CNG

The methodology used to assess different vehicle technologies from various points in their life cycle is often referred to as life cycle assessment (LCA). The life cycle can be classified into two major categories: the fuel cycle and the vehicle cycle. The GHG emissions impacting the CNG life cycle are predominately the result of production-phase fuel leakage mainly in the form of methane. Many researchers have made great efforts to understand the total impact of GHG Well-to-Wheels (WTW) life cycle analysis (LCA) of CNG as transportation fuel. Well-to-Wheels GHGs advantages of CNG over diesel and gasoline have been confirmed through various studies [109–111].

Comparing CNG and diesel light duty vehicles, Weiss et al. [112] have done an LCA study showing higher efficiency and reduction of CO_2 emissions for CNG compared to gasoline. Similarly Argonne National Laboratory's GREET model [113] estimates the life cycle petroleum use and greenhouse gas (GHG) emissions of light-duty vehicles running on CNG. The results of the model revealed that CNG emits approximately 6–11% less GHGs than gasoline throughout the fuel life cycle. In 2007, a study [114] for the California Energy Commission (CEC) found that both CNG and LNG reduce life cycle GHG emissions in both light- and heavy-duty vehicles compared to their gasoline and diesel counterparts. Rose et al. [115] concluded that a 24% reduction of GHG emissions may be realized by switching from diesel to CNG for refuse collection vehicles based on the real-time operational data obtained from the City of British Columbia, Canada. Karman et al. [116] found significant reductions of CO_2 emissions for vehicles in the city of Beijing, China, when switching to CNG. Few studies [117] stated that a CNG can emit a little more than a diesel fuel in real situation. The key component of natural gas is methane and this emission factor associated with natural gas powered vehicles can be significantly reduced by installation of an exhaust catalyst which coverts unburnt methane fuel (i.e. fuel slippage) to CO_2 and water. Therefore, the global warming potential of NGVs is reduced relative to their diesel and gasoline counterparts.

11. Economics aspect of CNG

One of the chief benefits of CNG is that it provides a source of affordable energy. As the world continues to operate with costly fuels such as diesel and gasoline, the low cost CNG provides a spark of hope. Although the environmental aspects and emission control of using CNG was the prime objective of natural gas application in road transport, especially inside big cities, in recent days with sharp rise in oil prices, the increasingly significant economic advantage of using CNG has become the real prime consideration for lot of new users [32]. In most countries, CNG is much cheaper per equivalent gallon than gasoline and diesel, even after considering the costs associated with compression and so even taking into account its lower thermal efficiency to diesel and gasoline there are considerable economic advantages of using CNG as a transportation fuel. In order to make it suitable as transportation fuel, natural gas requires very slight processing from production field to vehicle. While on other hand diesel and gasoline must be segregated from crude oil and passed through complex refining process. Furthermore is less vulnerable to price fluctuations and its resources are more evenly distributed over the earth as compared to oil [118]. The price advantage of natural gas over diesel and gasoline has often been considered as the most crucial parameter to attract consumer to switch their vehicle from conventional fuel to CNG [26,74,107,108,120].

Table 3 compares the retail fuel prices in US $ for the fiscal year 2011–2012 in top 15 CNG user countries. It can be observed that CNG pump price on average 50% less than the gasoline and diesel price in most countries that have had successful NGV penetration. The rapid growth of CNG vehicles in the last decade especially in Asia-pacific region was mainly because of this less fuel price of CNG with regard to gasoline/diesel.

The economics of running the CNG vehicles vis-à-vis its operation on petrol/Diesel has been worked out at the average global fuel price for the fiscal year 2011–2012. The results are presented in Fig. 8 and Table 4.

The US Department of Energy Alternative Fuel Comparison reports that for Jan–Mar 2011 CNG remained 1/3 time less expensive than gasoline fuel. Based on the reports released by the U.S. Energy Information Agency, CNG on average, cost 42% less than diesel on energy equivalent basis and projected to touch this figure to 50% by 2035. Similarly the Republic Services, the second-

Table 3
Retail fuel prices (US $) in top 15 CNG user countries.

Rank	Country	Gasoline	Diesel	CNG per liter gasoline equivalent	CNG per liter Diesel equivalent
1	Iran	0.42	0.17	0.30	0.34
2	Pakistan	1.02	0.79	0.72	0.80
3	Argentina	1.44	1.44	0.33	0.39
4	Brazil	1.72	1.11	0.92	1.05
5	China	1.05	0.98	0.56	0.63
6	India	1.38	0.85	0.60	0.69
7	Italy	2.03	1.85	0.85	0.95
8	Colombia	1.31	0.96	0.80	0.92
9	Uzbekistan	1.03	0.98	0.30	0.34
10	Thailand	1.25	1.06	0.27	0.32
11	Bolivia	0.83	0.66	0.30	0.29
12	USA	1.02	1.12	0.60	0.68
13	Armenia	1.31	1.19	0.49	0.56
14	Bangladesh	0.79	0.56	0.27	0.29
15	Egypt	0.33	0.20	0.07	0.09
Average		**1.13**	**0.93**	**0.49**	**0.56**

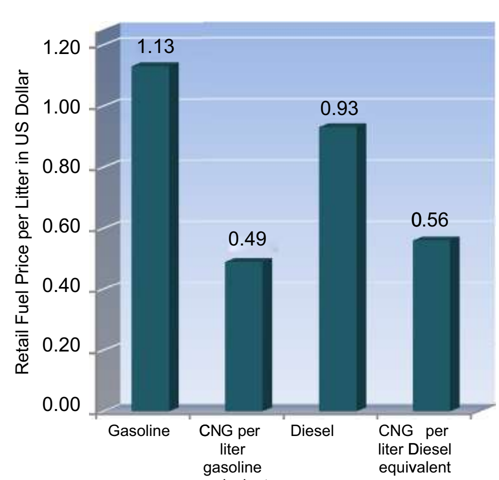

Fig. 8. Cost advantage of CNG fuel over gasoline and diesel.

Table 4
Cost comparison of CNG vs other fuel.

Description	CNG	Gasoline	Diesel
Vehicle type	Bus	Bus	Bus
km travelled per annum per vehicle	80,000	80,000	80,000
Total annual consumption of fuel in liters (consider unit of 'N m^3' in case of CNG)	36,184	39,400	32,000
Retail fuel price per liter US $ (consider unit of 'N m^3' in case of CNG)	0.52	1.02	0.92
Annual fuel cost (US $)	18,816	40,188	29,440
% Fuel cost saving CNG vs gasoline	113%		
% Fuel cost saving CNG vs diesel	57%		

largest waste management services company in USA, has achieved 50% fuel cost reductions through CNG deployment across multiple fleets [121]. Recently US Department of Energy conducted a survey about alternative transportation fuel and found that in contrast to conventional gasoline fuel fleets can save around 50% on fuel costs with CNG [122]. In 2004, NREL (National Renewable Energy competition) USA conducted a comparative evaluation of the emissions of transit buses operated by WMATA (Washington Metropolitan Area Transit Authority). In addition to establishing the emissions benefits of CNG buses, this project revealed significant fuel economy outputs for CNG buses compared to diesel buses [96]. In those regions, where government intends to substitute diesel with CNG, explicit strategies are established to maintain a cost benefit of CNG to diesel (e.g. in Pakistan) or to ban the diesel usage in city buses (e.g. in India) [19–26].

Fig. 9. Honda Civic GX CNG vehicle accident—New York State.

12. Safety aspect of NGVs

Safety of CNG vehicle is a very important aspect. It comes as a surprise to many to feel that natural gas is one of the safest transportation fuels available. Natural gas is safer than gasoline in many respects [83]. Natural gas vehicles are a safe alternative with a proven track record. A 1992 AGA survey of more than 8000 vehicles found that with more than 278 million miles traveled, NGVs injuries rates per vehicle mile traveled were 34% lower than for gasoline vehicles. There were no fatalities reported even though these vehicles were involved in over 1800 collisions.

The physical properties of CNG offer some safety benefits over diesel and gasoline. Physical properties of CNG which makes it an inherently safer than diesel or gasoline are as follows:

i. In contrast to gasoline/diesel fuel CNG has a narrow range of flammability, 4.3% to 15.2% by volume in air, which means that in concentrations in air below 4.3% and above 15.2%, natural gas will not burn even in the presence of a spark.
ii. CNG has a high auto-ignition temperature of 540 °C compared to 258 °C of gasoline and 316 °C of diesel. The auto-ignition temperature is the lowest temperature at which a fuel will ignite at which a fuel will ignite due to the heat only, without any external spark or flame. The high ignition temperature and narrow flammability range of natural gas lessen the chance of accidental ignition and combustion of the fuel.
iii. Natural gas is lighter than air so in case of accidental leakage the very low density of CNG at atmospheric pressure, 0.68 kg/m^3 compared to air, 1.202 kg/m^3, means that CNG would rise and disperse into the air rapidly instead of forming pools on the ground as in the case of diesel and gasoline, which reduces the probability of a fire if the tank is breached.
iv. CNG cylinders are designed and fabricated of special materials to resist the high pressures, with a safety factor which is usually greater than two [123], therefore, safer than ordinary petrol tanks. There are four types of cylinder designs (Table 5). Fig. 9 illustrates the safety attribute of CNG cylinder where CNG cylinder remained safe after a car has been totaled by 10,000 usg tanker.

The above physical properties do not guaranty that CNG vehicle are safer than diesel fuel. For instance in Pakistan, 2nd largest consumer of CNG, several CNG vehicles related accident has been observed for the last few years [26]. But this is mainly because of low quality of CNG system material e.g. CNG cylinder, CNG design & installation, maintenance system etc., driver's errors and lack of strict government CNG vehicle safety regulations in Pakistan [26]. Similarly, in 2002, investigators [124,125] matched the fire-safety risks associated with diesel and CNG school busses and found that total fire-fatality risk from CNG bus was 2.5 times higher than the diesel buses. As a whole, CNG is not more or less dangerous than diesel [126]. NGVs safety is highly reliant on the CNG system design, installation, materials, preventive maintenance, operating conditions and driver awareness not only the fuel cylinder or other components in isolation. CNG consumer should be provided sufficient safety information regarding safety issues associated with the NGVs such as gas leakages, preventive and inspection methods and emergency response in the event of vehicle collision and fire.

13. Barriers to CNG vehicles adaptation

CNG now have a firm foothold in global transportation markets, but there are still many hurdles to their widespread use. Some of the problems related to Compressed Natural Gas Vehicles are illustrated below:

1. One of the most important issues pertinent to Natural Gas Vehicles is the Driving Range, which is defined as capability of a NGV to travel a certain distance after each refueling. On volumetric basis, 1 m^3 of natural gas roughly corresponds to 1.0 l of gasoline or 1.1 l of diesel. Because of this lower energy density of natural gas as compared to gasoline or diesel, takes 3–4.5 times more space for storage than gasoline or diesel

Table 5
Types of CNG cylinder.

Type	Construction	Weight (%)	Cost (%)
Type-1	All metal (aluminum or steel)	100	40
Type-2	Metal liner reinforced by composite wrap (glass or carbon fiber) around middle (hoop wrapped)	55–65	80–95
Type-3	Metal liner armored by composite wrapping (carbon fiber or glass) around the complete cylinder (fully wrapped),	25–45	90–100
Type-4	Plastic gas-tight liner reinforced by composite wrap around entire tank (full wrapped)	30	90

which consequently reduced the vehicle range. The Driving Range is a major hurdle in the development and growth of CNG as transportation fuel [127].

2. Another problem with NGVs especially light duty NGVs is the loss of cargo space. CNG cylinders are large and occupy a lot of storage space and generally have to be placed in the boot of the car. Owing to this it significantly decreases the cargo space by almost 50% as compared to conventional fuel vehicle. But this deficiency has now been fixed by dedicated CNG vehicle which equipped with 2 to 3 cylinder all under the vehicle so no luggage space is lost either.
3. Refueling time for NGVs is longer than either diesel or gasoline vehicle and sometimes user have to wait for hours in long queues to get their vehicle refueled due to insufficient number of refueling stations in the areas where share of NGVs is high than conventional fuel vehicle e.g. Pakistan, Iran, India etc. Refueling is considered to be the ‘least safe’ moment of its use. The inadequate number of CNG refueling stations is a barrier to the embracement of NGVs by consumers. Similarly, the lesser number of NGVs required CNG refueling stations makes establishment and operation of a CNG station uneconomical. Janssen et al. [118] studied the effect of the concentration of CNG filling station and other problems pertinent to NGVs. They compared the experience of NGVs in Brazil, Argentina, India, United States and New Zealand. The results of their work revealed that for the sustainable use of CNG as transportation fuel two conditions must be addressed. First, for the CNG stations to be profitable there should be at least 1000 natural gas vehicle per CNG refueling station. Second, to minimize the refueling time and facilitate the motorists, the minimum range of CNG refueling stations should be at least 10–20% of the number of gasoline/diesel stations.
4. For heavy duty vehicles moving through countryside, the conversion to CNG presents several challenges, including the lack of a rigorous refueling infrastructure, higher vehicle capital costs and limited engine offerings. Until a competitive natural gas refueling infrastructure evolves, this alternative fuel is problematic for long haul, irregular route trucking operations.
5. Any accident to the natural gas transmission pipeline can cutoff the fuel supply of the whole city or of a specific region.

14. Conclusion

The major outcomes of this study are listed below:

1. Rising concerns about the harmful effects of emissions of diesel and gasoline have made CNG a very promising alternative fuel for the road transportation.
2. The NGV sector has shown tremendous growth over the last 15 year in most of the gas producing countries to offer a product which has behind it a tried and tested technology which guarantees the environment protection, is inexpensive and affordable.
3. CNG is clearly a powerful weapon for the countries in the battle to replace oil in the transportation sector, to reduce air pollution and to address the challenge posed by climate change.
4. Worldwide CNG vehicle technologies are well established and commercially available for all type of road transport vehicle.
5. To keep the torque and brake horsepower, of CNG vehicles comparable to their diesel or gasoline counterparts, dedicated CNG engines research should be accelerated.
6. CNG has several advantages over both diesel and gasoline fuel, including considerable emission and cost reductions, and making the countries more energy sovereign by reducing the dependency on oil.
7. The placement of the high pressure storage system especially in rather small transport vehicles must be improved concerning transport volume and accessibility but always with respect to economic effort.
8. Keeping in view the results obtained and the study of literature, it can be established that the use of natural gas as transportation fuel can contribute towards urban air improvement, reduce harmful health effects and social cost of ambient air pollutions.

Nomenclature

A/*F*	air–fuel ratio
AGA	American Gas Association
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
BTU	British thermal unit
CH_4	methane
CI	compression ignition
CNG	compressed natural fas
CO	carbon monoxide
CO_2	carbon dioxide
DOE	Department of Energy
GHGs	greenhouse gases
HC	hydrocarbon
kg	kilo gram
kJ	kilo Joule
LCA	life cycle assessment
L.H.V.	lower heating value
LPG	liquefied petroleum gas
m	meter
m^3	cubic meter
MBT	maximum brake torque
MJ	mega Joule
MTOE	million tonnes oil equivalent
N_2	nitrogen
NGV's	natural gas vehicles
NO_x	nitrogen oxides
OBD	on-board diagnostics
OECD	organization for economic cooperation and development

PAH polycyclic aromatic hydrocarbon
s second
SI spark ignition
TSP total suspended particle
TCF trillion cubic feet
WOT wide open throttle
TSP total suspended particles
VOC volatile organic compound
WMATA Washington Metropolitan Area Transit Authority

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Annexure-C

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ORIGINAL PAPER

International experience with compressed natural gas (CNG) as environmental friendly fuel

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Abstract Environmental concerns relating to gaseous emissions from transport have led to growth in the use of compressed natural gas (CNG) as transportation fuel worldwide with over 19 million natural gas vehicles (NGVs) currently in operation. This paper reviews the environmental advantages of natural gas fuel, presenting laboratory and real world comparative emission performance of NGVs with diesel and gasoline fueled vehicles. The aim is to clarify the worldwide experience of NGVs in terms of various emission factors i.e. CO_2, CO, NO_x, NMHC and PM. The paper provides a critical analysis of information collected and draws general conclusions on the worldwide NGVs experience. The results reveal that CNG in public transportation can contribute to the improvement of urban air, reduce adverse health effects and social costs of air pollution. It was observed that on a well-to-wheels basis, CNG produce less greenhouse gases as compared to conventional gasoline and diesel vehicles. The results showed that there is large variation in the resulted NMHC emission data of CNG fuel. Some studies reveal that CNG can significantly reduce NMHC emission while other concluded that CNG increase the NHMC emission.

Keywords CNG · Emission · Environment · Natural gas · NGV

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Abbreviations

BTEX	Benzene, toluene, ethylbenzene and xylenes
CARB	California air resources board
CBD	Central business district
CC	Cubic centimeter
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CRT	Continuously regenerating trap
DPF	Diesel particulate Filter
DOE	Department of Energy
GHG	Green house gas
HC	Hydrocarbon
kg	Kilo gram
kJ	Kilo joule
LPG	Liquefied petroleum gas
m3	Cubic meter
MBT	Maximum brake torque
MJ	Mega joule
MTOE	Million tonnes oil equivalent
N2	Nitrogen
NREL	National renewable energy laboratory
NGV's	Natural gas vehicles
NO_x	Nitrogen oxides
OC	Oxidation catalyst
PAH	Polycyclic aromatic hydrocarbon
PEMS	Portable emission measurement systems
TSP	Total suspended particle
WOT	Wide open throttle
THC	Total hydro carbon
TSP	Total suspended particles
ULSD	Ultra low sulfur diesel
UDDS	Urban dynamometer driving schedule
VOC	Volatile organic compound
WMATA	Washington metropolitan area transit authority
WN	Wobbe number

1 Introduction

The issue of environmental pollution created by conventional fossil fuels is becoming more important, as we are getting more concern about the environment of our planet. These concerns as well as the increasing cost of petroleum-based fuels and the stringent regulations regarding limits for exhaust emissions in recent years have triggered the use of alternative fuel for automotive engines [1,2]. The use of alternative fuels for engine is regarded as one of the major research areas for the age [3–5]. Several alternative fuels have been recognized as having a significant potential for producing lower overall pollutant emissions compared to gasoline and diesel fuel. Among all, Compressed natural gas (CNG) has been considered as one the best solutions for fossil fuel substitution because of its availability throughout the world, inherent clean burning, economical as a fuel and adaptability to the gasoline and diesel engines [2,6–11]. An increasing number of countries across the globe are jumping on the bandwagon to make use of compressed nature gas, due to its various benefits. Worldwide, the numbers of natural gas vehicles (NGVs) are growing so rapidly that the statistics lag behind and no sources of official statistics are universally agreed upon. In the last ten years, worldwide the NGVs population has escalated speedily at an annual rate of 24 % with the biggest contribution coming from the Asia-Pacific and Latin America regions (Fig. 1).

Today there are over 18 million natural gas vehicles distributed through more than 90 countries of the world with major concentrations in Pakistan, Iran, Argentina, Brazil, India, Italy and China [13]. The objective of this paper is to share the comparative emission performance of CNG vehicles operating at various parts of the world. This paper focuses on the comparative emission performance of NGVs, world-wide, using information from the USA, Europe, Finland, Austria, Germany, Asia, India, Australia, Italy, Korea, Egypt, France, Brazil, Sweden and Iran. Numerous papers have been published during the last ten years comparing emissions and performance of available CNG vehicles. The main findings of some selected reports will be discussed in the next section.

2 Comparative studies on emissions of CNG, diesel and gasoline engines

The environmental performance of transport modes is a crucial area and one subject to a wide range of analytical challenges. The use of natural gas as a transportation fuel

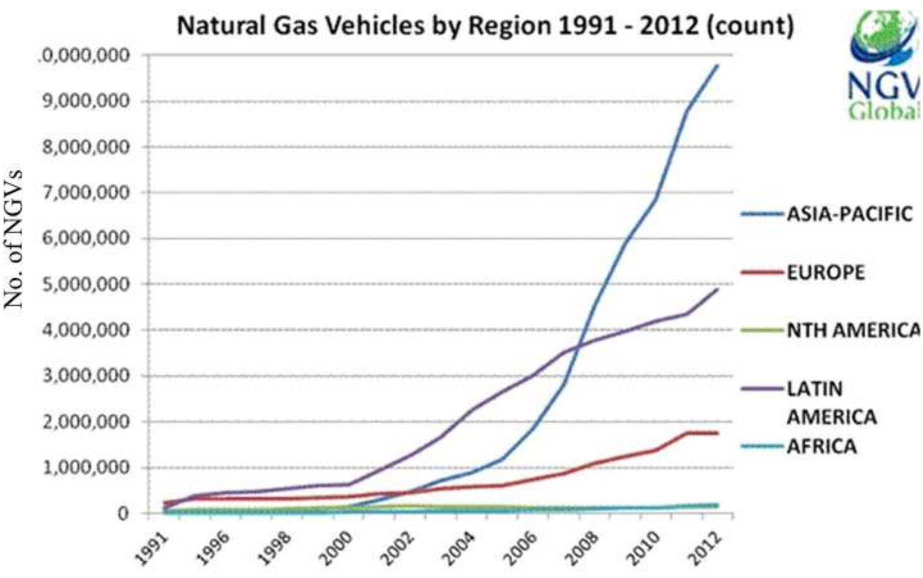

Fig. 1 Worldwide NGVs growth by region [12]

is associated with a number of potential benefits to the environment, particularly air emissions and noise. On a "well-to-wheels" basis, natural gas is one of the cleanest burning alternative transportation fuels commercially available today [14]. Emissions from properly functioning CNG vehicles (NGVs) are generally considered to be lower than emissions from gasoline operating vehicles [15]. A number of international studies demonstrate that CNG can reduce emissions in transport. Drawing from previous studies, this paper will analyze the environmental advantages of CNG fueled vehicle against its rival vehicle i.e. diesel and gasoline. The studies, each of them having somewhat different objectives, are summarized below.

In Delhi (Indian capital and world 2nd most densely populated city) the entire public road transport was switched over to CNG fueled vehicle from diesel and gasoline in 2002 after the verdict of Indian Supreme Court. Today Delhi has world largest CNG-fuelled public transport system. Comparison between ambient levels of pollutants in the year before and after the implementation of CNG vehicles in Delhi revealed substantial reductions in CO (10 %), total suspended particles (TSP) (14 %), NO_x (6 %) and SO_2 (22 %) [16]. In 1993 an extensive program was set up by Dutch government to compare gasoline and diesel vehicle emission with LPG and natural gas. The conclusion of the program was that gaseous fuels hold an advantage over liquid fuels [17]. Similarly Fontaras et al. [18] conducted an experimental work to measure the exhaust emissions of four waste collection trucks during normal work conditions in the city of Milan, Italy. One truck was equipped with a Euro V diesel engine and the other three were equipped with a Euro V CNG engine. All four trucks were provided with portable emission measurement systems (PEMS). The analysis of the results confirmed that CNG vehicles present an important advantage with regard to NO_x and PM emissions but lack the efficiency of their diesel counterparts when it comes to CO, HC. At university of Malaya, Kuala Lumpur, Aslam et al. [8] investigated the performance of 1468cc Proton Magma12-Valve, 4 Cylinder, engine having compression ratio 9.2:1. The test engine was converted from a gasoline engine and is equipped with a bi-fuelling system. The emission test results for engine rpm from 1500 to 5500 with WOT position showed that in comparison to gasoline fuel, CNG produced 50 % less emissions of HC (50 %), CO (80 %), CO_2 (20 %) and 33 % higher emissions of NO_x.

Similarly at K.N. Toosi University of Technology, Tehran, Shamekhi et al. [19] experimentally investigated engine performance and exhaust emissions of a Mazda B2000i bi-fuel SI engine for both natural gas and gasoline fuels over a wide range of engine operating conditions. Their investigation revealed that in case of CNG emissions of CO, CO_2 and HC were decreased in the range of 58–89, 0–11 and 37–58 % respectively. The NO_x emissions were the only ones that show an increase in their amount. Dondero et al. [20] carried out a research in Brazil as one of the pioneers in development of CNG retrofitted vehicles. They concluded that compared to gasoline powered vehicles, utilization of third generation conversion kits in CNG retrofitted vehicles found to exhibit average reductions of 20, 66, and 53 % in CO_2, NMHCs, and CO emissions, respectively, but average increases of 171 % in NO_x emission.

Emission tests conducted by two different laboratories of 37 dedicated CNG vans revealed that on average they showed notably lower regulated emissions than their gasoline counterparts [21]. In contrast to gasoline, the CNG vehicles produced lower emission of CO (40 %), CO_2 (18 %), NO_x (31 %) and NMHC (70 %). The investigation on the comparative emission analysis of CNG and gasoline in a retrofitted car engine has been performed by Jahirul et al. [22]. According to their results CNG produced lower HC, CO, O_2 emission and high NO_x emission throughout the speed range than gasoline. Emissions of CO, NO_x and special organic compounds (with Carter MIR ozone potential e.g. Benzene, Toluene, mp-xylene, Ethylbenzene etc) were measured for a range of vehicles using different fuels [23]. The results show that ozone potential was reduced by more than 90 % with CNG relative to reformulated gasoline and that toxic compound emissions (benzene, formaldehyde, acetaldehyde and 1,3-butadiene) were lower for CNG than for gasoline. Heidinger et al. [24] endeavored to test exhaust emission of bi-fuel gasoline-CNG fuelled car engine during real time operated conditions . The test results collected indicate that, with some further technological refinement, LDVs running on CNG can contribute significantly to the improvement of an urban environment. Turrio-Baldassarri et al. [25], measured the toxic emissions of a heavy-duty engine used for urban busses fuelled with CNG and compared the emissions to equivalent diesel engine under similar conditions. The results obtained showed that the CNG engine emissions, with respect to the diesel engine were nearly 50 times lower for carcinogenic PAHs, 20 times lower for formaldehyde, more than 30 times lower for PM and significant reduction for NO_x.

In recent publication by Piotr et al. [26] a study was conducted to assess and compare the emissions performance of a bi-fuel Euro 5 vehicle operating on gasoline and CNG, for comparison to the planned Euro 6 limits. On the basis of their analysis, it was found that the test vehicle met the Euro 6 emissions limits when using both fuel types, but with key differences in the emissions trends: NMHC emissions were much lower when running on CNG, while HC emissions were somewhat higher. NO_x and CO_2 emissions from the vehicle when fueled with CNG were 50 and 24 % lower respectively of those observed when running on gasoline.

In order to examine the real-world emission characteristics of light-duty CNG vehicles in China, Zhiliang et al. [27] measured the emissions from 20 CNG bi-fuel taxis, including 15 Euro 2 and 5 Euro 3 vehicles using a portable emission measurement system (PEMS) under actual driving conditions in Yichang, China. Compared with the emission values for light-duty gasoline vehicles reported from China, the CO_2 and CO emissions from the tested CNG taxis were clearly lower; however, significant increases in the HC and NO_x emissions were observed.

Ramjee et al. [28] carried out experimental work on a single cylinder 4-stroke bi-fuel engine to measure the exhaust emission of the test engine. They observed that the emission characteristics such as CO, CO_2, and HC except NO_x were lower than that of gasoline fuel. Das et al. [29] conducted the experiment on CNG bi-fuel passenger car and predicted the engine performance, fuel consumption and emissions. According to their result, the carbon monoxide (CO) emissions of CNG were very lower as compared to petrol engine. Engerer et al. [30] recommended that European countries should promote natural gas vehicles, affirming an environmental benefit as a main motive. Chandler et al. [31] worked on a project with US Department of Energy to evaluate the cost, maintenance, operational, and emissions characteristics of CNG as one alternative to conventional diesel fuel for heavy-duty trucking applications. They studied 13 CNG package delivery trucks and 3 diesel package delivery cars operating in the Hartford, Connecticut, area from UPS's Waterbury, Hartford, and Windsor. They found that CNG trucks had 75 % lower emissions for CO, 7 % lower CO_2, 49 % lower NO_x, and 95 % lower particulate matter than the diesel trucks of similar model. The hydrocarbon emissions were about 4 % higher for the diesel trucks than were the non-methane hydrocarbons for the CNG trucks.

In diesel engines CNG as a fuel can be used in dual fuel (70–85 % CNG +15–30 % diesel) mode and offers the advantage of reduced emissions of NO_x, particulate matter and CO_2 while retaining the thermal efficiency of the conventional diesel engine [32]. Similary Papagiannakis et al. [33] found that NO_x concentration and toxic carcinogenic pollutants as well as the CO_2 under dual-fuel operation are lower compared to normal diesel operation. Another study [34] comparing diesel and CNG engines in buses of the same model year operated over the Central Business District (CBD) test cycle showed that the CNG powered buses produced an average of 13.0 g/km of NO_x and 0.016 g/km of PM versus 19.7 and 0.41 g/km respectively for a similar diesel-powered bus. Both buses were open loop fuel controlled. By comparing the emissions of diesel engine and CNG buses as well as investigating their environmental costs, Rabl [35] concluded that the use of CNG buses is cleaner and more cost effective according to European standards.

Results of various studies performed in USA confirmed the PM emissions reductions range from 61 to 80 % and NO_x emissions reduction from 12 to 40 % for NGVs as compared to their diesel counterparts certified to US98/Euro III emissions levels. CO and THC emissions were considerably higher for CNG buses. Comparison of pollutant levels in Dhaka (the capital of Bangladesh, is one of the most densely populated cities in the world) before and after implementation of CNG also suggested an improvement of air quality using CNG [36]. In 2004, DOE's National Renewable Energy Laboratory (NREL) led an evaluation of the emissions of transit buses operated by the Washington Metropolitan Area Transit Authority (WMATA). The result shows that on average CNG buses produced 56 % lower NO_x emissions, 67 % lower CO_2 emissions, 72 % lower PM emission, 24 % higher CO emissions and 49 % higher NMHC emissions compared with the diesel buses [37]. The French Agency of Environment and Energy Management (ADEME) engaged a comprehensive program in 1998 dedicated to the comparative exhaust emission analysis of urban buses in France. According to the results [38] of the various tests, the performances obtained by the CNG vehicles were promising and confirmed the environmental interest of the solution. In comparison with diesel-powered buses, CNG-powered buses lead to about a 50 % reduction of NO_x and non-methane hydrocarbons emissions and a near-total absence of particulate matter. CO Emissions were 50 % high for CNG buses.

In a recent study Curran et al. [39] investigated the well-to-wheels energy use and greenhouse gas emissions from CNG vehicles and compared the results to conventional gasoline vehicle. The results revealed that on a well-to-wheels basis, NGVs produce 25 % less greenhouse gases than comparable gasoline vehicles and 29 % less than diesel vehicles. By summarizing the results of various emission studies conducted in United States, the Environmental Protection Agency states [40] that burning compressed natural gas as opposed to petroleum based fuels reduces the emissions of carbon monoxide by 90–97 %, and reduces the amount of carbon dioxide by 25 %. In addition to these reductions in greenhouse gases, there is also "little to no particulate matter" or carcinogens released by burning compressed natural gas as opposed to burning petroleum based fuels [40].

Although ambient air improvement is certainly one of the prime objective for the authorities promoting natural gas vehicles, some of the emission results have been disappointing or even poorer than those of gasoline vehicles, due to improper retro-fitting, maintenance, and system integration of NGVs [20,41–44] are often "tuned" to nonstoichiometric air/fuel rations.

Some studies point to problems with the NGV emissions. CNG is mostly methane, and combustion of methane releases different chemicals than petroleum—particularly formaldehyde, a human carcinogen [25,45]. Table 1 summarizes the major worldwide experiential studies conducted to evaluate the comparative emission performance of NGVs.

3 CNG and significance of the different emission components

Major pollutants emitted from transport sector are carbon dioxide (CO_2), nitrous oxide (N_2O), carbon monoxide (CO), oxides of nitrogen (NO_x), particulate matter (PM) and non-methane hydro Carbon (NMHC).

3.1 Carbon dioxide—CO_2

Carbon dioxide—CO_2 is the major source of emission associated to transport, because it is the natural outcome of combustion of carbon based fuels such as diesel and gasoline. Worldwide, road transport emits over 6.9 Gt CO_2 each year, accounting for 23 % of overall CO_2 emissions from fossil fuel combustion [46,47].

Besides other factor CO_2 emissions from the combustion of fuel largely depend upon the hydrogen-to-carbon ratio (H/C) of a fuel. Higher the hydrogen-to-carbon ratio (H/C) of a fuel, the amount of CO and CO_2 will be lower. CNG has the highest hydrogen-to-carbon ratio (H/C) (almost 4:1) than either gasoline (2.3:1) or diesel fuel (1.95:1). This led to the lower emission of CO_2 for the CNG than the gasoline or diesel fuel [48].

From the chemical equilibrium of combustion of CNG fuel, CO_2 emissions from a CNG engine can be decreased by more than 20 % in comparison with those of a gasoline engine operating with the same condition [49]. The CO_2 levels of a natural gas engine can even be lower than those of a diesel engine at the same air fuel ratio, while keeping almost the same thermal efficiency under very lean conditions [50].

As a simple rule of thumb based on average fuel efficiency data available to Chive Fuels (largest European LNG supplier) for every gallon of diesel displaced by natural gas in a dual fuel engine then the CO_2 saving is approximately 2.65 kg.

On a well-to-wheels basis, NGVs produce 22 % less greenhouse gases than comparable diesel vehicles and 29 % less than gasoline vehicles [51]. The California Air Resources Board (CARB) has conducted extensive analysis on this issue. It concludes that burning CNG produces about 68 g of carbon dioxide equivalent emissions per mega joule (MJ) (this includes all methane emissions), and that burning gasoline and diesel fuel produce approximately 94–95 g of CO_2 equivalent emissions per MJ. These

Table 1 Emission summary of major worldwide experiential studies

S. N.	References	Study year	Test method	Vehicle			Fuel	Emission factor (g/km)			
				Type	Disp. (cc)	After treatment		CO_2	CO	NO_x	NMHC
1	Kelly et al. [21]	1996	Real world operation, Washington DC, USA	Ded, CNG van	–	–	CNG	352	2.35	0.34	0.11
				Gasoline van	–	–	Gasoline	416	3.64	0.49	0.18
2	Heidinger et al. [24]	1996	Real world operation, Vienna, Austria	Bi-fuel car	1968	TWC	CNG	–	1.79	0.26	1.4
							Gasoline	–	2.41	0.41	0.31
3	Coroller et al. [38]	1998	CBD Cycle, Paris	3 CNG bus	9500	Nil	CNG	–	6	12.2	6.23
				4 Diesel bus	9800	Nil	Diesel	–	2.85	25.1	1.2
4	Clark et al. [34]	1999	Lab, USA	3 CNG bus	6500	OC	CNG	–	1.9	5.4	–
				3 Diesel bus	5900	OC	Diesel	–	1.5	13.2	–
5	Frailey et al. [107]	2000	CBD cycle, USA	3 CNG bus	5880	–	CNG	–	0.4	8.9	–
				3 Diesel bus	5880	–	Diesel	–	2.4	21	–
6	Chandler et al. [31]	2000	CBD cycle, Hartford	13 CNG bus	5900	OC	CNG	460	0.40	3.37	0.30
				3 Diesel bus	5900	–	Diesel	495	1.61	6.65	0.31
7	Ayala et al. [79]	2002	CBD cycle, Los Angeles	3 CNG bus	8500	Nil	CNG	–	6.84	11.81	7.40
				2 Diesel bus	8500	Nil	Diesel	–	0.84	18.77	0.05
			NYBC	3 CNG Bus	8500	Nil	CNG	–	19.08	12.09	16.84
				2 Diesel bus	8500	Nil	Diesel	–	4.47	31.70	0.13
8	NREL Emission Tests [65]	2002	CBD cycle Washington	5 CNG bus	8300	OC	CNG	–	0.187	8.46	4.53
				4 Diesel bus	8500	OC	Diesel	–	1.7	18	3.2
9	Lanni et al. [52]	2003	CBD cycle, New York	3 CNG bus	8500	–	CNG	1472	11.09	11.09	11.12
				2 Diesel bus	8500	DPF	Diesel	1787	14.82	14.82	0.04
10	Pischinger et al. [118]	2003	Dynamometer, Germany	Bi-fuel car	1800	–	CNG	–	0.27	0.125	0.20
					1800	–	Gasoline	–	0.70	0.130	0.27

Table 1 continued

S. N.	References	Study year	Test method	Vehicle			Fuel	Emission factor (g/km)			
				Type	Disp. (cc)	After treatment		CO_2	CO	NO_x	NMHC
11	Ullman et al. [53]	2003	Dynamometer	1 CNG bus	–	Nil	CNG	–	7.7	26.1	15
				2 Diesel bus	–	DPF	Diesel	–	2.8	22.7	0.6
12	Nylund et al. [54]	2004	OCTA, Finland	2 CNG bus	–	OC	CNG	–	–	7	–
				1 Diesel bus	–	OC	Diesel	–	–	8	–
13	Ristovski et al. [15]	2004	Dynamometer, Australia	Bi-fuel car	4000	None	CNG	361	1.12	0.67	–
							Gasoline	561	28	0.94	–
14	Melendez et al. [37]	2005	CBD cycle Washington	7 CNG bus	8300	OC	CNG	1370	0.215	9.62	4.35
				5 Diesel bus	8500	OC	Diesel	2034	0.174	12.8	2.92
15	Jayaratne et al. [55]	2009	Real world operation, Queensland, Australia	Ded, CNG bus	–	TWC	CNG	671	–	12	–
				Diesel bus	–	None	Diesel	834	–	10.5	–
16	Fontaras et al. [18]	2012	Real world operation, Milan, Italy	Dual-fuel bus	9500	DOC	Diesel-CNG	2430	7.43	32.3	0.21
				Ded, CNG bus	7790	TWC	CNG	3660	15.8	4.38	2.19
				Ded, CNG bus	7790	–	CNG	2300	1.66	3.91	0.55
				Ded, CNG bus	6900	–	CNG	3120	1.01	13.6	6.99
17	Hallquist [82]	2013	Road	7 CNG bus	–	Nil	CNG	–	<3	21	<4
				28 Diesel bus	–	DPF	Diesel	–	4.33	6.66	<4
18	Aslam et al. [6]	2005	Dynamometer, Malaysia	Bi-fuel car	1468	TWC	CNG	8.4 (vol.%)	1.2 (vol.%)	2000 ppm	300 ppm
							Gasoline	12.8 (vol.%)	9.2 (vol.%)	875 ppm	1000 ppm
19	Geok et al. [6]	2009	Dynamometer, Malaysia	Bi-Fuel Car	1468	None	CNG	10.2 (vol. %)	2 (vol.%)	–	110 ppm
							Gasoline	12.8 (vol %)	3 (vol.%)	–	380 ppm
20	Jahirul et al. [22]	2010	Dynamometer, Malaysia	Bi-Fuel Car	1594	None	CNG	7.82 (vol.%)	5.4 (vol.%)	619 ppm	313 ppm
							Gasoline	11.68 (vol.%)	10.5 (vol.%)	442 ppm	419 ppm

comparisons are well documented by CARB and are based on well-to-wheel analysis. The conclusion of various studies such as those conducted by CARB, is that natural gas can reduce greenhouse gas emissions by 20–30 % compared to diesel and gasoline. Some researcher [52–54] observed 15–20 % less CO_2 emission for CNG buses as compared to diesel transit buses. Jayaratne et al. [55] monitored the exhaust emissions from 13 CNG buses and 9 ultralow sulphur diesel in-service transport buses on a chassis dynamometer and found the CO_2 values for the diesel buses being about 20–30 % greater than that for the CNG buses at various load condition. Argonne National Laboratory (ANL) [56] using the greenhouse gases, regulated emissions, and energy use in transportation (GREET) Model, observed significant reductions (17 %) in life-cycle CO_2 emissions of light-weight CNG vehicles relative to equivalent light- weight gasoline vehicles with similar engine efficiencies. However, the overall reduction in GHGs is discounted some (down to 11 %) due to the methane emissions from the leakage associated with natural gas.

3.2 Carbon monoxide—CO

Carbon monoxide is a colorless, odorless, non-irritating gas produced primarily as a result of incomplete combustion of any carbonaceous fossil fuel. CO is the leading cause of poisoning mortality and may be responsible for more than half of all poisoning deaths reported worldwide each year [57]. The Centers for Disease Control and Prevention-USA reported that from 1968 to 1998, non-fire-related CO poisoning caused or contributed to 116,703 deaths, 70.6 % of which were due to motor vehicle exhaust, and 29 % of which were unintentional [58]. In addition, it reacts with O_3 in the upper atmosphere, producing CO_2, which depletes the ozone layer [59].

As discussed carbon monoxide is formed by incomplete combustion, which occurs when there is insufficient oxygen near the fuel (hydrocarbon) for complete combustion or when combustion is quenched near a cold surface in the cylinder. Besides having highest hydrogen-to carbon ratio, natural gas engines have two additional important characteristics: (a) low heating value compare to gasoline and (b) low flame propagation speed as compare to other fuels. These two factors reduced the maximum temperature inside the combustion chamber, and therefore, reducing dissociation from CO_2 to CO. Due to excellent lean flammability limit of CNG, it produces lean burning operation which conduces to the reduction of carbon monoxide and NO_x production in exhaust emission [60].

Although energy efficiency is higher for lean-burn than for stoichiometric gas engine, but the stoichiometric engine is capable to control emissions efficiently with a three way catalyst (TWC) [61,62]. But stoichiometric condition with TWC can only favor significant reduction of NO_x and NMHC emissions [63], however, CO emissions may tend to increase compared to leanburn engines [37,54,63,64].

Various studies have been conducted which confirm that the CO emission of the CNG was significantly lower than that of the gasoline and diesel vehicle at various load conditions.

National Renewable Energy Laboratory (NREL) conducted a project [65] to compare the real time emission performance 164 CNG transit buses versus 1269 conventional diesel counterparts operated by Washington Metropolitan Area Transit Authority (WMATA). The project demonstrated 89 % CO emission reduction of CNG buses to that of diesel buses. During 2003 [66], a series of emission measurements on diesel and CNG buses were conducted at Misr Lab, Cairo Egypt. As per results of this study CNG buses exhibited 105 % lower CO emissions than diesel buses.

3.3 Nitrogen oxides—NO_x

NO_x refers to the group of seven oxides of nitrogen i.e. NO, NO_2, N_2O, N_2O_2, N_2O_3, N_2O_4 and N_2O_5 [67]. NO_x are by-products of all carbon based fuel combustion processes and global transport sector contributes about half of the total NO_x emissions. There are a lot of adverse health effects associated with NO_x such as an increase in total mortality, cardiovascular deaths, and infant mortality [68]. Its exposure for longer duration may affect the lungs structure, lungs immune system, lungs metabolism, and impair the lungs function [69]. Besides an important air pollutant, NO_2 also reacts in the atmosphere to form ozone (O_3) and acid rain. Similarly N_2O is considered as "Greenhouse Gas" which, like carbon dioxide (CO_2), absorbs long wavelength infrared radiation to hold heat radiating from earth and thereby contributes to global warming.

Emissions of NO_x from combustion process in IC engines are primarily (around 90 %) in the form of NO [70]. As per Zeldovich et al., NO is generated due to availability of limit oxygen (about 200,000 ppm) in the combustion process above 1300 °C. Zeldovich proposed the following mechanism for the formation of thermal NO_x during combustion:

$$N_2 + O \rightarrow NO + N \tag{1}$$

$$N + O_2 \rightarrow NO + O \tag{2}$$

$$N + OH \rightarrow NO + H \tag{3}$$

Residence time and the concentration of nitrogen and oxygen also have an influence on the production of thermal NO [71]. Hu et al. [72] theoretically proved that NO_x formation depends directly on two factors: the concentration of reactants and temperature. Concentration of NO_x emission is strongly related to the air-fuel ratio and combustion temperature [73]. Lean air-fuel mixture and high combustion temperature are the favorable conditions for NO formation. Lean-burn combustion use a lot of excess air, usually up to twice the amount needed for complete fuel combustion while on other hand rich-burn engines operate at an almost stoichiometric air/fuel ratio (AFR), which is exactly enough air to burn all of the fuel. This excess air effectively cools down the peak combustion temperatures in the cylinder; that reduces the NO_x production. As CNG burns at a lower adiabatic flame temperature than gasoline or diesel, which results in low NO_x emissions [50,74,75]. Studies [74,76] have shown that NO_x reductions of 50–80 percent are possible when heavy-duty vehicles are operated on natural gas instead of diesel fuel. A recent study [78] done on behalf of the California Energy Commission concludes that CNG vehicles produce up to 29 % less NO_x emissions than comparable gasoline vehicles and up to 22 % less than comparable diesel vehicles. To compare toxicity between new and clean HD engine technologies in

California, a group of diesel buses with after-treatment devices and a lean-burn CNG bus with no after-treatment were compared over the Central Business District (CBD), the Urban dynamometer driving schedule (UDDS) and the New York City bus cycle (NYBC) [79]. The CNG bus was equipped with a 2000 DDC Series 50G engine; the diesel bus was equipped with a 1998 DDC Series 50 engine and an OC (oxidation catalyst). The observed NO_x values for CNG over the CBD, UDDS and NYB were 24.8, 31.3 and 18.6 g/km respectively against 48.6, 82.1 and 39.7 g/km for diesel busses. In Sweden, emission tests were conducted on CNG and diesel buses in the 1990's as part of several governmental programs in this area. The results of this study [80] showed that CNG buses produces 48 % less NO_x emssion in contrast to diesel buses.

In some studies, CNG has been shown to increase the amount of NO_x [19,20,28,81]. For instance recently Hallquist et al. [82] tested the emission factors of 28 individual diesel-fuelled and 7 CNG fuelled buses, selected from an in-use bus fleet in Sweden. As per their results the highest NO_x values (4–21 g/km, depending on Euro class) were obtained for the CNG buses compared to NO_x values of 2–11 g/km for diesel buses. In all studies which cite this phenomenon, it remains scientifically unexplained. However, even in studies citing these problems with CNG, the conclusion has been that compressed natural gas represents an improvement over conventional diesel/gasoline in terms of greenhouse gas emissions.

Possible reasons to this variability may be vehicle maintenance and variations in the CNG composition [79,83].

3.4 Particulate matter—PM

PM is a widespread air pollutant, consisting of a mixture of solid and liquid particles suspended in the air many of which are hazardous. Common chemical constituents of PM include sulfates, nitrates, ammonium, other inorganic ions such as ions of sodium, potassium, calcium, magnesium and chloride, organic and elemental carbon, crustal material, particle-bound water, metals and polycyclic aromatic hydrocarbons (PAH). Particles generated by IC engines are generally small. A significant proportion of diesel emission particles have diameters smaller than 0.1 μm [84,85]. Gasoline particles are mostly agglomerates ranging from 0.01 to 0.08 μm. In general, the particle sizes from CNG emission are less than 5 % that from diesel emission [86]. Ristovsk et al. [87] observed that particles from CNG emissions are smaller than from diesel or even petrol emissions and range from 0.01 to 0.07 μm, with majority being between 0.020 and 0.060 μm.

In the last two decades, Fine and ultrafine particulates, which exist in emissions of transportation, generated much interest [88]. Many epidemiological studies have shown that particles have adverse health effects [89]. Particles also have an effect on climate either directly via scattering and absorption of radiation or indirectly via its influence on the formation of clouds [82]. The mechanisms of harmful effects of microparticle on human health are not yet known, however, according to one hypothesis the nanoparticles (particles smaller than 50nm in diameter), are capable of penetrating deep into the gas-exchange region of the lung and further into the blood stream and thus may lead to systemic inflammatory processes in the body and changes in blood coagulation [90–95]. The human body cannot protect against exposure to ultrafine particles, which can enter the heart and lungs through inhalation and have serious health effects, including respiratory diseases and heart and lung conditions. Figure 2 shows how particles of different size penetrate the human body [96]. The evidence on the health effects of air pollution has been summarised in a number of the state-of-the-art reviews [97–103].

This led to the new ambient particle standard adopted by the US Environmental Protection Agency [for particles smaller than 2.5 mm in diameter (PM 2.5)] has led to more stringent future control for particle emissions. Exposure to the levels of suspended fine particulate matter found in many cities of the world has been shown to increase the risk of respiratory illness and other health problems. Much of the particulate matter in urban areas is due to transportation. CNG produces very tiny amounts of particulate matter.

CNG is a potentially advantageous fuel because particulate matter (PM) emissions are significantly reduced with natural gas fuels, since natural gas does not contain aromatic and polyaromatic compounds and contains less dissolved sulfur compounds than petroleum fuels [22,45,105,106]. Thus, the contribution of NGVs to smog formation can be less than that of comparable gasoline- and diesel-powered vehicles.

Results of various studies based on real world data [31,34,37,38,45,52–54,65,79, 80,86,107–110], which confirm the potential reduction of particulate matter emission of CNG fuel. Using natural gas buses to replace existing diesel buses in Santiago reduces annual PM emissions in 229 t/year, leading to an annual reduction in PM2.5 of 0.33 μg/m3. These reductions lead to health benefits of 9130 USD/year for each current bus replaced by natural gas buses [108]. On average the total particulate mass emissions of CNG fuelled engines are much lower, i.e. only 7–9 % of the emissions of diesel fuelled engines [34,35,54,111].

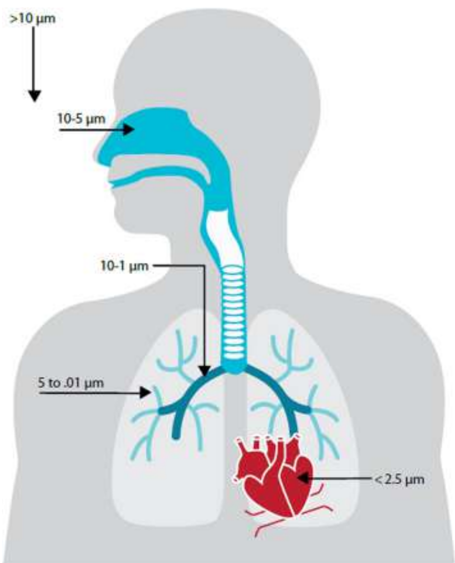

Fig. 2 Particles entering the human body [104]

There have been several studies conducted with the aim of comparing particle emissions from diesel and CNG buses. While, most of these studies have shown a consistency with respect to particle mass emission factors, there is considerable disagreement between results of particle number emission measurements. Table 2 presents a summary of the results of particle mass emission factors (MEF) in some previous studies. Pietikäinen et al. [88], conducted a study to assess the particulates of diesel and natural gas fuelled buses in Silic and found that under similar conditions the total lung dose of particulates originating from diesel fuelled engines was more than 60-fold, compared to the lung dose of particulates originating from the CNG fuelled engine. Jayaratne et al. [55] tested 22 different buses, including 13 CNG buses and 9 diesel buses under identical steady state engine load conditions in city of Brisbane, Australia and found that PM10 concentrations of CNG fueled bus were much lower than that for the diesel buses at all loads. Studies performed in California for school buses in 1999 show 61 % less PM from CNG buses with closed loop fueling management than from similar model and model year buses powered by 8.3 l diesel engines [46]. In New York, a study comparing different diesel emission control technologies and alternative fuels was performed on three CNG and two diesel buses sharing the same basic engine and rated power [52]. No after-treatment device was installed in the CNG buses, while the diesel buses were tested with continuously regenerating DPF (CRT). Results show that the CNG buses offer around 70 % reduction in PM emission, even without OCs, when compared to the baseline diesel vehicles. The continuously regenerating DPF technology offers PM emission reductions that outperform the low levels obtained by lean-burn CNG engines. The fuel sulfur content required by the DPFs was below 30 ppm.

In most of the reported cases, diesel buses with after-treatment systems have been compared to CNG buses without after-treatment devices. This differential approach does not reflect a clear assessment of emissions under best available technology (BAT) conditions, and puts CNG buses at a disadvantage with respect to clean diesels. A study comparing the BAT for diesel and CNG powered buses was performed in Helsinki, Finland, as part of a program to evaluate different options for bus transit operations [54]. Four CNG buses with central fuel injection system were tested: two with OCs and two with TWC. All of the CNG engines were turbocharged. The methane content of natural gas was 98 %. Similar new diesel vehicles were selected with and without after-treatment for reference. One of the three diesel buses had an after-treatment oxidation catalyst and the other a CRT filter. Ultra low sulfur diesel (ULSD) was used on all the tests. The vehicles were tested under half load conditions [54]. Results confirm that PM emissions of CNG buses are extremely low, independent of technology and use mileage.

3.5 Non-methane hydrocarbon (NMHC)

Hydrocarbon emissions result when fuel molecules in the engine do not burn or burn only partially. Hydrocarbons can have negative health impacts or contribute to the ground-level ozone, a major component of smog [54]. The rate of HC release is influenced by the molecular weight of the respective fuel. During expansion, drop in the pressure in cylinder draws compressed unburnt fuel from crevice volume to create

Table 2 Particle mass emission factor (PMEF) from comparative studies of diesel and CNG buses

S. N.	References	Study year	Vehicles	Test method	Fuel	After treatment	PMEF (g/km)
1	Wang et al. [110]	1997	Over 300 buses	CBD transient cycle	Diesel	–	20
					CNG	–	1
2	Coroller et al. [38]	1998	4 Diesel and 3 CNG buses	CBD Cycle, Paris	Diesel	–	0.35
					CNG	–	0.04
3	Clark et al. [34]	1999	3 Diesel and 3 CNG buses	CBD transient cycle	Diesel	OC	0.24
					CNG	OC	0.025
4	Frailey et al. [107]	2000	3 Diesel and 3 CNG buses	CBD transient cycle	Diesel	–	0.38
					CNG	–	0.012
5	Chandler et al. [31]	2000	3 Diesel and 13 CNG buses	CBD cycle, Hartford	Diesel	–	0.02
					CNG	OC	0.01
6	Ahlvik et al. [80]	2000	Diesel and 3 CNG buses	CBD transient cycle	Diesel	None	0.16
					Diesel	OC	0.112
					Diesel	DPF	0.011
					CNG	None	0.017
					CNG	OC	0.012
7	NREL Emission Tests [65]	2002	4 Diesel and 5 CNG buses	CBD cycle Washington	Diesel	OC	0.62
					CNG	OC	0.093
8	Ayala et al. [80]	2002	2 Diesel and 3 CNG buses	CBD cycle, Los Angeles	Diesel	None	74.02
					CNG	None	22.81
				NYBC	Diesel	None	392.17
					CNG	None	60.35
9	Lanni et al. [52]	2003	2 Diesel and 3 CNG buses	CBD cycle, New York	Diesel	DPF	0.0267
					CNG	None	0.0197

Table 2 continued

S. N.	References	Study year	Vehicles	Test method	Fuel	After treatment	PMEF (g/km)
10	Ullman et al. [53]	2003	2 school buses	CHSVC transient cycle	Diesel	None	0.115
					Diesel	PT	0.006
					CNG	None	0.033
11	Nylund et al. [54]	2004	2 Diesel and 3 CNG buses	BSC and OCC transient cycle	Diesel	None	0.17
					Diesel	OC	0.12
					Diesel	PT	0.02
					CNG	None	0.02
					CNG	OC	0.01
12	Melendez et al. [37]	2005	5 Diesel and 7 CNG buses	CBD cycle Washington	Diesel	OC	0.0081
					CNG	OC	0.0054
13	Kado et al. [45]	2005	2 Diesel and 3 CNG buses	3 transient cycles	Diesel	OC	0.056–0.074
					Diesel	PT	0.002–0.010
					CNG	None	0.014–0.058
				1 steady state at 55 m/h at 60 % power	Diesel	OC	0.014
					Diesel	PT	0.002
					CNG	None	0.014
14	Jayaratne et al. [55]	2008	Diesel and dedicated CNG buses	CBD Cycle, Queensland, Australia	CNG	TWC	0.163
					Diesel	None	96.5

reverse blowby. At the end of this reverse blowby, flame reaction quenched and some unreacted fuel particle remains in the exhaust. Rich air-fuel ratio with insufficient oxygen prompts the incomplete combustion of fuel as a misfire produces the unburnt hydrocarbons.

CNG majorly comprises of methane and since methane does not have carbon–carbon molecular bonds, natural gas combustion results in a substantially lower probability of benzene ring formation, which in turn means a reduction in formation of carcinogenic polycyclic aromatic hydrocarbons (PAHs) and soot [113]. Ristovski et al. [15] found that emissions of total PAHs and formaldehyde are significantly lower when the vehicle operates on CNG than on petrol. CNG contains less aromatic content and has a higher hydrogen/carbon ratio, both of which are responsible for the reduction of volatile organic compounds (VOCs) species in case of CNG fuelled vehicle. Yang et al. [114] have reported that low content of aromatics and a higher H/C ratio allow better reduction of aromatic hydrocarbons (VOCs). Similarly to find the comparative emissions of VOCs and BTEX of CNG and gasoline fueled vehicle, an experimental study was conducted by Asad et al. [115] on a bi-fuel vehicle fuelled on CNG and gasoline. According to their results VOCs and BTEX reduced by 85.2 and 86 % respectively, in case of CNG fuelled vehicle as compared to gasoline vehicle while for the formaldehyde there was an overall increase of 39.4 % in case of CNG. Turrio-Baldassarri et al. [25], measured the toxic emissions of a heavy-duty engine used for urban busses fuelled with CNG and compared to emission equivalent diesel engine under similar conditions. The results obtained show that the CNG engine emissions, with respect to the diesel engine were nearly 50 times lower for carcinogenic PAHs and 20 times lower for formaldehyde. Ristovski et al. [15] conducted an experimental work to evaluate the physical and chemical properties of emission products from a Ford Falcon 4 L six cylinder SI car engine under a variety of operating conditions, before and after it has been converted to CNG. The results revealed that there was a significant lowering of emissions of total PAHs and formaldehyde when the vehicle was operated on CNG. The presence of formaldehyde in the air is undesirable as it increases health risk and has relatively high ozone forming potential. Formaldehyde and PAHs have also known mutagenic and carcinogenic properties [15,114–116].

While most of the methane in CNG fuel is combusted, a small portion of it is unburned and emitted in the exhaust. As the key component of natural gas is methane, so in keeping with this major part of unburnt tailpipe emission for natural gas fuels may consist of methane. Although it is not toxic, methane has a global warming potential that is 23 times higher than that of CO_2 [54,116–118]. But today, natural gas powered vehicles are fitted with an exhaust catalyst which coverts unburnt methane fuel (i.e. fuel slippage) to CO_2 and water. Therefore the global warming potential of natural gas powered vehicles is reduced relative to their diesel counterparts.

4 Impact of CNG composition on emission characteristics

Natural gas is not a homogeneous mixture, but varies in composition which is highly dependent on the production area, season, and climate. Therefore its thermodynamics properties are dependent on its components. Several research studies [119–121] on the natural gas vehicles found that the exhaust emissions are greatly affected by varying compositions of natural gas. In SI engines, it has been observed by researchers [122] that natural gas fuel properties have a clear and direct effect on some emissions, such as CO_2 and NMHC, but not for other emission, such as THC, NO_x and CO. Generally, it has been agreed by researchers [122] that the fuels with higher hydrocarbons, higher WN (Wobbe number), and higher energy content exhibit less CO_2, CO, THCs emissions, high NO_x emissions while no effect on particulate matter (PM) emissions.

5 Conclusion

From the above details we may draw conclusions as follows:

1. CNG is clearly a powerful weapon for the countries in the battle to replace oil in the transportation sector, to reduce air pollution and to address the challenge posed by climate change.
2. Based on the results obtained and on literature studies, it can be concluded that the use of CNG in public transportation can contribute the improvement of urban air, reduce adverse health effects and social costs of air pollution.
3. On a well-to-wheels basis, CNG produce less greenhouse gases as compared to conventional gasoline and diesel vehicles.

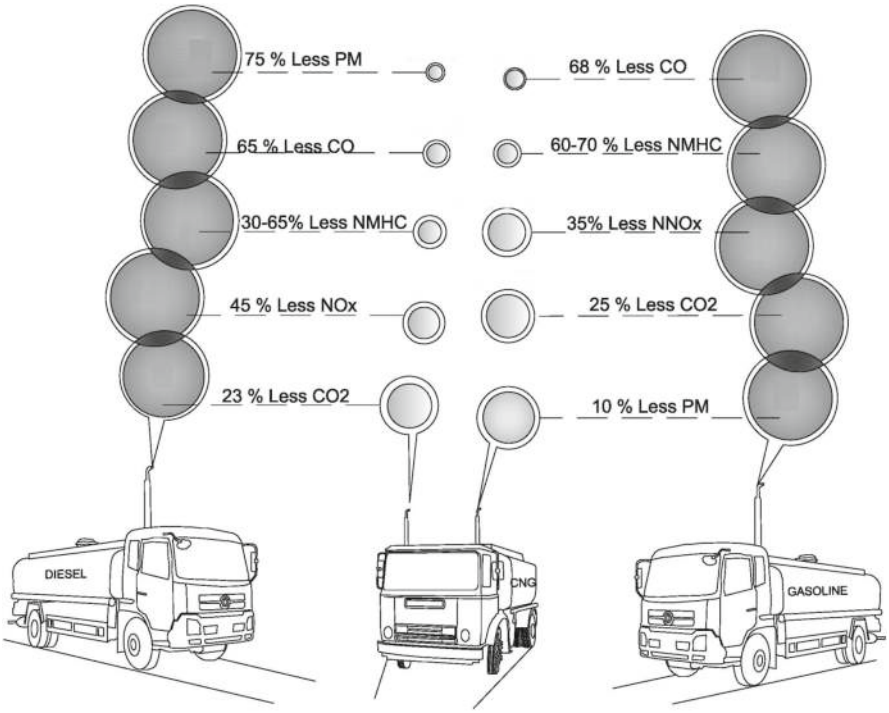

Fig. 3 Emission benefit of CNG vs diesel and gasoline

4. Keeping in view the results of various studies, the average potential reductions in the exhaust emission of CNG vs Diesel and gasoline fuel is illustrated with Fig. 3
5. Literature review shows that in contrast to diesel fuel, there is large variation in the resulted NMHC emission data of CNG fuel. Some studies reveal that CNG can significantly reduce NMHC emission while other concluded that CNG increase the NHMC emission.
6. There is large variation in emission data of the vehicles with the same engine technology. It shows that the condition of vehicles is an important determinant of the emission levels, often more important than fuel or engine type. Vehicles with properly operating engine and emission control systems consistently produce lower exhaust emissions than vehicles with malfunctioning or poorly tuned systems, regardless of fuel type used.
7. Although with the development of diesel engine technology, it burns considerably cleaner than they ever have before. However, CNG engines are more advantageous regarding emissions of particulate matter compared to traditional diesel without particulate capturing technologies.
8. CNG engines result in lower emissions of toxic compounds of PAHs and formaldehyde to that of gasoline engine.
9. Majority of CNG engine development is restricted towards heavy duty engines e.g. transit buses. There is a need to develop dedicated CNG engines for light duty vehicles i.e. cars.
10. Although reductions in emissions can easily be achieved in the current fleet of vehicles through the use of natural gas and catalytic converters, there is a tremendous potential for reducing emissions by means of dedicated CNG fueled vehicle.
11. Keeping in view the future stringent emission regulations and summing up the worldwide experiences with CNG transportation fleets up to now it can be concluded that with some further technical improvements, fueling the vehicles with CNG can be recommended as environmental friendly fuel.

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Annexure-D

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TECHNICAL PAPER

Safety issues associated with the use and operation of natural gas vehicles: learning from accidents in Pakistan

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Abstract The use natural gas in transportation is well established globally with over 18 million natural gas vehicles (NGVs) distributed through more than 90 countries of the world. This paper discusses several safety issues involved with using natural gas as a transportation fuel. After introducing the NGVs safety aspects and reviewing various standards for compressed natural gas (CNG) system, the paper discusses the 55 CNG-related accidents in Pakistan (which conduced to over 250 casualties) and analyzes the causes for these accidents and extracts “lessons to be learned” for CNG. The analysis reveals that due to low-quality CNG system material, e.g., CNG cylinder, CNG design and installation, maintenance system, etc., lack of strict government CNG vehicle safety regulations and driver negligence every year several CNG vehicles' accidents took place in Pakistan which showed a major threat to life in Pakistan.

Keywords Accident · Safety · CNG · Cylinder · Pakistan

List of symbols

AISI	American Institute of Steel and Iron
A/F	Air–fuel ratio
ANSI	American National Standards Institute
APCNGA	All Pakistan Compressed Natural Gas Association
BTU	British thermal unit
CMVSS	Canadian Motor Vehicle Safety Standards
CNG	Compressed natural gas
CO_2	Carbon dioxide
CSA	Canadian Standard Association
CVEF	Clean Vehicle Education Foundation
ECE	Economic Commission for Europe
EFV	Excess flow valve
FMVSS	Federal Motor Vehicle Safety Standards
ISO	International Organization for Standardization
LHV	Lower heating value
LPG	Liquefied petroleum gas
NFPA	National Fire Protection Association
NGVs	Natural gas vehicles
OGRA	Oil and Gas Regularity Authority
PRD	Pressure relief device
SCC	Stress corrosion cracking
TNT	Trinitrotoluene
USG	US gallon

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1 Introduction

Worldwide, urban air pollution is a serious health and environment concern in our major cities. Road transport, particularly that using diesel vehicles, is generally the major contributor to the declining air quality in urban areas. This has provoked increasingly stringent vehicle emission standards worldwide and stimulated research into alternative fuels and technologies that promise cleaner and lower emissions.

The use of alternative fuels for engine is regarded as one of the major research areas for the age [1–3]. In the present situation of rapid depletion of fossil fuel resources and the increase of environmental issues are main motives for the growth of alternative fuels. Various alternative fuels have been introduced into the transport sector, e.g., LPG, propane, bio-diesel, hydrogen, fuel cells. Out of these available alternate fuels, compressed natural gas (CNG) is the one which is meeting the maximum needs of countries world over, which want to switch over to alternate fuels [4–7]. CNG has been considered as one of the best solutions for fossil fuel substitution because of its inherent clean nature of combustion [8, 9] and lower fuel cost. It has now been recognized worldwide as environmentally friendly fuel [10, 11]. Therefore, the numbers of engine vehicles powered by CNG engines are growing rapidly [12, 13].

Today there are over 18 million natural gas vehicles distributed through more than 90 countries of the world with major concentrations in Pakistan, Iran, Argentina, Brazil, India, Italy and China [14]. In the last 10 years, worldwide, the NGVs population has escalated speedily at an annual rate of 24 % with the biggest contribution coming from the Asia–Pacific and Latin America regions.

With more and more fleet vehicles being converted to compressed natural gas operation, concerns have arisen about the safety of their fuel systems and the need for regulations to ensure safe operation. The potential for widespread operation of vehicles using compressed natural gas adds urgency to these concerns. The question a lot of people are asking themselves is, Is this stuff safe? This paper examines such concerns and questions. After introducing the NGVs safety aspects, we will study recent CNG-related accidents in Pakistan and will analyze causes for these accidents and will extract "lessons to be learned" for CNG.

2 CNG as fuel

The CNG used in natural gas vehicles (NGVs) is the same natural gas that is piped into millions of homes for cooking and heating. CNG is made by compressing natural gas (which is mainly composed of methane (CH4), to less than 1 % of the volume it occupies at standard atmospheric pressure. It is stored and distributed in hard containers at pressure of 20–25 MPa (3000–3600 psi), usually in cylindrical-shaped cylinder [15]. For these range of pressures, the equivalent amount of energy stored per unit volume is 27–33 % of that of gasoline. Table 1 represents the comparison between the physiochemical properties of CNG to that of diesel and gasoline.

Physical properties of natural gas provide some safety benefits over gasoline and diesel fuel. Physical properties of CNG which makes it inherently safer than diesel or gasoline are:

Table 1 Physiochemical properties of CNG versus gasoline and diesel [16]

Properties	CNG	Gasoline	Diesel
Octane/cetane number	120–130	85–95	45–55
Molar mass (kg/mol)	17.3	109	204
Stoichiometric $(A/F)_s$ mass	17.2	14.7	14.6
Stoichiometric mixture density (kg/m^3)	1.25	1.42	1.46
LHV (MJ/kg)	47.5	43.5	42.7
LHV of stoichiometric mixture (MJ/kg)	2.62	2.85	2.75
Combustion energy (MJ/m^3)	24.6	42.7	36
Flammability limit in air (vol % in air)	4.3–15.2	1.4–7.6	1–6
Flame propagation speed (m/s)	0.41	0.5	–
Adiabatic flame temp. °C	1810	2150	2054
Auto-ignition temp. °C	540	258	316
Wobbe index (MJ/m^3)	51–58	–	–

1. In contrast to gasoline/diesel fuel, CNG has a narrow range of flammability, 4.3–15.2 % by volume in air; that is in concentrations in air below 4.3 % and above 15.2 %, natural gas will not burn even in the presence of a spark.
2. CNG has a high auto-ignition temperature of 813 K (540 °C) compared to 531 K (258 °C) of gasoline and 316 °C of diesel. The auto-ignition temperature (also known as ignition temperature) is the lowest temperature at which a substance will ignite because of heat alone, without an additional spark or flame. The high ignition temperature and limited flammability range make accidental ignition and combustion of CNG unlikely.
3. CNG is lighter than air so in the event of accidental leakage the very low density of CNG at atmospheric pressure, 0.68 kg/m^3 compared to air, 1.202 kg/m^3, means that CNG would rise and disperse into the air rapidly instead of forming pools on the ground as in the case of diesel and gasoline, which reduces the probability of a fire if the tank is breached. However, Graham et al. (2000) argued that CNG vapors formed at low temperatures from leaks will generate large clouds of flammable vapor and increase the potential of an explosion coupled with a spark.
4. CNG cylinders are designed and built of special materials to withstand high pressures with a factor of safety that is typically greater than two [17], therefore, safer than ordinary petrol tanks. Figure 1 illustrates the safety attribute of CNG cylinder where CNG cylinder remained safe after a car has been totaled by 10,000 USG tanker. Similarly on December 2007, a driver in Malaysia was carrying explosive chemical (acetylene) container at rear compartment of his CNG vehicle. Due to the hot weather and enclosed environment the chem-

Fig. 1 Honda Civic GX CNG vehicle accident—New York

Fig. 2 CNG cylinder remained safe after explosion of chemical explosive chemical lying in trunk cabin of the vehicle

ical overheated and exploded. From the Fig. 2, it can be observed that the tank is still intact and not much affected by the explosion.

3 CNG cylinder design considerations

Natural gas as CNG is compressed at high pressures up to 200 bars and stored in cylinders. A CNG cylinder typically has a cylindrical shape with hemispherical domes on the ends. CNG cylinders are normally designed with a factor of safety that is typically greater than two [18]. There are four types of cylinder designs. Each type of cylinder has its benefits and liabilities. Major attributes of each type of cylinder are tabulated in Table 2.

3.1 Type-I cylinder

The Type-I cylinder is an all-metal constructed design. They are normally constructed from AISI 4130X low-alloy steel. Type-I cylinders are the type most commonly used for CNG storage in natural gas vehicles (NGVs) because the metalworking skills and equipment needed to produce them are widely available internationally. Steel cylinders are typically inexpensive and durable, but heavy. Steel cylinders offer the best resistance to fire effects, typically surviving twice as long as other designs when exposed to the standard bonfire test. Steel is an excellent conductor of heat to activate a pressure relief device. Safe working life of Type-I cylinders usually ranges from 15 to 20 years in most parts of the world. In Pakistan although currently there is no defined service life for Type-I CNG cylinders but they are requalified every 5 years through visual inspection and hydrostatic testing,

Worldwide there have been a number of failures of Type-I steel cylinders. Figure 3 shows one of such accidents, in which Type-I cylinder failed due to extensive external

Table 2 Types of CNG cylinder

Type	Construction	Market share (%)	Weight (kg/l)	Weight reduction (%)	Indicative cost US $/l	Service life (year)
Type-I	All metal (aluminum or steel)	93	0.80–1	–	3–5 $	20
Type-II	Metal liner reinforced by composite wrap (glass or carbon fiber) around middle (hoop wrapped)	4	0.52–0.68	15–35 %	5–7 $	20
Type-III	Metal liner armored by composite wrapping (carbon or glass fiber) around the complete cylinder (fully wrapped)	<2	0.41–0.45	44–48 %	9–14 $	15
Type-IV	Plastic (HDPE) gas-tight liner reinforced by composite wrap around entire tank (fully wrapped)	<2	0.30–0.39	51–66 %	11–18 $	20

Fig. 3 Type-II CNG cylinder failure

corrosion, the cylinder was not visually inspected for over 10 years. The cylinder was also subjected to over pressure by defective fueling system, the 16.5-MPa (2400 psi) cylinder was potentially subjected to 41.4 MPa (6000 psi).

3.2 Type-II cylinder

This is a metallic cylinder with a partial wrapping that goes around the cylinder. The wrapping is usually made of glass fiber, aramid fiber or carbon fiber, embedded in an epoxy or polyester resin. Metal supports approximately 55 % of the load and wrapping supports about 45 % in the Type-II cylinder design. In Type-II cylinder designs, the metal liner can contain the maximum fill without the hoop-wrap (1.25 times service pressure). This design allows the use of higher fiber stress levels than are used in full-wrapped designs. Once the hoop wrapping has been applied to the metal liner, an autofrettage cycle is performed. During autofrettage, the cylinder is pressurized hydraulically to a pressure such that the liner is permanently expanded and placed in compression by the applied tension of the composite overwrap. As a result of autofrettage, the fatigue performance of the cylindrical portion of the metal liner is increased. Hoop-wrapped designs are generally safer than full-wrapped designs because of the redundancy of the liner design. E-glass has been commonly used in this type of cylinder, but new designs, based on carbon fibers, are being developed. In USA the liner is generally fabricated using AISI 4130X low-alloy steels or AA 6061-T6 aluminum alloys. As compared to Type-I, Type-II cylinders cost about 50 % more to manufacture but can reduce the weight of the storage containers by 30–40 %.

Worldwide there have been some reported failures of the Type-II cylinder design. The failures were due to gross degradation of the composite overwrap together with overpressurization of the cylinder. Surface corrosion of exposed metal domes in Type-II cylinders can produce rusting or pitting, resulting in reduced wall thickness and eventual cylinder failure. Correct practice is to paint any exposed metal. Moreover, fatigue cracking of the metal liner due to the large number of pressure cycles can occur in this type of cylinder [19]. Surface abrasion or cuts can damage the composite and reduce the strength of the cylinder portion of the container. A cylinder should have a detailed visual inspection if there is evidence of abrasion/scuffing damage or a surface cut.

There have been many incidences of mechanical damage (detected prior to failure) to the composite wrap as a result of improper installation and environmental attack. Improvement in the installation code requirements should reduce the incidences of mechanical damage, and coating the glass fibers or the use of fibers resistant to SCC should reduce the incidences of environmental damage. Figure 4 shows an explosion of CNG-powered Korean transit bus with Type-II cylinder. The incident occurred on December 2007, while waiting at a traffic light in Seoul, South Korea and injured 17 people. There were signs of physical damage to E-glass wrap and indications of overpressurization. Potential failure of tank-mounted solenoid may have led to overpressure in cylinder.

3.3 Type-III cylinder

Type-III cylinders are used in a wide range of applications where weight reduction is important, for example, in transit buses and delivery trucks. These cylinders have a seamless metal liner overwound on all surfaces by a composite reinforcement that provides between 75 and 90 % of the strength to the vessel. Plastic gas-tight liner reinforced by composite wrap around entire tank, the entire strength of the tank comes from the composite reinforcement. The composite supports about 80 % of the internal pressure in the Type-III cylinder design. These cylinders are generally 75 % lighter than comparable steel cylinder. Type-III cylinders are full-wrapped cylinders consisting of a metal liner that is wrapped with continuous filaments in a resin matrix.

Fig. 4 A type-II CNG cylinder failure, Seoul, South Korea, 2007

Fig. 5 A type-III CNG cylinder explosion, California, 1996

Fig. 6 A type-III CNG cylinder explosion, California, 2007

The long-term integrity of the composite in a Type-III cylinder design is more critical to the cylinder's durability and safety than for the Type-II cylinder design. The composite supports about 75–90 % of the internal pressure. The liner provides the rest of the strength, plus acts as a rigid membrane to hold the gas and provide extra impact resistance to the product. The metal liner is presently manufactured using AA 6061-T6. These cylinders are generally 75 % lighter than comparable steel cylinder. These containers have seen less than 10 years of service life in NGVs. There have been four reported failures of Type-III fiberglass-wrapped cylinders only in the United States. The environmental damage issue can be reduced by coating glass fibers with an environmental coating or using fibers that are resistant to SCC. In 1996, a CNG cylinder of Dodge B250 Van equipped with four Type-III cylinder ruptured after filling (Fig. 5). Similarly on 26 May 2007, an airport shuttle van equipped with Type-III aluminum liner, E-glass fiber CNG tank burst during filling in California, USA (Fig. 6).

3.4 Type-IV cylinder

Type-IV cylinder is a gas-tight plastic liner that is non-load bearing over which an overwrap such as carbon fiber or fiberglass is applied in a full-wrapped pattern over the entire liner, including the domes. The liners of Type-IV tanks provide no structural strength to the product and act only as a permeation barrier. The composite wrap supports all of the gas pressure [17]. Therefore, the durability of the composite determines the safety and durability of the cylinder. The composite materials significantly improve corrosion resistance, fatigue resistance and overall safety of the CNG cylinder. The Type-IV design is attractive because it is the lightest weight of all designs. The cost of Type-IV cylinders, however, is roughly twice that of Type-II cylinders and 3.5 times greater than Type-I tanks. Currently the adoption of composite cylinder technology in Pakistan is in

Fig. 7 Ruptured type-IV cylinder remains from Honda Civic GX fire in Seattle USA, 2007

introductory phase and almost the entire cap of CNG being utilized in Pakistan is of Type-I cylinder usually imported from India and Italy. However, for the past 2 years, the CNG industry of Pakistan has witnessed a gradual shift from the type-I steel cylinders to an increased use of Type-IV composite cylinders in natural gas vehicles.

There have also been several cases of leaking in Type-IV cylinders due to plastic liner defects [17]. Carbon fibers have many favorable attributes, such as high strength and resistance to environmental attack. However, Type-IV carbon fiber cylinders are sensitive to impact damage—the brittle fibers can break when subjected to impact events such as dropping or being struck by road debris. When a Type-IV carbon fiber cylinder suffers impact damage, it may be difficult to see this damage. A cylinder should have a detailed visual inspection if there is evidence of abrasion/scuffing damage or a surface cut.

There have been a few failures of Type-IV cylinders. One of such incident occurred in a CNG-fueled Honda Civic in Seattle in March 2007, during which an arsonist set fire to a row of parked vehicles in an outdoor lot and subsequently exploded the CNG cylinder of the car. Figure 7 shows the remains of the Type-IV CNG tank.

4 Hazards and safety strategies of NGVs

Large quantity of mechanical and chemical energy is stored in compressed combustible gas cylinder. Theoretically, the pneumatic burst of a 130 l tank at a pressure of 200 bar releases an energy equivalent to the detonation of about 1.85 kg of TNT (8.7 MJ) [20]. High-speed projectiles are the main threat and are primarily responsible for deaths, injuries and property damage. However, the effect of shockwave should not be overlooked.

Fire onboard NGVs may be caused by internal or external factors. Internal factors include events such as electrical short circuits, excessive temperature of bus components including the braking system, the turbo compressor, the exhaust pipe in combination with combustible materials including polymeric materials, oil, dust and debris. Experience shows that fires usually start in the engine compartment. As far as external causes are concerned we can mention human error during maintenance (use of open flames, etc.), vandalism and propagating fires from nearby vehicles or infrastructure. To prevent tank burst and fire eruption; CNG cylinder are clad with the following devices.

4.1 Pressure relief device (PRD)

Tanks are normally equipped with an automatic pressure relief device (PRD) or relieve valves which are pressure and temperature sensitive. PRDs are a key component on the CNG fuel system because they open to allow the container to depressurize prior to tank failure or a potential explosion during a fire as they fuse under the effect of temperature rise (fire). The melting temperature of these fuses is about 383 K (110 °C). PRDs are fitted in such a way that they are not thermally shielded so they can appropriately respond to changes in temperature. The ports are also directed in such a manner that they do not cause damage to other nearby vehicles and pedestrians. In the event of a fire, if the gas is released into the open flame, jets of fire shoot out from the tanks much like the high flame on a Bunsen burner releasing pressure at a controlled rate, preventing the tank from exploding.

These devices should be manufactured by a qualified manufacturer and should be tested every 5 years to demonstrate operability. Failure to open and premature opening are two failure modes of concern. If the PRD opens at a pressure lower than its designed pressure, it will most likely reseat itself after a certain pressure drop. Failure to open can result in a tank failure.

When located in a vehicle compartment capable of accumulating natural gas, the container should have a PRD that vents to the outside of the vehicle. The vent line should have no diameter less than the outlet diameter of the PRD and should be constructed of metallic tubing. The discharge line should be vertically oriented, and the line should be secured at intervals to minimize damage to or failure of the line. The outlet of each vent line should be protected by caps, covers, or other means to keep water, dirt, and insects from collecting in the line. These protective devices should not restrict the flow of gas. Since 1984 CVEF has recorded 22 incidents of release of CNG by the PRD activation [21]. Figure 8 shows that these CNG fuel cylinders were prevented from failing by PRDs which were successfully activated in a fire.

Fig. 8 Cylinder remained safe due to successful activation of PRDs

Prevailing regulatory standards of CNG cylinders only specify a bonfire test of a cylinder where the fire source is placed at standard distance of 1.65 m [22, 23]. But the majority of the CNG cylinder's failures were caused by localized fire effects where the flame exposure was at a location on the tank remote from the TPRD (temperature-activated pressure relief device) location. Note that TPRDs do not tend to activate unless they are exposed directly to a high heat source, or direct flame impingement. To address the issue of localized fire, some standards include a statement to the effect that one should optimize the location of TPRDs on cylinders depending on the installation configuration. However, one reason the localized fire issues have not been addressed in the standards is because cost effective methods of protecting cylinders have not been investigated. Typically the TPRDs can be found attached to a valve at one or both ends of a tank.

Alternative methods for protecting a tank from fire effects involve coating systems that insulate from the heat, and methods of detecting heat or fire that will remotely activate a pressure relief device. Methods of protecting CNG tanks from fire effects, other than the standard use of TPRDs, may be separated into three types of systems:

1. Coating systems that have intumescent properties
2. Heat insulating wraps or shells
3. Heat detection systems that activate remote pressure relief devices

4.2 Shutoff valves

CNG vehicle often equip with automatic solenoid shutoff valve to prevent fuel from flowing out of the cylinder unless the engine is running or after accident. When the engine is running, it creates a vacuum, which basically pulls the natural gas through an automatic shutoff valve. This valve is located directly on the storage cylinders. If the engine is not running, the lack of vacuum will cause the automatic shutoff valve to stop the flow of gas at the storage cylinders. These valves require special procedures and tools to be certain that the cylinder is empty. If there is a failure of a line, valve, or connector in the CNG fuel system that results in a leak, most likely the leak condition can be isolated.

4.3 Excess flow valves

Excess flow valve (EFV) is a mechanical safety device installed either inside or outside the cylinder valve or cylinder. It is used to automatically stop the flow of gas in cases of a gas leakage in CNG piping system. They are designed to close when the gas flow rate through them exceeds the expected range of normal operation, for example, due to a downstream leak or valving error that provides an unintended release path to the atmosphere. EFVs are intended to bring the release under control until the leaking element (e.g., pipe, valve) can be blocked in and positively isolated for corrective action. If the EFV fails to operate properly it must be replaced. The EFV cannot be repaired or rebuilt. Indications of improper operation include tripping during normal engine operation.

5 Worldwide safety regulations for CNG vehicles

Worldwide, various safety and design requirements for CNG fuel system components such as gas cylinders, cylinder valves, fuel lines, filling connection, pressure regulator, gas–air mixer, electrical systems are being used. Table 3 depicts the prevailing NGVs standards/regulations in various regions.

In Europe, UN-ECE regulation R-110 is followed for safety of CNG vehicle fuel systems and their installation. This regulation is one of the mandatory requirements for whole vehicle type approval (WVTA) of CNG vehicles as per latest WVTA framework European directive 2007/46/EC. Apart from ECE R-110, many countries in Europe also follow ISO 11,439 for safe design of CNG fuel system components.

In USA, Federal Motor Vehicle Safety Standards (FMVSS) are widely used for vehicle self-certification. FMVSS 303 and FMVSS 304 are used for CNG vehicle

Table 3 Worldwide NGVs safety regulations

Countries	Standards/regulations
Germany, France, Italy, Netherland, Sweden, Belgium, Hungary, Spain, UK, Austria, Poland, Greece, Turkey, Azerbaijan, South Africa, South Korea, Thailand, Iran	ECE R-110 ISO 11439
USA	FMVSS 303 & 304, ANSI NGV3.1-2014, NFPA-52
Canada	CMVSS 301.2
India	IS-15490
New Zealand	AS/NZS 2739
Pakistan	Pakistan CNG rules1992 based on NZS 5454—1989
Australia	AS/NZS 2739 ECE R-110 ANSI/NGV 2 ISO 11439
Japan	JGA NGV02
Brazil	ISO 11439
Canada	CMVSS 301.2

fuel system safety and its integrity including gas cylinder safety. Apart from Federal regulations, there are also other voluntary standards such as NFPA-52 (Vehicular Gaseous Fuel Systems Code) and ANSI NGV3.1-2014 (basic requirements for CNG vehicle fuel containers) in USA.

In Canada, CNG vehicles must comply with Canadian Motor Vehicle Safety Standards CMVSS 301.2—CNG Fuel System Integrity. The CMVSS 301.2 Regulation requires that manufacturers of CNG vehicles demonstrate compliance by: (a) providing vehicle crash test data; or (b) demonstrating compliance with Sect. 4 of CSA B109—Natural Gas for Vehicles Installation Code.

Type approval of CNG vehicle in India is governed by Central Motor Vehicle Rule no. 115-B, which refers to Automotive Industry Standards AIS-024 and AIS-028 for safety and installation requirements. In Delhi—Indian capital—the entire public road transport was switched over to CNG-fueled vehicle from diesel and gasoline in 2002 after the verdict of Indian Supreme Court. Today Delhi has world's largest CNG-fuelled public transport system.

In Delhi, around 15 CNG bus fire incidents were reported during 2002–2007. Summary of technical flaws noted in these CNG buses:

- Damage to high-pressure gas piping.
- Pulling out of high-pressure gas pipes from fittings.
- Failure of PRDs. There was an unusually high number of burst disc failures.
- Short circuit in electric wiring creating sparks.
- Insufficient flexibility in the high-pressure gas piping.

To address these issues a separate safety council was set up by the Indian government to deal with CNG-related safety issues and carry out "root-cause" evaluations of CNG-related safety problems, identify solutions, and ensure implementation. Independent third-party inspection was introduced in which buses identified with flaws are sent back for remedial action. A special check list for this specialized inspection has been prepared. A set of remedial measures have been recommended, and are being put in place, which involves all parties from the chassis builder, converter, the Transit Corporation, and inspection agencies in taking corrective action.

Testing centers are being set up for periodic inspection. All buses have been asked to register with the authorized service stations for periodic checkups. A common periodic testing checklist is followed at each of these centers. Audit of periodic testing centers is being carried out. After the implementation of these strategies no significant NGVs accident has been experienced place in Delhi.

6 CNG scenario in Pakistan

In Pakistan, due to available price difference between CNG and gasoline/diesel, Government's consumer friendly policy, ample regulatory framework and extensive efforts, CNG industry has developed significantly at an unprecedented rate of around 52.5 % per annum during the last few years [24]. Currently the country has 3100,167 vehicles running on CNG. Over the past 10 years (2001–2010) there is more than 11, 000 % rise in natural gas consumption by this sector. Besides several advantages which CNG brings to Pakistan's Transport sector, increasing NGV's accidents are a major threat to life in the country. Every year several CNG vehicles' accidents took place in the country. Table 4 provides an overview of NGV's accidents in Pakistan that have involved explosions or fires.

7 Causes of NGV's accidents in Pakistan

The accidents highlighted in Table 4 can be categorized into two parts:

1. Fire explosion
2. Cylinder explosion

7.1 Fire explosion

Fire explosion of the CNG vehicle that took place is attributable to the following factors:

Table 4 Summary of major CNG vehicles accidents in Pakistan (all of cylinders mentioned belong to Type-I cylinder category)

S. No.	Date	Accident description	Place	Vehicle	No. of deaths	No of injured	Causes
1	30-Mar-08	Explosion of CNG cylinder	Attock	Pickup	2	3	Explosion took place during refilling at CNG station due to substandard cylinder
2	6-Oct-08	Explosion of CNG cylinder	Peshawar	Car	2	4	Explosion took place during refilling at CNG station due to substandard cylinder
3	7-Jun-09	Explosion of CNG cylinder	Rawalpindi	Car	2	4	Explosion took place during refilling at CNG station due to substandard cylinder
4	14-Dec-09	Explosion of CNG cylinder	Mirpurkhas	Car	4	4	Explosion took place during refilling at CNG station due to substandard cylinder
5	18-Feb-10	Explosion of CNG cylinder	Lodhran	Van	6	15	Gas cylinder installed in the van had crossed the standard age and needed to be checked
6	21-Oct-10	Explosion of CNG cylinder	Swabi	Car	2	2	Explosion took place during refilling at CNG station due to substandard cylinder
7	5-Jan-11	Explosion of CNG cylinder	Lahore	Car	–	4	Explosion took place during refilling at CNG station due to substandard cylinder
8	13-Feb-11	Explosion of CNG cylinder	Near Lahore	Van	3	12	Explosion took place during refilling at CNG station due to substandard cylinder
9	12-Jul-11	Fir explosion in CNG bus	Near Islamabad	Mini-bus	9	3	Gas leakage from any point of CNG piping system and caught fire possibly of short circuit
10	3-Sep-11	Fire explosion in CNG van	Near Lodhran	Van	4	21	Gas leakage from any point of CNG piping system and caught fire possibly of short circuit
11	1-Nov-11	Fire explosion in CNG van	Khairpur	Van	4	8	Gas leaked from the CNG cylinder, setting the van on fire followed by a blast
12	29-Nov-11	Fire explosion in CNG van	Islamabad	Van	12	7	In an effort to save an oncoming pedestrian, the vehicle hit the median on the GT Road. The vehicle caught fire following the accident, after gas leaked from its three CNG cylinders
13	29-Nov-11	Fire explosion in CNG van	Near Taxila	Van	14	7	The van crashed into a tree after one of its tires burst. The vehicle caught fire following the accident, after gas leaked from its CNG cylinder
14	3-Dec-11	Explosion of CNG cylinder	Multan	Car	2	1	Explosion took place during refilling at CNG station due to substandard cylinder
15	10-Dec-11	Fire explosion in CNG bus	Near Vehari	Van	17	10	The tragedy took place after the van driver, while attempting to overtake another wagon, lost control of his vehicle and hit a tractor trolley laden with large cans of cooking oil
16	13-Dec-11	Explosion of CNG cylinder	Gujranwala	Mini-bus	1	4	Explosion took place during refilling at CNG station
17	17-Dec-11	Explosion of CNG cylinder	Peshawar	Car	–	6	Explosion took place during refilling at CNG station due to substandard cylinder
18	18-Dec-11	Explosion of CNG cylinder	Near Khurianwala	Van	5	14	Sparking produced by Van Faulty wiring looms conduce to fire explosion
19	21-Dec-11	Explosion of CNG cylinder	Eminabad, Gujranwala	Van	6	15	The van rammed into a road's demarcation wall while saving a cyclist and caught fire due to CNG leakage
20	21-Dec-11	Explosion of CNG cylinder	Khairpur, Setharja	Van	13	12	CNG cylinder of the van exploded when the vehicle was traveling on highway
21	23-Dec-11	Explosion of CNG cylinder	Noshehra, Pabbi	Pickup	1	3	Explosion took place during refilling at CNG station due to substandard cylinder
22	24-Dec-11	Explosion of CNG cylinder	Rawalpindi	Mini-van	–	–	Unknown causes

Table 4 continued

S. No.	Date	Accident description	Place	Vehicle	No. of deaths	No of injured	Causes
23	24-Dec-11	Fire explosion in CNG van	Rawalpindi	Van	–	–	Fire explosion have resulted from gas accumulation due to leakage
24	27-Dec-11	Explosion of CNG cylinder	Islamabad	Car	–	–	Unknown causes
25	29-Dec-11	Explosion of CNG cylinder	Peshawar	Car	–	3	Explosion took place during refilling at CNG station due to substandard cylinder
26	18-Feb-12	Explosion of CNG cylinder	Muzafargarh	Car	4	–	Car collided with a bridge. Due to collision, the gas cylinder in the car exploded
27	18-Mar-12	Fire explosion in CNG van	Near Lodhran	Van	2	16	Fire erupted due to gas leakage from high-pressure piping
28	2-May-12	Fire explosion in CNG van	Sheikhupura	Mini-van	6	4	Gas leakage from any point of CNG piping system and caught fire possibly of short circuit
29	16-Jun-12	Explosion of CNG cylinder	Narowal	Van	2	–	Unknown causes
30	18-Aug-12	Explosion of CNG cylinder	Mansehra	Car	–	5	Explosion took place during refilling at CNG station
31	7-Oct-12	Fire explosion in CNG car	Near Khairpur	Car	7	22	The bus collided with a car near Khairpur. The collision causes fire due to leakage in the CNG system of car. The fire subsequently engulfed the bus
32	18-Nov-12	CNG cylinder explosion	Karachi	Mini-bus	2	4	Due to low-quality cylinder, explosion took place during gas filling at CNG station
33	26-Nov-12	Fir Explosion in CNG Van	Near Manga Mandi	Van	7	4	The fire extended in the van due to lighting cigarette
34	26-Nov-12	CNG cylinder explosion	Mardan	Three wheeler	–	4	Due to low-quality cylinder, explosion took place during gas filling at CNG station
35	11-Dec-12	Explosion of CNG cylinder	Karachi	Car	–	3	Unknown causes
36	21-Dec-12	Fir Explosion in CNG Van	Chichawatni	Van	4	10	Sudden fire explosion took place due to gas leakage
37	9-Jan-13	Explosion of CNG cylinder	Faisalabad	Van	1	4	The van was on its way when its cylinder exploded
38	20-Jan-13	Explosion of CNG cylinder	Nowshehra	Car	1	3	Explosion took place during refilling at CNG station due to substandard cylinder
39	7-Feb-13	Explosion of CNG cylinder	Karachi	Car	–	2	According to initial reports CNG cylinder of a car blew up at a car parking due to unknown reasons
40	8-Apr-13	Fir explosion in CNG van	Faisalabad	Van	4	–	Sudden Fire Explosion took place due to gas leakage
41	31-Mar-13	Fir explosion in CNG van	MandiJab-haran	Van	3	16	The vehicle caught fire due spark produced by short circuit near petrol fuel line which is subsequently spread toward CNG cylinder
42	2-May-13	Explosion of CNG cylinder	Karachi	Three wheeler	1	3	Sudden explosion of CNG cylinder took place at road
43	3-May-13	Fir explosion in CNG van	Larkana	Van	4	10	Sudden fire explosion took place during traveling due to gas leakage
44	12-May-13	Explosion of CNG cylinder	Bannu-Mirali Road, Bannu	Van	15	3	Sudden Explosion of CNG cylinder, causes unknown
45	25-May-13	Fir explosion in CNG van	Gujarat	Van	18	7	The blaze was apparently caused by a spark when the driver of the dual-fuel van switched from gas to petrol
46	14-Jul-13	Fir explosion in CNG van	District Layyah	Van	–	8	Sudden fire explosion took during gas refueling at CNG station, probably due to gas leakage

Table 4 continued

S. No.	Date	Accident description	Place	Vehicle	No. of deaths	No of injured	Causes
47	30-Jul-13	Fir explosion in CNG van	Karak	Van	17	1	As a result of the collision between passenger van and a truck, the gas leakage took place which conduce to fire explosion
48	4-Aug-13	Fir Explosion in CNG Van	Faisalabad	Van	4	6	Sudden fire explosion took place due to gas leakage
49	9-Sep-13	Fir explosion in CNG van	Chiniot	Van	17	8	The Van collided with a truck coming from the opposite side. The collision caused the CNG cylinder to go off with a loud bang turning the van into a fireball.
50	16-Sep-13	Fir explosion in CNG van	Muzaffargarh	Van	3	5	Sudden fire explosion took place during traveling due to gas leakage
51	20-Dec-13	Fire explosion in CNG van	Near Hyderabad	Van	11	11	The vehicle caught fire because of a leakage of gas from high-pressure piping
52	7-May-14	Explosion of CNG cylinder	Rawalpindi	Car	1	2	Explosion took place during refilling at CNG station due to substandard cylinder
53	21-Jul-14	Explosion of CNG cylinder	Chamkani, Peshawar	Car	4	3	Explosion took place during refilling at CNG station due to substandard cylinder
54	21-Jul-14	Explosion of CNG cylinder	Karachi	Bus	3	8	Explosion took place during refilling at CNG station due to substandard cylinder
55	27-Sep-14	Explosion of CNG cylinder	Kohat	Car	1	2	Explosion took place during refilling at CNG station due to substandard cylinder

7.1.1 Gas leakage

In most cases, leakage of gas from high-pressure piping due to:

1. Failure of high-pressure piping;
2. Dislodging of high-pressure fitting;
3. Damaging of high-pressure pipe due to impact, mechanical wear and tear and constant vibration; all these can occur without a collision of the vehicle;
4. Improper installation of high-pressure pipe fittings which can result in damage and dislodging of high-pressure pipe fittings;
5. Bursting of unapproved valve;
6. Leakage of gas from the cylinder valve;
7. Leakage of gas from the filling valve;
8. Bursting/leakage of gas from the CNG pressure regulator due to malfunctioning of the first stage valve.

7.1.2 Sparking

Sparking of air–gas mixture created in the passenger cabin due to:

1. Cigarettes;
2. Lighter and match box;
3. Electrical instruments, etc., carried by the passengers;
4. Faulty wiring looms or components like the one in the accident mentioned at serial no. 07 in Table 4 was due to faulty wiring.

7.1.3 Collision of CNG vehicle

After the collision CNG vehicle the unwanted ignition could be caused:

1. Short circuiting of battery and electrical wiring;
2. Contact of fuel with hot surfaces, i.e., engine, exhaust manifold, radiator, etc.;
3. By spark created when kinetic energy of motion is converted into heat energy.

Figure 9 highlights some of the fire explosion accidents mentioned in Table 4.

7.2 CNG cylinder explosion

The factors that can be attributed to the explosion of CNG cylinders are listed below:

1. Usage of unapproved cylinders, welded cylinders and cylinders that are not manufactured for CNG use, e.g., oxygen cylinder, acetylene cylinder. The accident mentioned at serial no. 07 of Table 2 and Fig. 10 hap-

Fig. 9 Pictorial view of accidents mentioned in Table 4 involving fire explosion (**a**) accident at S. No. 19 (**b**) accident at S. No. 28 (**c**) accident at S. No. 45 (**d**) accident at S. No. 18 (**e**) accident at S. No. 51 (**f**) accident at S. No. 09

pened just because of substituting CNG cylinder with acetylene gas cylinder which is used for gas welding.

2. Failure to properly maintain and operate fueling stations has been a secondary cause for some cylinder failures.
3. Usage of old cylinder beyond the expiry life of cylinder.
4. Failure of PRDs during fire eruption.
5. Almost most 100 % of CNG cylinders being used in Pakistan are of Type-1.
6. Some CNG stations have been found to refuel the vehicles beyond the allowable maximum pressure of 20 MPa (200 bars).

Figure 11 highlights some of the CNG cylinder explosion accidents mentioned in Table 4.

8 Lessons learned and recommendations

Analyzing the causes responsible for the CNG-related accidents that took place in Pakistan, following learning and remedies are proposed. Some learning's are common with the Pakistan case and some others are specific.

8.1 To avoid CNG cylinder explosion

Improper installation of cylinders has led to the majority of cylinder failures:

1. Only approved CNG cylinder comply with prevailing international standards, e.g., ANSI NGV3.1-2014

Fig. 10 Explosion of non-CNG cylinder during refueling at CNG station

FMVSS 303 & 304, ECE R-110, ISO 11439, AS/NZS 2739 (applicable to Type-I cylinder) must be used in CNG-converted vehicles.

2. As shown in Fig. 12 the cylinder should have marking standard number and the approval seal duly stamped. If the cylinder has no label, then in such conditions either the workshop's technical manager or OGRA (Oil and Gas Regularity Authority) should be informed.
3. To depressurize the cylinder in the event of fire each CNG cylinder should be equipped with a PRD manufactured as per ISO-14159.
4. To avoid the fire inside the passenger compartment, CNG cylinders should be installed at the roof of the buses.
5. As cylinder PRDs are only required to protect against pressure build up due to fire, not overpressure from stations. Therefore, to protect the CNG cylinder against over pressurization, CNG refueling dispenser should have two separate pressure relief valves.
6. In vans (Hiace, Mazda, etc.) CNG cylinder may be placed a) on the over carriage if it is strong enough to hold the weight of cylinders and the center of gravity of the vehicle is not disturbed, b) beneath the vehicle and c) at the end (behind last seat) of the passenger cabin. If the cylinders are installed behind the last seat it is recommended to isolate the passenger cabin from this portion.
7. It is not recommended to place CNG cylinders beneath the passenger seats as after the accident the breaking and dislodging of high-pressure pipe and fitting are the main causes of fire in the passenger compartment of a CNG vehicle.
8. To stop gas flow from cylinders in the event of leakage in CNG piping system, Excess Flow Valves (EFV) manufactured in accordance with the ISO 15500-14 specifications should be installed in each cylinder of public transport.
9. CNG cylinders must be properly mounted and fastened in the commercial vehicles, such that in the case of accident the cylinders are not detached from the fastening. Detaching of the CNG cylinder may cause leakage of gas, breaking of pipes/fitting and injury to the passengers.
10. The mounting brackets used for cylinder mounting must be securely fastened to the vehicle at a location that provides sufficient strength to retain the cylinder in the event of collision. Brackets must meet the minimum specification defined in the at least updates of the following standards:

    a. ANSI/NFPA 52 vehicular fuel systems code
    b. ISO 15501-2 Road vehicles—CNG fuel systems—part 1: safety requirements
    c. CGA B149.4 M1991 NGV installation code
    d. FMVSS 304 CNG fuel container integrity
    e. CSA B109 natural gas for vehicles installation code
    f. ANSI/AGA NGV3.1/CGA 12.3, fuel system components for natural gas powered vehicles

11. To protect the cylinder from external collision, no portion of the CNG cylinder or cylinder accessory should be located ahead of the front axle or behind the point of attachment of the rear bumper to the vehicle.
12. To avoid external collision, each CNG cylinder of the vehicle should be mounted in a location that would minimize damage from a collision.
13. To prevent slippage of the cylinder during accident, the bracket holding CNG cylinder should be designed strong enough to withstand road accidents.
14. Strict regulations should be enforced for the cylinder removal after their useful life and the cylinders removed at end of life should be destroyed using proven methods.
15. CNG cylinder must be periodically inspected after every 2 years or 40000 km whichever comes first so that tanks affected by corrosion or abrasion can be removed from service.
16. Periodic cylinder inspection should be conducted through a qualified pressure vessel inspector who

Fig. 11 Pictorial view of accidents mentioned in Table 4 involving cylinder explosion during refueling at CNG station (**a**) accident at S. No. 54 (**b**) accident at S. No. 52 (**c**) accident at S. No. 02 (**d**) accident at S. No. 39 (**e**) accident at S. No. 04 (**f**) accident at S. No. 06

may analyze cylinder fitness for further use with the help of visual and ultrasonic inspection tools without hydrostatic testing.

17. To avoid corrosion of the cylinder, proper painting of the cylinder should be ensured.
18. In case any CNG station is found dispensing CNG at excess pressure, it may be reported to Oil and Gas Regularity Authority (OGRA) for strict action against the station to ensure public safety.

8.2 To avoid fire explosion

1. Only approved (imported) high-pressure piping/fitting must be used in the CNG vehicle; because the breaking and dislodging of high-pressure pipe and fitting are the main causes of fire in CNG vehicle after the accident.
2. Corrosion-resistant fuel lines (generally stainless steel) must be mounted, braced, and supported to minimize vibration and protected against damage, corrosion, or breakage due to strain or wear. No use of cast iron, plastic, galvanized pipe, aluminum or copper. Fueling connection must be ANSI listed. [Ref. NFPA-52 Sects. 4.8 and 4.10].
3. To prevent the gas leakages inside the passenger cabin of the vehicle, the high-pressure pipe should not pass from the passenger cabin in any public service vehicle. The pipe routing should either pass over roof or beneath the vehicle.

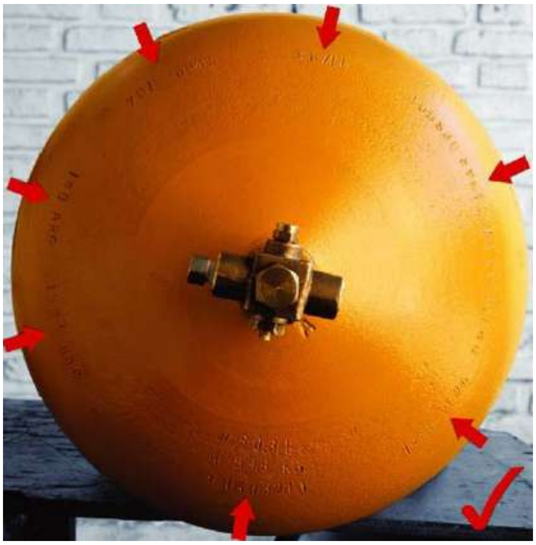

Fig. 12 Type-I CNG cylinder marking standard number

Fig. 13 Cylinder remained safe due to successful activation of PRDs

4. To prevent the gas leakages from high-pressure fittings of CNG fueling system, pipework must be properly installed on fixed part of the vehicle's body, preferably chassis. Care should be taken that there are no friction points which can damage the pipe due to intrinsic vibration of the vehicle. The intervals between two attachment points should not exceed 0.6 m.
5. Corrugated pipe should be used to protect high-pressure pipe from mechanical damage. Plastic fitting should be provided on holes made on the vehicle body so that the high-pressure piping remains stable. It will protect the pipe from vibration and metal to metal contact with body of the vehicle.
6. Suitable number of loops must be given whenever there is a change in direction of high-pressure pipe and only one loop is enough if the pipe maintains one direction. These spiral loops will protect the pipe from vibrations and pressure shocks due to sudden change in gas velocity during accidents, which can result in damage and dislodging of the pipe from fitting.
7. A manual shutoff valve should be provided in the high-pressure line in the vehicle where multiple CNG cylinders are used.
8. To avoid gas leakages through valve, only approved CNG cylinder valves must be used.
9. A Non-Return Valve (NRV) must be installed between cylinder and the filling valve. It will prevent leakage of gas due to malfunctioning of filling valve.
10. Dust plug should also be provided on the filling valve. Dust can damage the piston of the filling valve resulting in leakage of gas.
11. To prevent the gas flow towards engine (hot engine may provide an ignition source), a valve that automatically prevents the flow of CNG to the engine when the engine is not running, even if the ignition is switched on must be provided.
12. Gas solenoid valve should be installed on the three-way cylinder valve to stop leakage of gas from high-pressure line which is going to the CNG pressure regulator, in case of accident. It will also depressurize the CNG kit when the vehicle is switched off.
13. It is also recommended to integrate the gas solenoid valve with the accelerometer as it will work as an impact sensor. The gas solenoid valve will stop the flow of gas once accelerometer detects a collision. The accelerometers are widely used in automotive industry in the air bag protection systems.
14. Cylinder's valves should be protected from physical damage using the vehicle structure, valve protectors, or a suitable metal shield.
15. To avoid gas accumulation inside the passenger cabin, cylinder valve should be installed with air-tight cover and vented out of NGV.

8.3 General guidelines

1. Only approved CNG conversion kits must be installed in the vehicle.

2. A condition-based monitoring system should monitor the condition of key equipment in the CNG fuel system with the objective of taking any needed maintenance actions prior to the failure of the equipment.
3. The CNG fuel system should be monitored for pressure changes that would indicate a leak.
4. The CNG isolation valves should be periodically operated to verify their ability to change states. The PRDs should be tested periodically to verify their ability to open, and the PRD vent lines should be inspected for obstructions and for verification that they discharge to the exterior of the vehicle (away from ignition sources).
5. CNG vehicle fleet operators, service providers (e.g., gas cylinder inspectors), accident investigators, public transport facility operators, regulatory agencies and the emergency services should be given adequate training on CNG systems—technical and safety characteristics.
6. To counter the any accidental fire inside the passenger cabin, self-activating fire extinguisher system should be installed in the public transport at proper position.
7. Proper/adequate tools must be used for the installation of CNG system. Most of the CNG kit conversion facility do not even have torque wrench which is required for the installation of cylinder valve and mechanical safeties. Overtorquing of cylinder valve can damage the threads of CNG cylinders in the long run besides producing unwanted localized stress; it can also make mechanical safeties ineffective.
8. To avoid short circuiting, the electrical wiring/connection of the vehicle should be of standard quality and must be properly installed.
9. In presence of PRDs with proper functioning there is very little chance of CNG cylinder explosion. Figure 13 illustrates the accident mentioned at serial no. 23 of Table 2. In this accident although the CNG cylinders remained inside the burning vehicle for an hour but none of the cylinder exploded in the accident.
10. Uncertified vehicles shall not be given fitness certificate/route permits by relevant transport authorities.
11. Uncertified vehicles shall not be allowed to be filled by CNG Stations.
12. Public awareness campaign about safety aspects associated with usage of CNG must be launched through electronic and print media.
13. For public transportation at least, it should be made compulsory for the drivers to go through training and some sort of road education, before they are given a permit to drive buses, vans, etc. The licenses issued to the drivers of public transport, should be different than the ones issued to private vehicle owners. Traffic police of each province, should be asked to check the licenses on a regular basis and also, the license should be made in such a way that it is hard to duplicate or fake.
14. There have been lots of verbal complaints by the CNG filling station's operators that some third parties inspection companies have engineer with lack of expertise in the field CNG technology. To avoid such inspectors, there must be strict criteria to become a third-party inspection engineer for CNG technology. There was also widespread corruption (esp. bribery) in inspections of CNG stations; this trend must not be transferred to the inspection of CNG vehicles. Corruption in CNG sector must be checked.
15. Going through standard training program regarding the safety issue of NGVs should be included in the mandatory requirement for availing CNG vehicle driving license.
16. For proper preventive maintenance of CNG fuel system, a comprehensive annul CNG vehicle inspection form should be developed by concern government authority.
17. To check the fitness of CNG vehicles, identification marking sticker system must be promulgated by the concerned regularity authority. After duly checking the vehicle, a sticker having alphanumeric/data matrix codes should be pasted on the wind screen of the vehicle (valid for 1 year for private vehicle and for 6 months for public transport). In this way the details of the vehicles may be verified by sending the code (on the sticker) through SMS.
18. To avoid utilization of unapproved cylinders, damaged, expired and non-approved cylinders shall be seized by concerned authority.
19. CNG public transport should have genuine third-party/passenger insurance.
20. Necessary amendments should be made in the law to plug loopholes and to empower the traffic police and law enforcement agencies to crack down on unsafe practices.

9 Conclusion

1. In any fuel, including those used in motor vehicles, can be dangerous if handled improperly. Fuels contain energy, which is released when the fuel is ignited. Gasoline is a potentially dangerous fuel, but by understanding how to handle it, we have learned to use it safely. The same is true of natural gas. As with all vehicle fuels, natural gas can be used safely if the unique properties of the fuel are understood and follow the safety regulation.
2. CNG vehicle safety is strongly dependent on design, materials, installation, operating conditions and maintenance, not just the cylinder or other components in isolation.

3. Due to low-quality CNG system material, e.g., CNG cylinder, CNG design and installation, maintenance system, etc., and lack of strict government CNG vehicle safety regulations, every year several CNG vehicles accidents took place in Pakistan.
4. Over the past 5 years nearly 55 road accidents involving NGVs taken place in Pakistan, which caused over 250 casualties.
5. The main reason of CNG accidents occurred in Pakistan is due to lack of awareness about rules and regulation and driver negligence.
6. The main reasons of CNG cylinders explosion in Pakistan are usage of unapproved cylinders, welded cylinders and cylinders that are not manufactured for CNG use, e.g., oxygen cylinder, acetylene cylinder.
7. Currently the adoption of composite cylinder technology in Pakistan is in introductory phase and almost the entire cap of CNG cylinder being utilized in Pakistan is of Type-I cylinder usually imported from India and Italy. However, for the past 2 years, Pakistan CNG industry has witnessed the need for adopting well-proven technologies such as composite cylinders (Type-IV) which is prevailing in other countries.
8. CNG majorly comprises of methane which has global warming potential 23 times higher than CO_2. Hence, in the event of a CNG vehicle accident, the release of natural gas will also contribute to global warming.
9. Pakistan CNG safety rules 1992 do not cover all the required safety measures to prevent CNG vehicle accidents. These rules must be updated in light of prevailing international standards such as FMVSS 303 & 304, ECE R-110, ISO 11439 and NFPA 52.

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Annexure-E

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Research progress in the development of natural gas as fuel for road vehicles: A bibliographic review (1991–2016)

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ABSTRACT

Among all alternative fuels, compressed natural gas (CNG) has been considered as one the best solutions for fossil fuel substitution because of its availability throughout the world, inherent clean burning, economical as a fuel and adaptability to the gasoline and diesel engines.

This bibliography reviews the potential of CNG as a transportation fuel. The added bibliography at the end of this article contains 1102 references to papers, conference proceedings and theses/dissertations on the subject that were published between 1991 and 2016. These references have been retrieved from 137 scientific journals. The references are classified in the following categories: Regional Experience with CNG Vehicles; Economic Aspect of CNG Vehicles; CNG Engine's Design, Control and Performance; Combustion and Fuel Injection Characteristics of CNG Engines; CNG/ Diesel Dual Fuel Operations; Hydrogen Enriched CNG Vehicles; Environmental Aspect of CNG Vehicles; Safety Aspect of CNG Vehicles.

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1. Introduction

The yield of scientific articles is generally rising fast and professionals are no longer able to be fully abreast with all pertinent information. The rising specialization in various scientific arenas has triggered the dissemination of subject-oriented journals and conference proceedings focused to specialist audiences. The scholars have now more options for sharing the results of their scientific work, but on the other hand exploring the relevant information may be a laborious and time-consuming process. Moreover, sometimes the researchers are not willing to devote time to exploring the relevant information. It has been pointed out that in the field of engineering, informal knowledge channels are most frequently used for getting information [1].

With increasing government restriction of tailpipe emissions from vehicles powered by internal combustion engines and growing concern over the use and exhaustion of fossil fuel, alternative fuels has gained popularity [2,3]. Natural gas has a widely used alternative fuel for a variety of reasons including ready availability and its low cost and low emissions potential relative to conventional fuel and its applicability in convention diesel and gasoline engines [4]. Natural gas is scattered in many regions of the world so that it can stable supply. Therefore natural gas has been subjected widely as a kind of clean alternative fuel for engines [5–7].

The bibliography provided at Annexure-B contains 1102 references to journal's papers, conference proceedings and theses/dissertations on the subject that were published between 1991 and 2016. These references have been retrieved from 137 scientific journals listed at Annexure-A.

The bibliography is divided into the following parts and concerns:

- Regional Experience with CNG Vehicles
- Economic Aspect of CNG Vehicles
- CNG Engine's Design, Control and Performance
- Combustion and Fuel Injection Characteristics of CNG Engines
- CNG/ Diesel Dual Fuel Operations
- Hydrogen Enriched CNG Vehicles
- Environmental Aspect of CNG Vehicles
- Safety Aspect of CNG Vehicles

It is difficult for the authors to recap the wide topics of this article in a form of the state-of-the-art review article; therefore a bibliography is presented here. Hope, this bibliography will save time for researchers looking for information pertinent with the subjects listed below, not having access to large databases or not willing to spend time on uncertain information retrieval.

2. Regional experience with CNG vehicles

The word is turning towards substitute to gasoline and petroleum-based energy that is taking an upward trend in terms of price. Across the globe, various countries have experienced that CNG is good for the consumer and friendly to the environment while pushing the country into more independent state [8]. An increasing number of countries across the globe are jumping on the bandwagon to make use of CNG, due to its various benefits.

This section of the bibliography covered the case studies of various countries and cities regarding their experience for using the CNG as a transportation fuel. The case studies of the countries and cities listed: UK, USA, Pakistan, China, Japan, Germany, Argentina, Switzerland, Brazil, Qatar, Korea, Indonesia, Malaysia, Sweden, Algeria, Nigeria, Ireland, Milan, Tokyo (Japan), Dhaka (Bangladesh), Delhi (India), Santiago (Chile), Madrid (Spain), Beijing (China), New York (USA), Brussels (Belgium), São Paulo (Brazil), Salvador (Brazil), Rio de Janeiro (Brazil).

3. Economic aspect of CNG vehicles

One of the major advantages of CNG is that it offers a cheap source of energy. As the world continues to run with expensive fuels such as and gasoline and diesel, the low-cost CNG offers a glimmer of hope. Although emission reduction using natural gas was the main focus of CNG application as a transportation fuel, especially in metropolitan regions, in recent days, with a sharp rise in oil prices, the increasingly considerable cost benefit of using natural gas has become a real major consideration for many new users. In most countries, natural gas is much cheaper than per equivalent gallon of diesel and gasoline, even after accounting for the costs linked with compression and even considering its lower thermal efficiency against diesel and gasoline, there are significant economic benefits of using CNG as a transportation fuel. Gasoline and diesel must be passed through the complex refining process, while natural gas needs very less processing from field to the vehicle engine. It is also less prone to price fluctuations and as compared to its resources are more evenly distributed around the world.

One of the important factors for comparing the economic aspect of automotive technology is the associated maintenance cost. Although a review of the literature found no previous empirical work that has examined the issue of maintenance cost competitiveness of latest NGV or diesel technologies based on total lifecycle costs. However, there are few studies which examined the operating cost associated with natural gas vehicles. Based on limited studies and research on comparative operating costs, evidence supports both cost increases, cost decreases costs are equivalent [9–14].

However the association of high cost with the development of refueling infrastructure (pipelines and filling stations for CNG vehicles) remains the most significant barrier to the adaptation of CNG as an alternative fuel but with sufficient visibility on demand, supportive economics, and government incentives these barriers appear surmountable. Nearly all of the countries where CNG infrastructure has been developed; incentive programs offered to investors such as loans, subsidies, exemptions from import duties and the lowering or elimination of import tariffs on machinery, equipment, and kits (price-supplier); and exemption from sales taxes for the construction and operation of refueling stations. Once subsidies for fueling stations and NGV customers run out, the expected profitability of new CNG filling facilities is no longer attractive enough. In e.g. Canada, reducing investments in fueling stations caused the collapse of the whole NGV sector [15]. Costs of installing CNG infrastructure can vary significant depending on size, capacity and the way natural gas is dispensed (fast-fill, time-fill). Consequently, costs can vary widely from project to project and country to country. As the land is a significant component in building a CNG station so the cost depends on the decision to build the station on a new site, or incorporate CNG fueling at an existing site such as an existing diesel fuel station. Worldwide the average costs identified in various studies to construct a CNG station ranged between $600,000 and $1,000,000 per station excluding land cost. In Pakistan the country having the highest number of CNG station after China, the average cost of constructing a CNG station is comparatively much low and amounting to 150,000 US $. Table 1 provides estimates of total costs to construct a CNG station in Pakistan.

In addition to short-term economics, there are several socio-economic aspects associated with the development of natural gas as vehicular fuel. One of the significant impacts of the NGVs will be

Table 1
The estimated cost of standard size CNG refueling station in Pakistan in 2012.

Items	Cost (US $)
Building - civil works	1,783,217
Compressor	5,354,895
Cooling Plant	1,148,601
Dryers and filters	358,741
Dispensers	463,951
Pressure meters	243,357
Storage cylinders	581,119
Gas Security	1,888,112
Preliminary Expenses	800,000
Total Labor Cost	2,708,678
Miscellaneous Materials	469,406
Total	**15,000,077**

the opportunities for local businesses. These opportunities include new construction jobs associated with building new stations and supply infrastructure; employment associated with retrofits of existing engines and jobs related to manufacturing or supplying parts and equipment needed to expand the industry. In Pakistan, the 2nd largest user of CNG, the NGVs sector of the country has attracted more than one billion US $ investment have created more than 121,000 cumulative (direct and indirect) job opportunities [8]. Moreover, as the prices of natural gas compared to gasoline or diesel fuel is significantly less and stable in most of NGVs user countries so it enhances the buying capacity of customers.

The most observable social advantage associated with operating vehicles with CNG pertains to the environmental advantage of natural gas. As previously discussed in Section 8, compared to oil, natural gas releases lower levels of carbon dioxide, sulfur, nitrogen oxides, and ash. By emitting fewer harmful chemicals into the air, natural gas can help alleviate different environmental problems. Compared to oil, natural gas releases lower levels of carbon dioxide, sulfur, nitrogen oxides, and ash. By emitting fewer harmful chemicals into the air, natural gas can help alleviate different environmental problems. Secondly, since natural gas combustion produces a lower level of nitrogen oxides and particulate matter, it will contribute significantly less to smog formation and acid rain, preventing damages to crops, wildlife, and humans' respiratory systems.

Topics handled in this section: comparative economics of CNG; cost-effectiveness evaluation of diesel vs. CNG for buses; commercializing CNG as a fuel; potential of CNG transport; policy development for marketing CNG; CNG vehicles energy consumption life-cycle analyses; empirical analysis on the adoption of CNG; global opportunities for CNG as a transportation fuel; fuel consumption of CNG vehicles.

4. CNG engine's design, control, and performance

The octane number of natural gas is ranging from 120 to 130. Due to this high value of octane number, CNG has a higher knock resistance than gasoline which enables the use of higher compression ratio and thus higher engine efficiency. The performance of CNG-fueled engine highly depended on the engine design and type i.e. mono-fuel, bi-fuel or dual fuel. However, the major performance draws back with natural gas vehicles is the 15–20% loss in brake horsepower of the engine. The major attributes for this power losses low flame propagation and lost in volumetric efficiency. Due to the low densities, gaseous fuels occupy 4–15 of intake passage volume resulting in significant reduction of volumetric efficiency when compared to liquid fuels. With its low volumetric efficiency, power loss in CNG is 10% when compared to gasoline.

Topics included: effects of natural gas compositions on the performance of CNG engine; comparative experimental performance evaluation of CNG engines; assessment and effect of compression ratio on performance; evaluation of CNG engines under lean burn conditions; performance of turbocharged CNG SI engines; performance of a partially stratified charge CNG engines; development of electronic control unit for dual-fuel Engines; optimization of control parameters for CNG engines; fuel management system for CNG vehicles; A/F ratio calculation for a SI CNG engines; fluid-dynamic and numerical simulation of CNG injection system; advances in waste heat recovery systems for CNG engines; integrated powertrain control for NGVs; oxidation catalysts for NGVs.

5. Combustion and fuel injection characteristics of CNG engines

The natural gas used in natural gas vehicles is the same natural gas that is used in domestic sector for cooking and heats. CNG is produced by compressing the conventional natural gas (which is mainly composed of methane –CH4) to less than 1% of the volume it occupies at standard atmospheric pressure. It is stored and distributed in a rigid container at a pressure of 200–248 bar (2900–3600 psi), usually in cylindrical shapes metallic cylinder. Table 2 represents the comparison between the physiochemical properties of CNG to that of diesel and gasoline.

The combustion properties of natural gas are significantly different from regular fuel i.e. diesel and gasoline. Natural gas can burn cleaner than gasoline. This is due main to more favorable thermodynamic properties of the mixture, lowered peak cylinder temperatures reducing engine heat losses and reduced pumping losses through reduced throttling. As compared to diesel and gasoline, CNG has a longer ignition delay time due to low flame propagation speed. CNG has lower flame propagation speed as compared to conventional liquid fuels, such as gasoline and diesel [16]. This lower flame propagation speed reduces the engine brake horsepower by 5–10%.

The following topics are handled: combustion concepts for mono-fuel, bi-fuel and dual fuel operation of natural gas in IC engines; Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), Reactivity Controlled Compression Ignition (RCCI); numerical simulation of CNG combustion; Effect of EGR on CNG combustion; kinetic models of CNG combustion; the influence of fuel composition on the combustion; Different injection strategies; Sequential Port Injection, direct injection with homogeneous mixture, direct injection with stratified mixture, partially-stratified natural gas injection; electronically

Table 2
Physiochemical properties of CNG vs Gasoline & Diesel.

Properties	CNG	Gasoline	Diesel
Octane/Cetane number	120–130	85–95	45–55
Molar mass (kg/mol)	17.3	109	204
Stoichemetric $(A/F)_s$ mass	17.2	14.7	14.6
Stoichemetric mixture density (kg/m^3)	1.25	1.42	1.46
L.H.V. (MJ/kg)	47.5	43.5	42.7
L.H.V. of stoichemetric mixture (MJ/kg)	2.62	2.85	2.75
Combustion Energy (MJ/m3)	24.6	42.7	36
Flammability limit in air (vol% in air)	4.3–15.2	1.4–7.6	1–6
Flame propagation speed (m/sec)	0.41	0.5	–
Adiabatic Flame Temp. °C	1890	2150	2054
Auto-ignition Temp. °C	540	258	316
Wobbe Index (MJ/m^3)	51–58	–	–

controlled gas injection system; spark ignited direct injection (SIDI); spark plug fuel injector (SPFI) System;.

6. CNG/diesel dual fuel operations

Diesel engines were traditionally preferred due to its lower running cost and better torque characteristics; however, during the past decade, stringent emissions norms have mandated the use of several advanced combustion and after-treatment technologies, which in turn have made the diesel engine power train expensive and complex. In recent years, a concern over the emissions of a greenhouse gas like CO2 and particulate matter PM has further posed an additional challenge to the development of diesel engines. One way to overcome these problems is by employing dual fuel technology in which part of diesel fuel is supplemented by natural gas which is fumigated in the intake manifold.

Existing diesel engines may be converted readily to operate primarily on CNG, using diesel as a spark plug to achieve ignition. Due to the high ignition temperature of natural gas, it needs very high compression ratio for auto ignition i.e. about 38:1. Owing to this, it should be ignited with another fuel (diesel)—pilot injection. The substitution rates vary depending on the engine load. A maximum substitution rate up to 90% can be obtained with the currently available dual-fuel engines. Substitution rate affects both engine performance and emission. When required the system allows the engine to run on 100% diesel. The use of diesel fuel allows the retention of the diesel compression ratio and its efficiency while the natural gas contributes to fuel economy and is responsible for lowering emissions. The peak combustion temperature reduces which reduces NOx emission. Drastic reduction in PM emission has been observed when the engine operates under dual fuel mode.

Topic handled in this section: performance of a diesel/CNG dual-fuel engine; effect of engine parameters on the performance of dual-fuel engines; performance characteristics of a turbocharged dual fuel engines; combustion simulation of dual fuel engines; knock characteristics of dual-fuel combustion; NOx reduction from a dual-fuel engines; numerical study of the pollution formation in dual-fuel engine; after treatment system for dual-fuel operation; emission characteristic of dual-fuel engine; effects of natural gas percentage on performance of dual-fuel engine.

7. Hydrogen enriched CNG vehicles

As discussed 5–10% power loss occurs in CNG-fueled engines due to the low flame propagation speed of natural gas. One effective method to address the problem of slow flame propagation speed of the natural gas is to mix the CNG with the fuel having fast burning speed e.g. hydrogen. Hydrogen (H_2) is considered as the best additive for CNG due to its fast flame propagation speed (265–325 cm/s), much better lean-burn ability and small quenching distance. This gives the potentiality to develop engines with better performance and lower environmental impact [17]. As hydrogen is a carbon-free fuel, the reduction in CO_2 emissions is a direct function of H_2 content in the blend.

Topic listed in this section: kinetic modeling HCNG engine; combustion analysis of SI HCNG engine; CO_2 emissions from HCNG engine; numerical evaluation of HCNG engine performance; emission characteristics of HCNG engine; effect of H_2 addition to duel-fuel engine; effect of H_2 addition on CNG HCCI combustion, effect of compression ratio on HCNG engine performance; life cycle greenhouse emissions from HCNG engine.

8. Environmental aspect of CNG vehicles

Exhaust gas emissions from transportation industries have become one of the most prominent environment and social-economic issue. The industry is moving toward alternative fuel due to several reasons including climate change from an increase of greenhouse gas emissions, the increase of health problems in polluted cities and the political and social instability related to oil supply and price. CNG is identified as a leading candidate for the green transportation fuel among other alternative fuels. The main constituent of CNG is methane, the simplest alkane with only one carbon atom and consequently no carbon-to-carbon bonds. The simple chemical structure of methane makes it an inherently clean burning fuel. When used as motor fuels, this results in low particulate (PM) emissions and low toxicity of the exhaust gasses. However, the nitrogen oxides (NOx) emissions of an engine are first and foremost determined by the combustion scheme and possible exhaust gas after- treatment. Tables 3,4 summarizes the major worldwide experiential studies conducted to evaluate the comparative emission performance of NGVs.

Topics handled in this section: experimental comparative emission analysis of CNG in bi-fuel engines, impact of CNG on air quality; comparative life-cycle emissions analysis of CNG; regulated and unregulated exhaust emissions from CNG vehicles; physical properties of the particle emissions from a CNG vehicles; evaluating carbon emissions reduction by use of CNG; on-road measurement of regulated pollutants from diesel and CNG vehicles; real-time NOx measurements from CNG and diesel transit buses; Influence of CNG compositions on the regulated emissions; well-to-wheels of CNG fuel; environmental benefits of CNG buses; comparative ultrafine particle emissions from diesel and CNG buses.

Tables 3,4 summarize the major worldwide experiential studies conducted to evaluate the comparative emission performance of NGVs.

9. Safety aspect of CNG vehicles

Safety of CNG vehicle is a very important aspect. In terms of handling, CNG is much safer than gasoline in many respects [43]. The physical properties of natural gas offer some safety advantages over gasoline and diesel fuel. For example, at the atmospheric condition, the natural gas has an auto-ignition temperature of 540 °C in contrast to 258 °C and 316 °C for gasoline and diesel respectively. This high auto-ignition temperature of natural gas hinders the possibility of ignition in an open environment. Similarly as compared to diesel/gasoline natural has a narrow flammability range i.e. 4.3–15.2% by volume in air, which lowers the chance of accidental fire of the fuel. Moreover due to gaseous fuel and being lighter than air, CNG will dissipate into the air rapidly, whereas diesel and gasoline will pool on the ground, increasing the risk of fire. Natural gas is also non-toxic and will not contaminate groundwater if leaked.

Topics included in this section: safety issues associated with the CNG vehicles; risk assessment of CNG buses; CNG cylinders failure causes; safety features implementation in CNG vehicles; modeling of CNG vehicles refueling; FEA analysis of CNG cylinders; risk analysis of CNG cylinders; health monitoring of CNG cylinders; gas leakage analysis around CNG buses; behavior of a CNG tank during fire.

9.1. Concluding remarks and future directions

The available literature shows that CNG has seen some significant success in terms of adoption as a transport fuel in various

Table 3
Emission summary of major worldwide experiential studies.

S.N.	Study	Study Year	Test Method	Vehicle			Fuel	Emission Factor (g/km)			
				Type	Disp. (cc)	After treatment		CO2	CO	NOx	NMHC
1	Kelly et al.[18]	1996	Real world operation, Washington DC, USA	Ded, CNG Van	–	–	CNG	352	2.35	0.34	0.11
				Gasoline Van	–	–	Gasoline	416	3.64	0.49	0.18
2	Heidinger et al. [19]	1996	Real world operation, Vienna, Austria	Bi-Fuel Car	1968	TWC	CNG	–	1.79	0.26	1.4
							Gasoline	–	2.41	0.41	0.31
3	Coroller et al [20]	1998	CBD Cycle, Paris	3 CNG bus	9500	Nil	CNG	–	6	12.2	6.23
				4 Diesel Bus	9800	Nil	Diesel	–	2.85	25.1	1.2
4	Clark et al.[21]	1999	Lab, USA	3 CNG Bus	6500	OC	CNG	–	1.9	5.4	–
				3 Diesel Bus	5900	OC	Diesel	–	1.5	13.2	–
5	Frailey et al.[22]	2000	CBD cycle, USA	3 CNG Bus	5880	–	CNG	–	0.4	8.9	–
				3 Diesel Bus	5880	–	Diesel	–	2.4	21	–
6	Chandler et al. [23]	2000	CBD cycle, Hartford	13 CNG bus	5900	OC	CNG	460	0.40	3.37	0.30
				3 Diesel Bus	5900	–	Diesel	495	1.61	6.65	0.31
7	Ayala et al.[24]	2002	CBD cycle, Los Angeles	3 CNG Bus	8500	Nil	CNG	–	6.84	11.81	7.40
				2 Diesel Bus	8500	Nil	Diesel	–	0.84	18.77	0.05
			NYBC	3 CNG Bus	8500	Nil	CNG	–	19.08	12.09	16.84
				2 Diesel Bus	8500	Nil	Diesel	–	4.47	31.70	0.13
8	NREL Emission Tests[25]	2002	CBD cycle Washington	5 CNG bus	8300	OC	CNG	–	0.187	8.46	4.53
				4 Diesel Bus	8500	OC	Diesel	–	1.7	18	3.2
9	Lanni et al.[26]	2003	CBD cycle, New York	3 CNG Bus	8500	–	CNG	1472	11.09	11.09	11.12
				2 Diesel Bus	8500	DPF	Diesel	1787	14.82	14.82	0.04
10	Pischinger et al. [27]	2003	Dynamometer, Germany	Bi-fuel car	1800	–	CNG	–	0.27	0.125	0.20
					1800	–	Gasoline	–	0.70	0.130	0.27
11	Ullman et al. [28]	2003	Dynamometer	1 CNG bus	–	Nil	CNG	–	7.7	26.1	15
				2 Diesel Bus	–	DPF	Diesel	–	2.8	22.7	0.6
12	Nylund et al. [29]	2004	OCTA, Finland	2 CNG Bus	–	OC	CNG	–	–	7	–
				1 Diesel Bus	–	OC	Diesel	–	–	8	–
13	Ristovski et al [30]	2004	Dynamometer, Australia	Bi-Fuel Car	4000	None	CNG	361	1.12	0.67	–
							Gasoline	561	28	0.94	–
14	Melendez et al. [31]	2005	CBD cycle Washington	7 CNG bus	8300	OC	CNG	1370	0.215	9.62	4.35
				5 Diesel Bus	8500	OC	Diesel	2034	0.174	12.8	2.92
15	Jayaratne et al. [32]	2009	Real world operation, Queensland, Australia	Ded, CNG Bus	–	TWC	CNG	671	–	12	–
				Diesel Bus	–	None	Diesel	834	–	10.5	–
16	Fontaras et al [33]	2012	Real world operation, Milan, Italy	Dual-Fuel Bus	9500	DOC	Diesel-CNG	2430	7.43	32.3	0.21
				Ded, CNG Bus	7790	TWC	CNG	3660	15.8	4.38	2.19
				Ded, CNG Bus	7790	–	CNG	2300	1.66	3.91	0.55
				Ded, CNG Bus	6900	–	CNG	3120	1.01	13.6	6.99
17	Hallquist[34]	2013	Road	7 CNG bus	–	Nil	CNG	–	< 3	21	< 4
				28 Diesel Bus	–	DPF	Diesel	–	4.33	6.66	< 4
18	Guo J et al.[35]	2014	Real world operation, Beijing, China	Euro-V, 4 Ded CNG Bus & 3 Diesel Bus	8400	OC, SCR	CNG	894	5.72	3.42	7.9
					8400	OC	Diesel	709	1.99	4.3	0.03
19	Arvind et al[36]	2015	UDDS Cycle, Los Angeles, USA	US-EPA 2010, Ded CNG Bus & Diesel Bus	8900	TWC	CNG	–	4.72	0.358	0.0186
					12,400	DPF	Diesel	–	2.82	3.42	0.0727
					12,800	DPF, SCR – 1	Diesel	–	0.134	1.230	0.0006
					12,800	DPF, SCR – 2	Diesel	–	0.0248	3.80	0.0093
					11,900	DPF, SCR – 3	Diesel	–	0.0311	5.83	0.0434
20	Aslam et al.[37]	2005	Dynamometer, Malaysia	Bi-Fuel Car	1468	TWC	CNG	8.4 (vol%)	1.2 (vol%)	2000 ppm	300 ppm
							Gasoline	12.8 (vol%)	9.2 (vol%)	875 ppm	1000 ppm
21	Geok et al.[38]	2009	Dynamometer, Malaysia	Bi-Fuel Car	1468	None	CNG	10.2 (vol%)	2 (vol%)	–	110 ppm
							Gasoline	12.8 (vol%)	3 (vol%)	–	380 ppm
22	Jahirul et al[39]	2010	Dynamometer, Malaysia	Bi-Fuel Car	1594	None	CNG	7.82 (vol%)	5.4 (vol%)	619 ppm	313 ppm
							Gasoline	11.68 (vol%)	10.5 (vol%)	442 ppm	419 ppm

countries around the world. Although worldwide, the environmental benefits of CNG vehicle technologies are well established, but according to the latest studies, putting together the short lifetime of methane and a high estimate for fugitive methane emissions can result in lifecycle emissions for CNG vehicles exceeding those of modern diesel engine technology equipped with exhaust emission filter. Until this issue is settled, the environmental benefits of natural gas vehicles are uncertain. Similarly, a hurdle facing the NGVs right now is the price of oil, which has halved in price in the last year. The questions the industry needs to confront are firstly, how long we will have relatively lower oil prices and what impact this will have on the development of NGVs. In the prevailing low oil prices, securing a return on investment is pivotal to the success of NGVs and at present, this may be a challenge. Governmental incentives, such as those offered in most of the countries may help.

Table 4
Particle mass emission factor (PMEF) from comparative studies of diesel and CNG buses.

S.N	Study	Study Year	Vehicles	Test Method	Fuel	After treatment	PMEF (g/km)
1	Wang et al.[40]	1997	Over 300 buses	CBD transient cycle	Diesel	–	20
					CNG	–	1
2	Coroller et al[20]	1998	4 Diesel & 3 CNG buses	CBD Cycle, Paris	Diesel	–	0.35
					CNG	–	0.04
3	Clark et al.[21]	1999	3 Diesel & 3 CNG buses	CBD transient cycle	Diesel	OC	0.24
					CNG	OC	0.025
4	Frailey M. et al.[22]	2000	3 Diesel & 3 CNG buses	CBD transient cycle	Diesel	–	0.38
					CNG	–	0.012
5	Chandler K. et al.[23]	2000	3 Diesel & 13 CNG buses	CBD cycle, Hartford	Diesel	–	0.02
					CNG	OC	0.01
6	Ahlvik P. et al.[41]	2000	Diesel & 3 CNG buses	CBD transient cycle	Diesel	None	0.16
					Diesel	OC	0.112
					Diesel	DPF	0.011
					CNG	None	0.017
					CNG	OC	0.012
7	NREL Emission Tests[25]	2002	4 Diesel & 5 CNG buses	CBD cycle Washington	Diesel	OC	0.62
					CNG	OC	0.093
8	Ayala et al.[24]	2002	2 Diesel & 3 CNG buses	CBD cycle, Los Angeles	Diesel	None	74.02
					CNG	None	22.81
				NYBC	Diesel	None	392.17
					CNG	None	60.35
9	Lanni T. et al.[26]	2003	2 Diesel & 3 CNG buses	CBD cycle, New York	Diesel	DPF	0.0267
					CNG	None	0.0197
10	Ullman TL. et al.[28]	2003	2 school buses	CHSVC transient cycle	Diesel	None	0.115
					Diesel	PT	0.006
					CNG	None	0.033
11	Nylund N. et al.[29]	2004	2 Diesel & 3 CNG buses	BSC & OCC transient cycle	Diesel	None	0.17
					Diesel	OC	0.12
					Diesel	PT	0.02
					CNG	None	0.02
					CNG	OC	0.01
12	Melendez M. et al.[31]	2005	5 Diesel & 7 CNG buses	CBD cycle Washington	Diesel	OC	0.0081
					CNG	OC	0.0054
13	Kado N. et al.[42]	2005	2 Diesel & 3 CNG buses	3 transient cycles	Diesel	OC	0.056–0.074
					Diesel	PT	0.002–0.010
					CNG	None	0.014–0.058
				1 steady state at 55 m/h @ 60% power	Diesel	OC	0.014
					Diesel	PT	0.002
					CNG	None	0.014
14	Jayaratne E. et al.[32]	2008	Diesel & dedicated CNG buses	CBD Cycle, Queensland, Australia	CNG	TWC	0.163
					Diesel	None	96.5
15	Gua J et al.[35]	2014	Euro V- 3 Diesel & 4 dedicated CNG buses	Real world operation, Beijing, China	CNG	OC, SCR	0.307
					Diesel	OC	1.09
16	Arvind et al[36]	2015	US-EPA 2010, Ded. CNG and Deisel Bus	UDDS Cylce, Los Angeles, USA	CNG	TWC	1.68
					Diesel	DPF	2.367
					Diesel	DPF, SCR – 1	6.03
					Diesel	DPF, SCR – 2	4.58

Acknowledgment

The bibliography presented is by no means complete but it gives various comprehensive aspects of Compressed Natural Gas (CNG) as a transportation fuel. The authors wish to apologize for the unintentional omissions of missing references.

Annexure-A. (Journal's List)

1. Advances in Mechanical Engineering
2. Alexandria Engineering Journal
3. Applied Mechanics and Materials
4. Applied Thermal Engineering
5. Applied Energy
6. Applied Acoustics
7. Atmospheric Environment
8. Australian Journal of Basic and Applied Sciences
9. Al-Khwarizmi Engineering Journal
10. American Journal of Engineering and Applied Sciences
11. Atmospheric Pollution Research
12. American Journal of environmental sciences
13. Atmospheric Chemistry and Physics
14. Aerosol Science and Technology
15. Applied Catalysis B: Environmental
16. Corporate Environmental Strategy
17. Chinese Journal of Catalysis
18. Catalysis Today
19. Chemistry and technology of fuels and oils
20. Control Engineering Practice
21. Computers & Fluids
22. Ecological Economics
23. Energy Policy
24. Engineering Failure Analysis
25. Environmental Monitoring and Assessment
26. Environmental Toxicology and Pharmacology
27. Energy Systems
28. Energy for Sustainable Development
29. Energy conversion and Management
30. Energy Sources
31. European Journal of Scientific Research
32. Environmental Development

33. Environmental Progress & Sustainable Energy
34. Environmental Science & Policy
35. Energy
36. Energy & fuels
37. Energy Sources, Part A: Recovery, Utilization & Environmental Effects
38. Environment and Behavior.
39. Frontiers of Energy and Power Engineering in China
40. Fuel
41. IOSR Journal of Engineering
42. International Journal of Hydrogen Energy
43. Indian Journal of Science and Technology
44. International Journal of Emerging Technology & Advanced Engineering
45. Iranian Journal of Chemistry & Chemical Engineering
46. International Journal of Environmental Research
47. International Journal of Ambient Energy
48. International Journal of Crashworthiness
49. International Journal of Automotive and Mechanical Engineering
50. International Journal of automotive technology
51. Iranian Journal of Environmental Health Science & Engineering
52. International Journal of Engine Research
53. International Journal of environmental studies
54. International Journal of green energy
55. International Journal of Engineering, Transactions B: Applications
56. International Journal of Power & Energy Systems
57. International Journal of Engineering
58. International Journal of Vehicle Design
59. International Journal of Control and Automation
60. Journal of Luoyang Institute of Technology
61. Journal of KONES Powertrain and Transport
62. Journal of Energy & Environment
63. Journal of Visualization
64. Journal of Energy
65. Journal of the Energy Institute
66. Journal of Natural Gas Chemistry
67. Journal of Exposure Science & Environmental Epidemiology
68. Journal of hazardous materials
69. Journal of Cleaner Production
70. Journal of Energy Chemistry
71. Journal of Industrial Research
72. JSAE Review
73. Journal of University of Shanghai for Science &Technology
74. Journal of Power Sources,
75. Journal of engineering for gas turbines and power
76. Journal of the Brazilian Society of Mechanical Sciences & Engineering
77. Journal of Natural Gas Science and Engineering
78. Journal of Loss Prevention in the Process Industries
79. Journal of Chemical Engineering
80. Sichuan University of Science and Technology
81. Scientia Iranica
82. Journal of Combustion Science and Technology
83. Journal of Scientific and Industrial Research
84. Journal-Tsinghua University
85. Journal of dynamic systems, measurement, and control
86. Journal of mechanical science and technology
87. Journal of Aerosol Science
88. Journal of the Transportation Research Board
89. Journal of Transport Economics and policy
90. Journal of Energy Resources Technology
91. Journal of Highway and Transportation Research and Development
92. Journal of the Korean Institute of Gas
93. Journal of Combustion
94. Mathematical and Computer Modeling
95. Mathematics and Computers in Simulation
96. Mechanical Engineering
97. Microporous and Mesoporous Materials
98. Natural Gas Industry
99. Numerical Heat Transfer – Part A
100. Lubrication Science
101. Oil & gas science and technology
102. Proceedings of the IMechE, Part O: Journal of Risk and Reliability
103. Proceedings of the IMechE, Part D: Journal of Automobile Engineering
104. Proceedings of the Combustion Institute
105. Progress in Energy and Combustion Science
106. Progress in Solid State Chemistry
107. Pakistan Journal of Engineering & Applied Sciences
108. Polish Journal of Chemical Technology
109. Polish Journal of Environmental Studies
110. Power Engineering
111. Resource and Energy Economics
112. Risk Analysis
113. Renewable and Sustainable Energy Reviews
114. Reinforced Plastics
115. Renewable Energy
116. SAE International Journal of Fuels and Lubricants
117. SAE International Journal of Engines
118. SAE International Journal of Alternative Powertrains
119. Separation and Purification Technology
120. Studies on Russian Economic Development
121. Sustainability: Science, Practice, and Policy
122. Science China Technological Sciences
123. Science of the Total Environment
124. Safety Science
125. Thermal Science
126. The Review of Economics and Statistics
127. Transaction of ASME, Journal Engine & Gas Turbines Power
128. Transportation Research Part A: Policy and Practice
129. Transportation Research Part D: Transport and Environment
130. The Journal of Defense Modeling & Simulation: Applications, Methodology, Technology
131. Transactions of CSICE
132. Transactions of the Chinese Society of Agricultural Machinery
133. Transactions of the Korean Society of Mechanical Engineers B
134. Transport
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136. The Annals of Regional Science
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Annexure-F

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Falling oil prices: Causes, consequences and policy implications

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ABSTRACT

Following four years of high stable prices at about 107 $ per barrel, crude oil prices have fallen sharply since summer 2014 and are projected to stay at low level for an extended period. There are multiple factors which are being considered behind this plunge in the oil's prices. Most observers have conjectured that domestic oil boom in the United States and Iraq is the major cause for the falling oil prices. Some have suggested that a major shock to oil price expectations occurred after the November 2014 meeting of OPEC, when they did not cut production despite the steady increase in non-OPEC oil production.

In the first part of the publication, we quantitatively analyzed the effect of various factors on the oil prices and then we studied the contribution of geopolitical strategies of US and Saudi Arabia towards this oil crash. We conduct comparatively analysis of the recent drop in oil prices with previous incidents up to 1996. We than show that the demand and supply formula cannot be implemented to the current oil plunge.

We studied the economic and financial consequences of the current oil bust. Lastly the paper discusses the projections of oil prices.

1. Introduction

Global oil prices have fallen sharply over the past two years, resulting in one of the most dramatic declines in the price of oil in recent history. The collapse of oil prices from around $114 in June 2014 to $46 in January 2015, has led to a large body of literature analyzing the causes of this steep oil price drop and its macro-economic implications. However, most of this literature is mainly written by international organizations (see, for instance, the IMF blog by Rabah and Oliver (2014), investment banks (such as Goldman Sachs Global Investment Research division's report on "The New Oil Order" (Damie et al., 2015)), various (energy) economists, and of course mostly internal reports by oil and gas companies. Most of written work is speculative and some of it downright conspiratorial. There are yet only a handful of papers, which apply rigorous and quantitative analysis of the recent oil price shock. Most notably, Christiane and Lutz (2015) argue that demand factors were most important in explaining the behavior of oil prices, while the Studies (Baes et al., 2015; Aasim et al., 2015; Mănescu and Nuño, 2015) argue that supply (rather than demand) factors played the largest role. Christiane and Lutz (2015) used the reduced-form representation of the structural oil market model developed in Kilian and Murphy (2014) and argued that, out of a $49 fall in the Brent oil price, $11 of this decline was due to adverse demand shocks in the first half of 2014, $16 to (positive) oil supply shocks that occurred prior to July 2014, while the remaining part was due to a “shock to oil price expectations in July 2014 that lowered the demand for oil inventories and a shock to the demand for oil associated with an unexpectedly weakening economy in December 2014, which lowered the price of oil by an additional $9 and $13, respectively”. Fantazzini (2016) suggested that there was a negative bubble in oil prices in 2014/15, which decreased them beyond the level justified by economic fundamentals. A negative financial bubble is a situation where the increasing pessimism fuelled by short positions lead investors to run away from the market, which spirals downwards in a self-fulfilling process. Similarly Rabah and Oliver (2014) suggested that unexpected lower demand between June and December 2014 could account for only 20–35% of the price decline, while Hamilton (2014) found that only two-fifths of the fall in oil prices was due to weak global demand.

Various potential factors which could have influenced the oil price decline are discussed in an extensive World Bank policy research note by Baffes et al. (2015). The study found that supply shocks roughly accounted for twice as much as demand shocks in explaining the fall in oil prices. An alternative explanation was put forward by Tokic (2015) who suggested that the 2014 oil price collapse was partially an irrational over-reaction to the falling Euro versus the dollar. This is consistent with Donahue (2016) who stated that a stronger dollar, coupled with a slowing global economy, was one of many reasons for the recent falling oil prices.

The report issued by Bank of International Settlements, Switzerland (Domanski et al., 2015) showed that production and consumption alone are not sufficient for a fully satisfactory explanation of the

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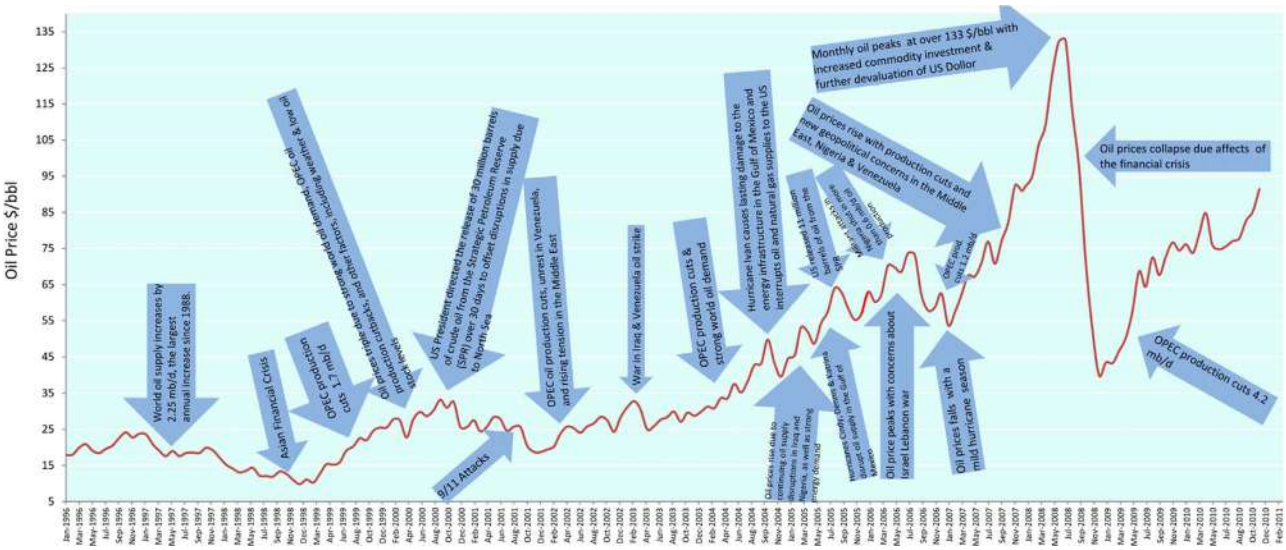

Fig. 1. Crude oil price trend (1996–2010).

collapse in oil prices. In this regard, the report advanced the idea that “if financial constraints keep production levels high and result in increased hedging of future production, the addition to oil sales would magnify price declines. In the extreme, a downward-sloping supply response of increased current and future sales of oil could amplify the initial decline in the oil price and force further deleveraging”. On the other hand the work done by Behar and Ritz (2016) shows that although the relative importance of each factor is difficult to pin down, OPEC's renouncement of price support and rapid expansion of oil supply from unconventional sources appear to have played a crucial role since mid-2014.

Similarly Tokic (2015) suggested that the oil price collapse 2014/2015 could have been caused by the increased leverage of oil firms (the debt of oil and gas sector increased from $1 trillion in 2006 to $2.5 trillion in 2014): the increasing need to keep high production levels and to hedge future production to satisfy financial constraints could have easily amplified the initial price decline due to economic fundamentals. Therefore, a revised and more effective regulatory framework should include not only oil traders/speculators, but all market participants including oil producers. The design of this revised framework is definitively an important avenue of future research.

In this paper, we extend the literature in a number of respects. We have discussed the various other possible causes of the recent oil plunge geopolitical strategies of oil exporting countries, disparities of recent oil plunge with the previous ones and problems with the oil prices projections.

Clearly, this sharp drop in oil prices is an issue of highest national and international importance that needs to be addressed properly based on empirical facts and historical knowledge. Many policymakers have been pondering the question of what caused this sudden decline, the severity of which surprised even industry experts, and whether the decline is likely to continue (Rabah and Oliver, 2014). Although sustained declines in the price of oil have occurred before, notably in 1986 and in late 2008, a natural question is whether this oil price decline is different and, if so, how. Considering the past events of such sharp drop in prices synchronized with considerable variations in inflation, the causes and outcomes of and OPEC's policy reactions to the recent episode of crude oil prices have triggered an intensive debate. The main aim of this study is to improve the theory of recent oil plunge by analyzing different scenarios based on event study and get more accurate oil price analysis results closer to reality. This study presents an evaluation of the recent plunge in oil prices to address five main questions that have been the focus of recent discussions:

- How does the recent plunge in oil prices associate with previous episodes?
- What causes a sharp drop in oil prices?
- How the oil prices looks in future?
- How falling oil prices could affect oil exporting and importing countries
- What are the financial and macroeconomic implications?
- What are contributions of geopolitical strategies toward recent plunge?

We address the above questions to use event base study methodology by examining the various parameters affecting which affect the oil prices over the period January 1996 through February 2016. Our main findings can be summarized as follows: The supply and demand haven’t changed enough to create a 72% plunge in oil prices. It means that the major fall in oil prices since June 2014 may be about a shift in trading (most probably due to changing role of oil pricing reporting agencies – PRAs, see Fig. 4), rather than a change in the fundamental supply and demand equation.

The rest of the paper is structured as follows. Section 2 describes the indicators of global activity and their ability to capture the demand for oil. Section 3 highlights the historical perspective of oil prices decline from 1998 to 2008. Section 4 investigates the role of the major influencers. Section 5 discusses the conspiracy theories and geopolitical strategies associated with the recent oil plunge. Section 6 describes the consequences of low oil prices. Section 7 assesses the future oil prices. Section 7 concludes.

2. Historical perspective of decline in oil prices: 1998–2008

In this section, we examine world crude price movements over the 1998–2009 period (Fig. 1), and analyze the driers of those prices movements. The first one, in 1998, when oil prices had crashed almost 50%, from $24 in 1997 to near $12 per barrel in 1998 causing extreme panic in oil exporting countries. The key reasons for crash were excessively high levels of oil inventories due to dwindling demand and fears of a prolonged Asian financial crisis. In the summer of 1997, Thailand, South Korea, Malaysia and other countries were subject to a flight from their currency and serious stresses on the financial system. Owing to this, investors developed doubts about the Asian growth story, putting economic and financial strains on a number of other Asian countries. The dollar price of oil soon followed them down, falling below $12 a barrel by the end of 1998. In real terms, that was the lowest price since 1972, and a price that perhaps never will be seen again.

The Asian crisis proved to be short-lived, as the region returned to growth and the new industrialization proved itself to be very real indeed. World petroleum consumption returned to strong growth in 1999, and by the end of the year, the oil price was back up to where it had been at the start of 1997. The oil price continued to climb an additional 38% between November 1999 and November 2000, after which it fell again in the face of a broader global economic downturn. In spite of poor oil prices, the global economic recovery remained sluggish during most of 1998, partly because of financial stress in the US and major emerging markets. It gained momentum only in 1999–2000, as growth in the US, Euro Zone and a number of large developing economies recovered. One of the key difference of 1998 oil price decline to recent drop was that 1998 oil prices decline occurred from a normal oil price level (roughly $30 in current dollars), meaning it very quickly approached marginal cost levels.

From December 1999 to August 2001, the oil prices remained stable with average price 25 $/bbl. But again in 2001 the disturbances and insecurity triggered by 9/11 terrorist attacks, intensified a growth slowdown. Softening global economic activity and growing uncertainty were the major drivers behind the sharp drop in the prices of crude oil around that time. However, aggressive financial policy facilitating by the Federal Reserve and other major central banks bolstered a rapid recovery in activity, while low oil prices might have provided some further support.

In addition to these events, the December 2002 oil strike in Venezuela, which resulted in a loss of almost 3 md/d of crude oil production, brought a sharp increase in world prices of crude. This was followed shortly after by the U.S. attack on Iraq, which removed an additional 2.2 mb/d over April to July. These would both be characterized as exogenous geopolitical events. Kilian (2008) argued they should be included in the list of postwar oil shocks.

Global economic growth in 2004 and 2005 was quite impressive, with the IMF estimating that real gross world product grew at an average annual rate of 4.7%. World oil consumption grew 5 mb/d over this period, or 3% per year. These strong demand pressures were the key reason for the steady increase in the price of oil over this period, though there was initially enough excess capacity to keep production growing along with demand. However, as seen in Fig. 2, production did not continue to grow after 2005 till August 2006.

Oil prices started to rise in 2004. According to IEA, the surge in oil prices since the end of 2003 can legitimately be described as an oil shock (Hamilton, 2009), though a slow-motion one. The oil prices raised from 25 US $/bbl in April 2003 to 74 US $/bbl by July 2006. One of the largest causes for the run-up in oil prices in that period was the sharp rise in demand for oil from China and other Asian developing nations. Between 2000 and 2008 China's GPD growth rates averaged 10% per year. High demand from Asia was the beacon that attracted financial investors to the oil market starting in 2004, because oil was seen as underpriced. The price of crude oil, which averaged only 34 $/bbl in January 2004, rose steadily. During the Israel-Lebanon war of July 2006, oil prices reached 75 $/bbl. Prices fell briefly below 55 $/bbl in January 2007 due to a mild winter.

Beginning in 2007, oil prices entered their most volatile period in history, when the oil prices raised from $92 a barrel in January 2008 to a record high of $147 a barrel on July 11, 2008, before collapsing to less than $40 a barrel in December 2008. The volatility was characterized by sharp increases in the prices of crude oil, immediately followed by equally sharp declines. This volatility was the result of a combination of numerous background “structural factors and specific market events, namely:

i. The large volume of institutional investment in the crude oil market;
ii. Falling value of US dollar;
iii. Asian oil demand growth;
iv. The rise of NOCs (National Oil Companies);
v. Related hypersensitivity to geopolitical factors (in particular to the events in Middle East, Nigeria and Venezuela;
vi. Rising marginal cost of oil production;
vii. The established pattern of non-OPEC supply growth; and
viii. OPEC production cut.

Unlike many other historical oil shocks, there was no dramatic geopolitical event associated with the oil shock of 2007-08. Ongoing -instability in places like Iraq and Nigeria were a contributing factor. Another is that several of the oil fields that had helped sustain earlier production gains reached maturity with relatively rapid decline rates. Production from the North Sea accounted for 8% of world production in 2001, but had fallen more than 2 mb/d from these levels by the end of 2007 (Hamilton, 2009). Mexico's Cantarell, which recently had been the world's second largest producing field, saw its production decline 1 mb/d between 2005 and 2008. Whereas previous oil price shocks were primarily caused by physical disruptions of supply, the price run-

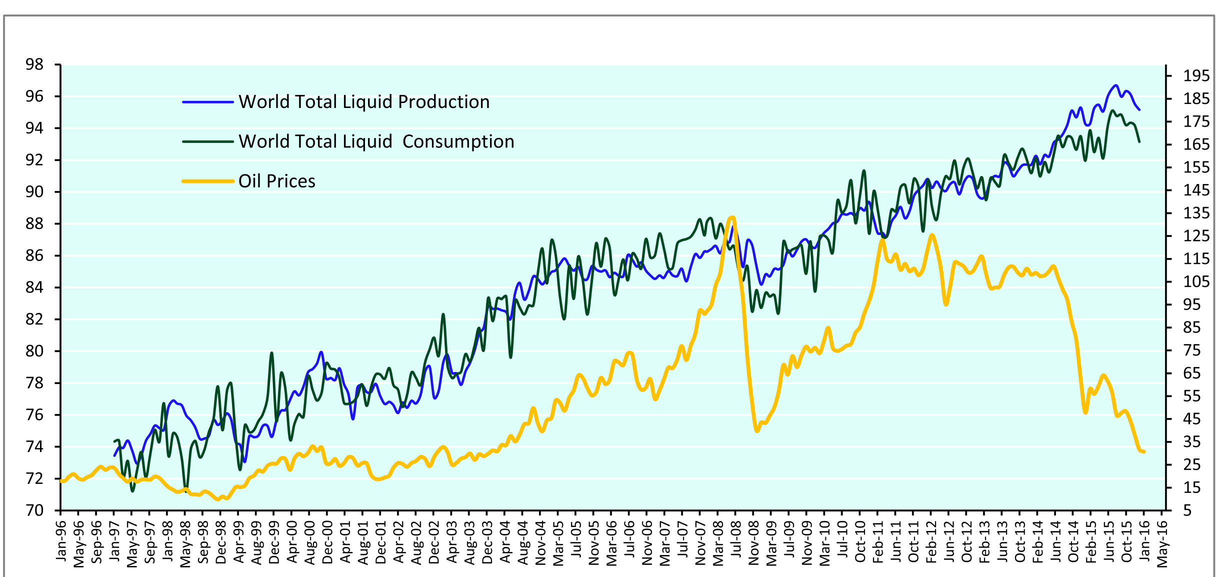

Fig. 2. Oil prices vs supply/demand.

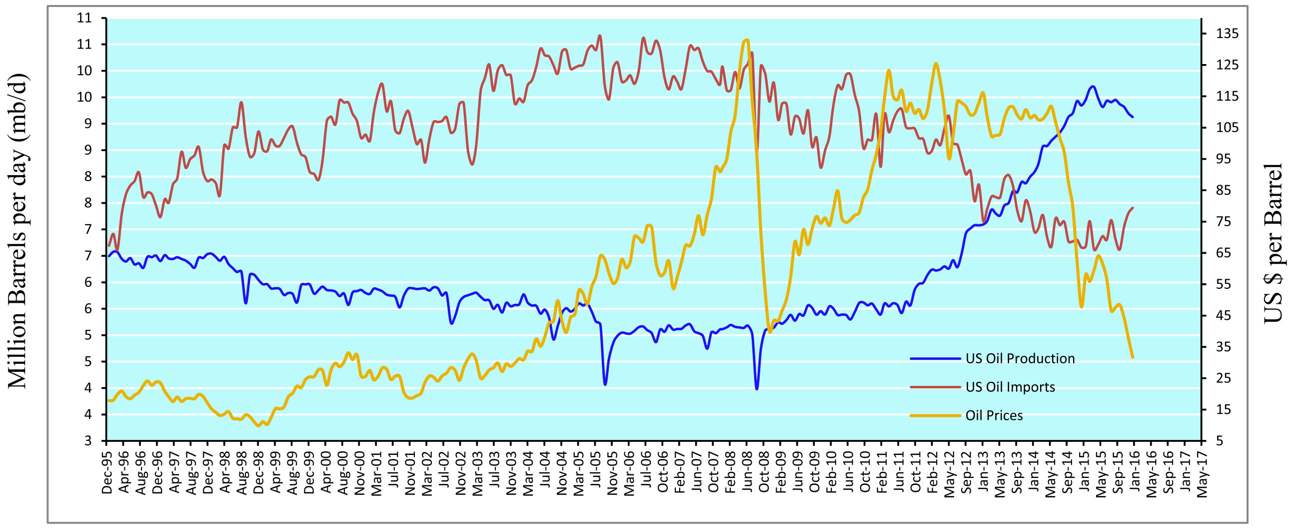

Fig. 3. Oil prices vs us oil production/imports.

up of 2007–08 was caused by strong demand confronting stagnating world production (Hamilton, 2009).

The great global recession started in the 2nd half of 2008, reduced the demand for oil in many sectors including transportation, manufacturing and construction. In April 2010, the IEA reported that world oil demand fell by 1.3 Mb/d from 86.2 Mb/d in 2008 to 84.9 Mb/d in 2009. Weak oil demand by the recession was the major factor causing the late 2008/early 2009 collapse in oil prices. The daily oil prices, which had peaked at 147 $/bbl in July 2008, declined to a bottom of only 39 $/bbl by late December 2008.

A series of measures and events have served to cause a recovery in world crude oil prices:

- In the fall of 2008, responding to falling oil prices and weak oil demand, OPEC announced 4.2 Mb/d of production cuts (the largest cut in the history of the cartel).
- OPEC also announced an oil prices target of $70 to $ 80 per barrel of crude oil. At that target price, the budgets of most OPEC member countries will be balanced.

Due to these measures, by April 2010, crude oil was trading at more than 80 $/bbl, more than double the low prices of December 2008.

In many ways, the recent shale oil boom resembles the extension of oil supplies from the North Sea and the Gulf of Mexico offshore fields in 1970 s and early 1980s. The technology to produce oil from offshore fields was even available in 1950 s but the high prices of oil in 1970 s made the use of such technology cost-effective. During 1973-83, Gulf of Mexico and North Sea collectively enhanced the global oil market by some 6 million barrel per day – as much as by unconventional oil sources i.e. US shale oil and Canada sand oil supplied to the global oil market during 2007–2014.

3. Global oil demand and supply

More than any other sector of the market, the energy sector, and in particular oil, is influenced by two main aspects: the supply/demand mechanism and market expectations, being the sector mostly based on futures contracts. Demand for oil is related to economic activity, so the higher the economic activity and the higher oil demand, and to seasonal aspects, it spikes for example during winter time. On the other hand, supply is determined by weather, which can affect production, and by geopolitical issues.

A first question is whether there have been important changes in global oil production since June 2014. Unexpected changes in oil production traditionally have been considered important in explaining oil price fluctuations (Hamilton, 2003). Rabah and Oliver (2014) found surprise increases in global oil production as one of the main causes of the decline in the price of oil. However it is often difficult to have a clear understanding of the total supply of oil, since many of the world's large suppliers are not transparent about what they produce.

Fig. 2 shows world total liquid supply and consumption since 1996. Empirical estimates suggest that the supply factors have played a somewhat larger role than demand factors in driving the drop in the price of oil from October 2014 upto February 2016. These results are also compatible with those in some recent studies. For instance, Rabah and Oliver (2014) found that demand linked factors contributed 20–35% to the plunge while supply related factors OPEC's policy not to cut production were more significant in driving the fall in oil prices. Hamilton (2015) claims only 40% of the drop in oil prices in 2nd half of 2014 was caused by weak global demand. Baumeister et al. Christiane and Lutz (2015) argue that more than half of the oil price decline reflects the combined impacts of earlier oil demand and supply shocks and the remaining impacts comes from slowdown in global economy. These demand and supply shocks that occurred between January and June 2014 have been caused by negative demand shocks associated with an unexpected slowdown of the global economy. By early 2014 demand for steel from China weakened, and so did the demand for iron ore. As a result, the price of iron ore started plunging. For example, the index of the spot market price of iron ore with 62% ferrous content for delivery in Qingdao port in China started falling as early as January 2014 and by the end of the year matched the cumulative decline in the price of oil.

The major contributor to demand factor is the domestic increase in production from United States and Iraq. US domestic oil production rose from about 5.6 million barrels per day (mb/d) in 2010 to 9.4 million barrels per day (mb/d) today (Fig. 3), pushing out oil imports that need to find another home. Saudi, Nigerian and Algerian oil that that was once supplied to United States, is now competing for Asian markets, and the supplier are enforced to lower the prices.

As shown in Fig. 3, the domestic supply surge greatly offset US net crude oil imports, shrinking them from 8.5 mb/d in 2012 to less than 6.6 mb/d in October 2015. US oil imports from OPEC have fallen to a 28 year low. Moreover the same technologies that have enabled the shale oil shale boom – fracking and horizontal drilling – have also led to a nearly 40% increase in U.S. natural gas production since 2007. Now one of the lowest cost fuels, natural gas is expected to further reduce the United States' reliance on oil, particularly for electricity generation, heating, chemical manufacturing, and even transportation.

Similarly one other contributor to the demand factor was the increase investment in renewable energy in countries like China and USA that have always been the biggest oil buyers. In China investments increased by 32% to 89.5 billion US $ and the growth continued despite falling prices of oil and gas. China accounts for 29% of global investment in clean energy and their lead is expected to increase in the following years because of their imperative need to reduce urban pollution. At the beginning, analysts were of the opinion that the recent oil plunge would harm the growing markets for renewable energy and reduce the attractiveness of cars which use alternative fuel sources. But contrary to their opinion, the investment in renewable energy (other than biofuels) has increased. This is because the renewable energy sources except bio-fuel are used to produce electricity while oil accounted for only 5% of the global power generation.

The oil consumption in the US and Europe peaked about 10 years ago and has been on a downward trend ever since. This largely reflects the improving efficiency of motor vehicles, with fuel economy of new cars in the Europe and USA, measured in terms of miles per gallon, around 20% higher than 10 years ago. However the overall world consumption rate is following the increasing trend as shown in Fig. 1. The same is also confirmed by IEA "Oil market report" which estimated that consumption grew by 1.8 mb/d on a global basis in 2015 (Oil Medium-Term Market Report, 2012). The pickup in consumption in oil importers has so far been somewhat weaker than evidence from past episodes of oil price declines would have suggested, possibly reflecting continued deleveraging in some of these economies (World Economic Outlook, 2016).

Fig. 2 shows that the current oversupply is about 2%. This does not seem like much but it actually has a huge effect on oil prices. The oversupply could be further increased with the recent release of economic sanctions on Iran. With the sanctions lifted, Iran can once again sell more oil to global markets. However it is worth mentioning that price can change faster than the fundamentals of supply and demand. In the last seven month period (June 2015–January 2016) the price of oil fell by 52% while there was no change in the demand or supply over those months to justify such a large change (Fig. 4).

It is not true that the decrease in world oil demand over the past two years has come from China due to slower economic growth there as stated by various reports (Hornby, 2015; Foroohar, 2015; Walker, 2015). In fact in 2014 the consumption increased by 2% in second half of year and 3% for year 2015. In fact last year, despite economic headwinds all year, China registered an all-time high in oil consumption. Fig. 4 exhibits that since June 2014 consumption has been increased in China rather than reduction. Both OPEC and the IEA expect Chinese oil demand to grow somewhere around 3% this year (Johnson, 2016). This seems to be consistent with the study by Wu and Zhang (2014) who question the effects from October 2005 to November 2013 of China's real crude oil net imports and real monthly Brent oil spot price changes. They find that, in the short- and long-run, China's crude oil net imports do not significantly affect Brent price changes. However, using variance decomposition, they show that China's crude oil net imports contribute to Brent price volatility approximately 10%.

As in Fig. 5 we can observe that the oil prices do not follow the demand and supply's principle in true spirit. It means that there are some other factors which can affect the oil market significantly. The most important of these factors is global geopolitical strategies. We discuss the role of the geopolitical strategies in current oil plunge in section 05. Those who claimed that the current oil plunge is due to supply/demand disturbance of the oil market especially due to US shale oil boom, have missed empirical estimates released by various organization before summer 2014 about the current demand/supply status. For instance Short-Term Energy Outlook report which was released by US Energy Information Administration (EIA) just before the 2014 oil crisis, projected the oil prices, U.S. total crude oil production, world total oil production and consumption for the year 2014 and 2015. Figs. 6 and 7 illustrate the relevant data of the report in graphical form. It can be seen that the projected figures of the production and consumption are in very close match with each other. This consequently means that the demand and supply formula is not applicable for the current oil plunge. Even the claim of surge in US oil production cannot be fully justified as the same was already forecasted by the report. All parameters except prices remained almost on the same track as they were projected.

Fig. 8 illustrated the historical relation between oil prices and OECD inventory level. It can be observed that the OECD inventory level has been increased by some 15% since June 2014.

4. The role of the major influencers: shale oil, OPEC, Saudi Arabia, Dollar4.1. The evolution of U.S. shale oil production

One of key factor driving the collapse in recent oil prices is the unexpectedly extraordinary renaissance in the US shale oil production. Output surged from 5 million bpd in 2008 to an average of more than 8.5 million bpd in 2014, and stood above 9 million bpd at the start of 2015.

The US shale oil revolution has changed the perception of the oil industry and has dramatically revitalized oil exploration and production while unlocking vast new reserves of oil. Shale oil refers to conventional oil trapped in very low-permeability tight formations known as shales, which makes extraction difficult. In order to release the oil and gas from shale, drillers use a method called hydraulic fracturing, also known as fracking, essentially pumping water, sand and chemicals at high pressure to fracture the shale formation and create artificial permeability. Shale oil developers use a technique called pad drilling, with up to ten drill wells radiating horizontally for distances of up to six miles from a single site, or pad. Shale-oil and gas

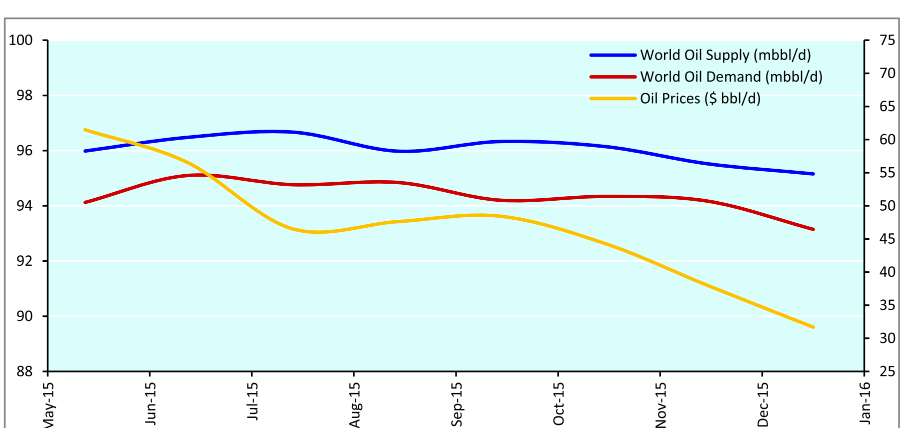

Fig. 4. Oil prices vs supply/demand.

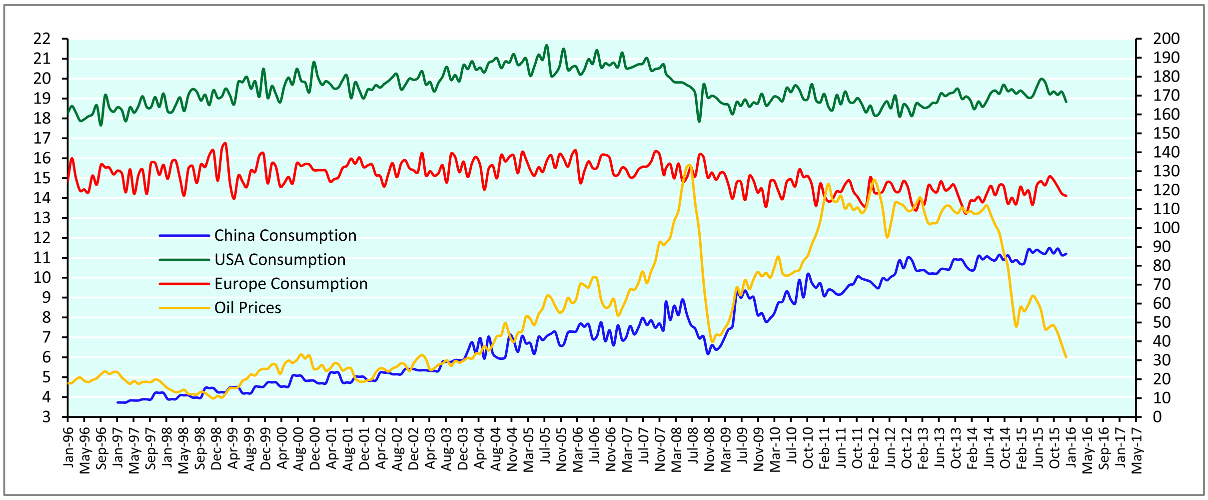

Fig. 5. Oil prices vs consumption by China, USA & Europe.

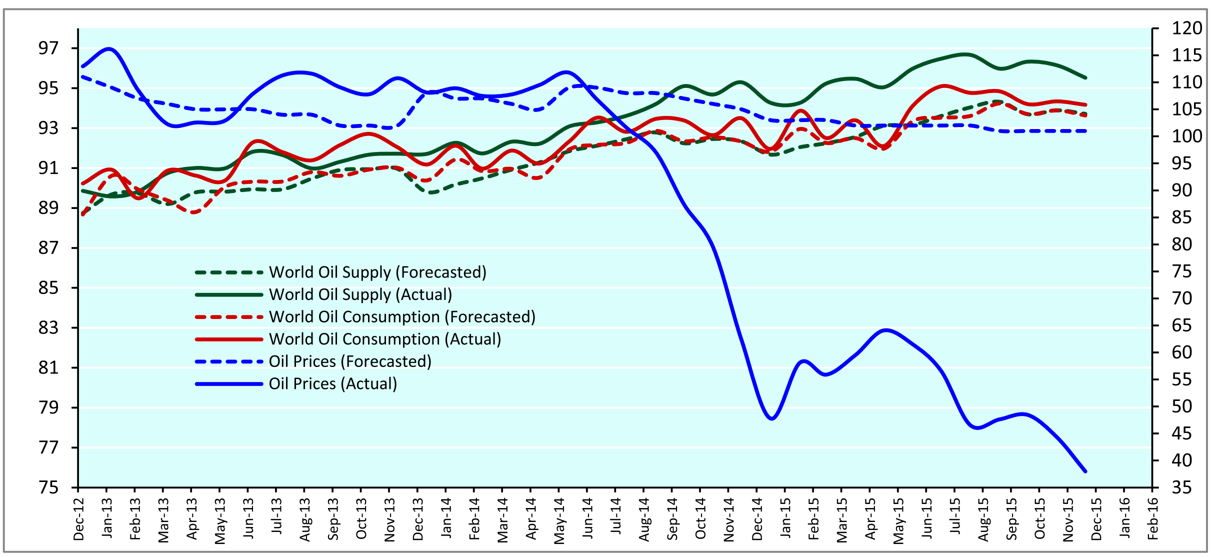

Fig. 6. Actual price/supply/demand vs EIA projection of price/supply/demand.

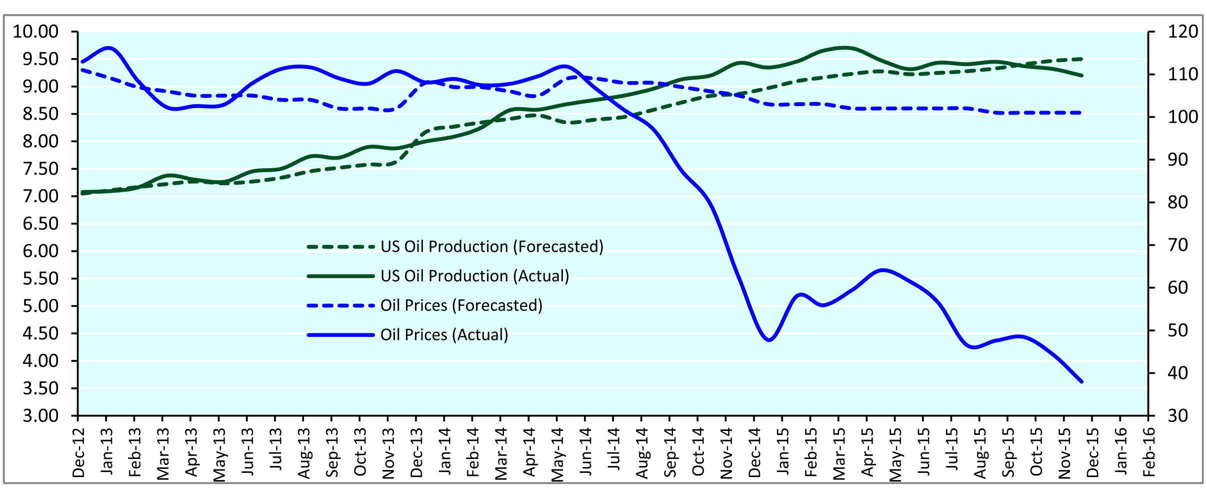

Fig. 7. Actual US production vs EIA projection of US production.

fracking was first developed in the early 2000 s in the United States in the Barnett shale formation beneath northern Texas and Oklahoma. These shale oil formations have been known to geologists for decades, but they were never economic to produce until the advent of fracking and directional drilling technology. By 2012, the International Energy Agency - IEA projected that the United States would become the world's leading crude oil producer, overtaking Saudi Arabia by the mid-2020s and evolving into a net oil exporter by 2030 (World Energy

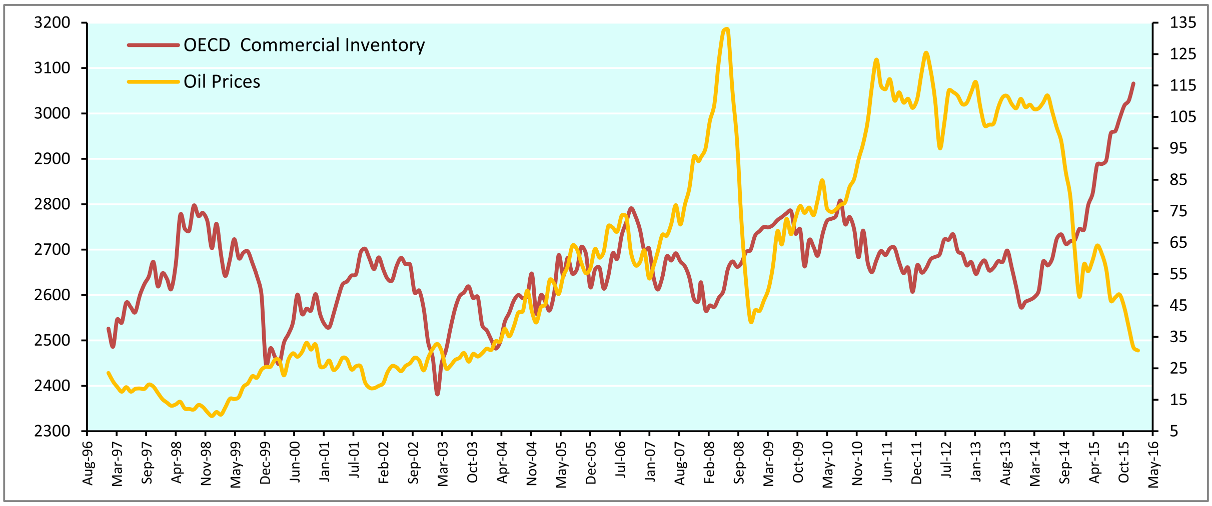

Fig. 8. Oil prices vs OECD commercial inventory level.

Outlook, 2012).

The key shale regions in the US are the Bakken, Eagle Ford, Niobrara, Permian, Utica, Marcellus (see Fig. 9), and Haynesville, respectively. Out of these seven shale regions, the Bakken, Eagle Ford, Niobrara, and Permian are the four major shale crude oil producing regions.

The persistent high levels of oil prices in recent years made shale oil exploration economically viable. However, several factors were in place in the United States that allowed the shale oil revolution to occur first there and not elsewhere: a history of shale gas exploitation, legal incentives for land owners and an advanced oil production infrastructure (Alquist and Guénette, 2014). Outside the United States, shale oil production is expected to take off only slowly, despite the fact that technically recoverable resources of shale oil are estimated to be abundant worldwide i.e. five times the size of the ones in the Unites States (Energy Information Administration, 2013). Nevertheless, the unconventional technologies used for shale extraction could be used to boost the production of existing conventional oil fields globally.

The use of increasingly sophisticated drilling techniques and huge improvements in cost efficiencies has not only reduced the costs associated with the production of shale oil, but it has also made the extraction resemble a manufacturing process in which the quantity produced can be altered in response to price changes with relatively ease, which is not the case for conventional oil extraction which requires large capital expenditure and lead times. The drilling time for shale oil continue to become increasingly more efficient. Two years ago, it took six weeks to drill a single well. Today, it takes approximately two weeks. Cost-saving technologies include more efficient exploration methods, onsite automation systems and intelligent production monitoring software. Beyond cheaper hardware the next saving opportunity lies in advances including more automation: intelligent control systems requiring less physical workforce, less downtime and improving yields of existing wells. It is worth to note that due to the current advances in shale oil production it now takes only 20 days and $10 million to drill for shale while it takes $10 billion and five to ten years to launch a deep-water oil project (Worstall, 2016).

Fig. 9. Marcellus shale outcrop in Pennsylvania.

The shale oil projects differ from conventional ones in that they require relatively low capital costs and have a shorter life-cycle (2.5–3 years from the start of development to full extraction) than that of a conventional well, with production typically falling by as much as 70–80% in the first year (McCracken, 2015). As a result, oil supply from these sources is likely to respond far more quickly to changes in prices than conventional oil production. The lead times between investment decisions and production of US shale can be measured in weeks, rather than the years taken for conventional production. As such, as prices fall, investment and drilling activity will quickly decline and production will soon follow. Likewise as prices recover, shale oil will increase, limiting any spike in oil prices. In this respect, shale oil becomes the new swing producer and will act as a form of shock absorber for the global oil market.

With low oil prices it becomes increasingly harder for higher cost production methods, like U.S. shale, to compete with low-cost producers like Saudi Arabia. Last year Reuters estimated (Caine, 2014) that the marginal cost of producing one new barrel of oil for U.S. shale producers was between $70 and $77 whereas Middle East Onshore marginal cost was between $10 and $17. Thus, oil prices below $70 per barrel, US shale would no longer be profitable whereas Middle East could still reap significant profits. While owing to advancements of production efficiency over the past year, some experts arguing that break-even prices could be as low as $30 for U.S. shale producers, such low-cost production is likely only available in the best areas of already existing oil plays (Kemp, 2015). Furthermore due to steep decline rates of shale wells, continuous investment is needed for production to keep flowing from these wells.

Those who cite record US oil production figures in early 2015 as proof of the resilience of US shale producers misunderstand the connection between prices and output. It is precisely the most heavily indebted and highest cost producers – in this case the US shale oil producers – who in conditions of an oil price fall are under the greatest pressure to step up production to maintain their cash flow so that they can service their debts.

4.1. Refracturing technology for shale oil

A rapid decline in shale wells has prompted a new movement towards refracturing depleted or lower producing wells in what is dubbed as a “shale revolution” to combat against the current challenges in the US shale market. Refractures, popularly known as “refracs,” have snagged industry's interest recently. It stimulates bypassed pay intervals, re-inflates natural fissures and often contacts “new” rock. The practice of re-fracturing wells is not new. Conventional vertical wells have been re-fractured for many years to try to gain a boost in production, with a wide range of success. The benefits of re-fracturing have historically been so unpredictable that it became commonly referred to as “pump and pray.” Not exactly a term that a board of directors wants to hear come out of the mouth of its CEO when discussing strategy. But in the last ten years the fracturing technology has evolved many times over, which makes re-fracturing a much more appealing opportunity today. The oldest generations of wells that were drilled with the earliest versions of technology are the best candidates for re-fracturing. Those wells used far fewer fracture stages and considerably less proppant (frack sand) than what is common in wells drilled and fracked today. According to Halliburton, since 2010, the number of fracture stages per well has jumped by 30% and the proppant/sand cranked down the wells has doubled.

Currently only a small share, about 1–2%, of shale wells have been refracked, however, IHS Energy Insight Report “To Frac or Refrac: Prospects for Refracturing in the United States” predicts that by 2020 refracked wells will account for as much as 11% of horizontal wells fractured in the U.S. However there are some farcking experts who are not conceived with the current status of refrac technology. These experts believe that:

- the refracs technology is not ready for prime time and the challenge is that identifying candidates for refracs, and deciding how to refrac the well, are not that simple. There are a lot of gaps in data that need to be there to make good decisions about how to design a refrac operation [by Chris Robart, a director at IHS Energy].
- refracs is technically risky and economically expensive [by Richard Spears, vice president of oil services consultants Spears & Associates]
- not all wells are refrac candidates and it is important to evaluate wells first [by David Adams of oil services giant Halliburton]
- refrac technology would gain acceleration if oil prices recover to $70–$80/[Daniel Choi, E & P analyst for Lux Research]
- Others say there is no easy way to ensure the refrac treatment will go to the left-behind parts of the reservoir when it is placed on a long lateral (horizontal portion of a well) of, say, 6000 or 7000 feet.

While the total cost of developing a horizontal well could reach as much as $8 million, the cost of a refracturing project could be as low as 25% of this at around $2 million. In principle the technique appears to be logical, however as low oil prices have presented the challenges of keeping well production up and operating costs down, a unique and timely emphasis on de-risking of refracturing operations with overall cost reduction is needed.

4.2. The role of OPEC and their strategy

The Organization of Petroleum Exporting Countries (OPEC) was set up in the mid-1960 s with the aim to promote the interests of some of the world's key producing countries, many of them located in the Middle East. The cartel consists of twelve countries that hold about 72.6% of the world total proved crude oil reserve (Mohsen and Nahid, 2015) and currently producing 40% of the world's crude oil demand. Since its inception, the influence of OPEC on global oil prices has been mixed. From rise in oil prices in 1973 and 1979, to the oil price plunge of 1986, and to the roller-coaster story from 2005 to 2008, OPEC has been libeled for exercising quasi-monopolistic control over rising oil prices, and dismissed for being incapable to apply any control over plunging oil prices (Lin and Tamvakis).

It typically acts as a “swing producer” in the oil market, increasing its production in the face of supply disruptions in other producers or rises in demand, and reducing it in the opposite case (Anton and Galo, 2013).

Fig. 9 shows the historical production trend of OPEC. When oil prices dropped significantly in the past, OPEC countries would cut their oil production to bolster the price of oil: for example, in 2008/9 with the global economy in deep recession, and oil prices plunging from $145 to $35, OPEC cut production by nearly 3 Mb/d helping to stabilize prices. Similarly, OPEC raised production sharply in 2004 when global demand suddenly surged. However in the recent episode of oil plunge, inspite of growing fiscal deficits in many OPEC nations (John, 2014), the cartel did nothing. At its recent 166th, 167th and 168th big meetings on 27th November 2014, 5th June 2015 and 4th December 2015 respectively held in Vienna, OPEC couldn't quite agree on a response and ended up keeping production unchanged, thus dropping oil prices even further in the global market. Against this backdrop, one wonders why the cartel, is not taking steps to cut production so prices could be stabilize on the world market. We believe the two major reasons to answer this question are the geopolitical strategies and US shale oil boom. OPEC is now facing a permanent headwind in the shape of shale oil. Each rise in price will be capped by a surge in US output.

Following its decision not to cut oil production after November 2014 meeting, OPEC expected oil prices to drop to $70 a barrel, which they thought would be enough to squeeze many shale oil producers out of the market. The reality proved otherwise, shale oil producers were able to react quickly in order to reduce their costs through various cost-cutting measures to weather the storm of low oil prices. And many of them managed to survive at those prices. For OPEC, that meant only one thing; oil prices have to slump further, therefore OPEC's members pursued their market-share strategy and kept pumping. In January 2015, oil prices were down at levels around $45–$55. During that time, OPEC's Secretary-General was calling the bottom in oil prices. He offered a bullish statements during his speech in London on Jan. 26 by saying 'Now the prices are around $45-$55, and I think maybe they have reached the bottom and we will see some rebound very soon’. It was not too long after that, oil prices fell further making the remark of OPEC's Secretary-General another layer of noise. Things didn't go as OPEC expected and oil prices are still falling till today to levels not OPEC nor anyone else has expected at that time. At the time of OPEC's decision in 27th November 2014, the global markets were probably oversupplied by 1–2 million bpd. If OPEC had merely decided to remove 2 million bpd off the world markets – only 5.5% of the group's combined 2014 production – the price drop could have easily been arrested and maintained in the $80–$90/bbl range. That would have still given them 38.9% of the global crude oil market. Fig. 10.

Although some argue that the current OPEC's policy implies that it will no longer act as the swing oil producer. Instead, the marginal cost of unconventional oil producers may play this role (Kaletsky, 2015; Basu and Indrawati, 2015). But analyzing the current situation of US shale oil and Canadian sand oil market, it seems that OPEC is winning, but it'll take time for oil prices to jump. Current data looks like the pressure OPEC has put on U.S. shale producers is working. Most companies can't make money with oil as low as $30 per barrel, but it'll also take time to squeeze those players out of the market. In conclusion the authors believe that OPEC will still play a critical role in balancing the global oil market in future.

4.2.1. Oil prices and OPEC member's budgets

Plunging oil prices have left many crude-exporting countries with budgets that simply will not balance. According to an analysis by Bloomberg (Smith et al., 2014) in December 2014, all of the OPEC's

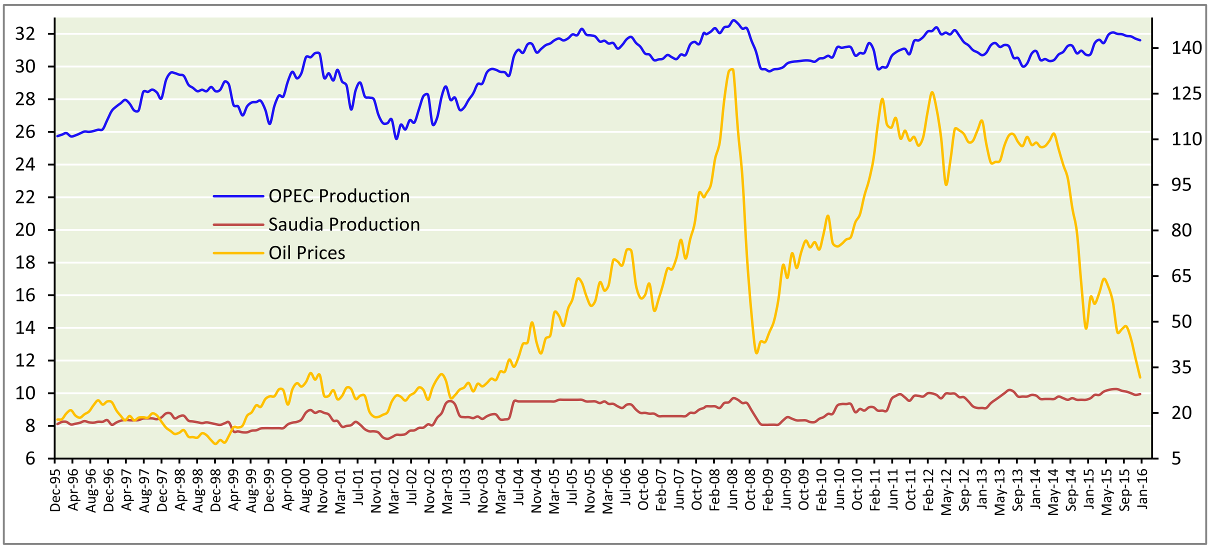

Fig. 10. Oil prices vs OPEC and Saudi Arabia production.

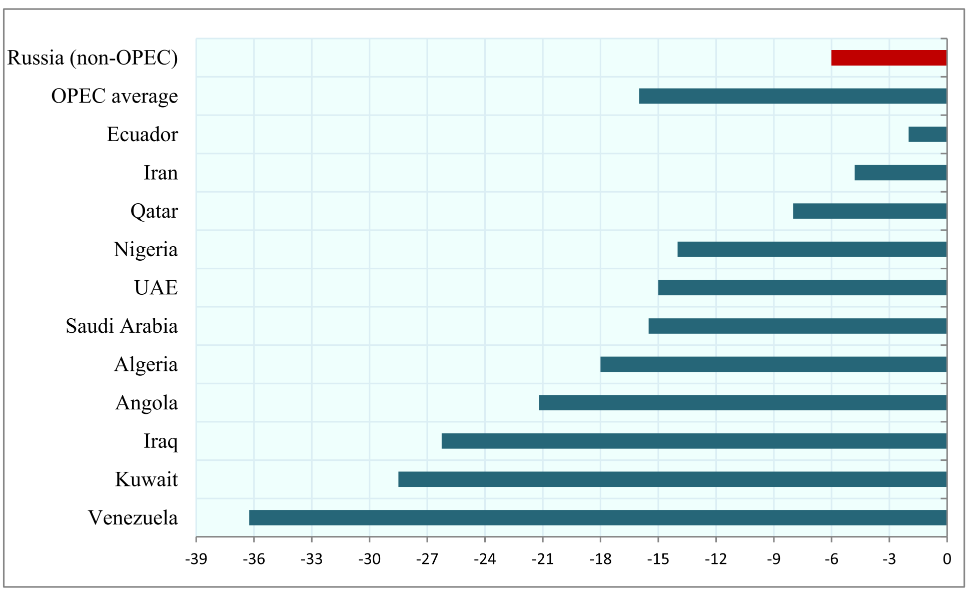

Fig. 11. Percent decrease in GDP, 2014–2015.

member states except Qatar can no longer rely on oil exports to balance their budgets. According to Fig. 11, which plots the percent decrease in GDP between 2014 and 2015 by country, Venezuela, Iraq – and Kuwait suffered the largest GDP decreases and Qatar, Iran and Ecuador the least. The combined GDP of OPEC member countries dropped from *$3392 billion in 2014 to $2849 billion in 2015, a decrease of $543 billion.*

A simple way of gauging a country's overall exposure to low oil prices is to calculate the percentage of its GDP supplied by oil export earnings. However, measuring GDP is not a straightforward exercise in practice because different data sources sometimes give wildly conflicting figures. For example, the 2013 nominal GDP of Venezuela was $US 227.2 billion according to the IMF and $US 438.3 billion according to the World Bank.

Due to low oil prices the oil exporters are exporters are getting less revenue, and have their budgets and external balances under significant pressure for last two years. One way to illustrate the vulnerabilities of oil-exporting countries is to compute the so-called fiscal break-even prices – that is, the oil prices at which the governments of oil-exporting countries balance their budgets. Fig. 12 shows the estimated level oil price needed for major oil producing countries to balance their budgets for the year 2014, 2015 and 2016. It can be seen most countries require a price above 80 $/bbl to balance their government budgets. It's important to note here that these estimates are not the same as the OPEC countries' "official" budget estimates, which are generally lower.

Chaoul (2013) estimated that the 2014 budget of Saudi Arabia assumed a crude oil price 67 $/bbl with production rate of 9.7 mbpd. But actual price of Saudi oil averaged 95.8 $/bbl in 2014, 43% higher than that used in the budget. For budget 2015, the kingdom didn't reveal the oil prices which it used to calculate its annual budgets. So analysts estimated them, making assumptions about several other variables such as planned oil exports and production for the following year. In this regard, four analysts' oil price estimates were in a range of $55 to $63 (Alturki et al., 2014; Saudi, 2015; Shaikh et al., 2014; Tully, 2014). Owing to this the Kingdom faced a record deficit of $ 98 billion (Press Release Recent Economic Developments and Highlights of Fiscal Years, 1436/1437 (2015) and, 1437/1438, 2016) for the fiscal year 2015 and it is planning for another budget shortfall (based on the oil price 45 $/bbl) in the current year, projected at $87 billion (Press Release Recent Economic Developments and Highlights of Fiscal

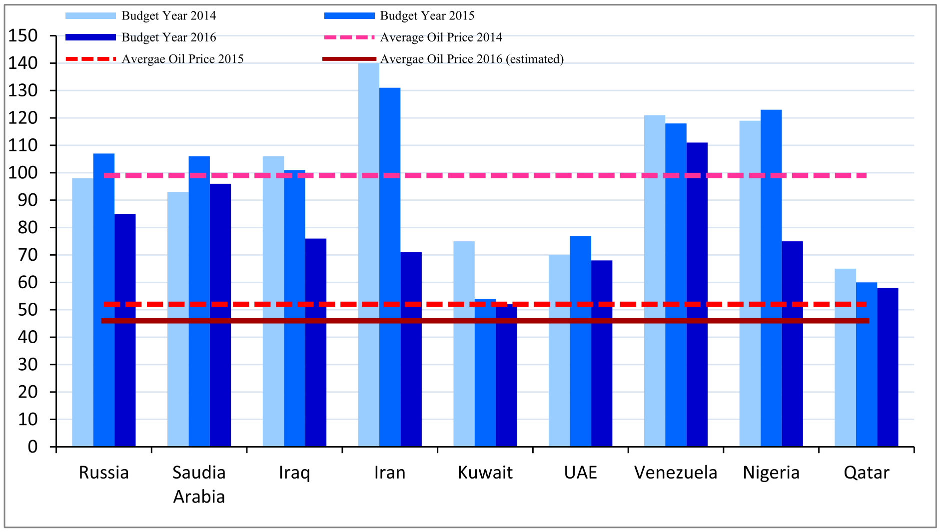

Fig. 12. Oil price needed to balance the budget.

Years, 1436/1437 (2015) and, 1437/1438, 2016). In long term the kingdom needs 80+$/bbl oil price to balance its fiscal and social budgets.

On the other side, the annual budgets of Iran for the fiscal years (started in March) for 2014 and 2015 was based on oil prices of 100 $/bbl and 72 $ /bbl respectively while the new budget for 2016 is anticipating sales of oil at an average price of 35 $/bbl. The current Iranian government intends to reduce Iran's dependence on oil from an average of 45% of all revenues to about 31.5%.

The oil price collapse since June has had only a modest impact on Iran – so far. But lower revenues have already forced the government to significantly reduce budget projections and even decrease Iran's dependence on oil. Similarly the other OPEC members e.g. Kuwait and Qatar are assuming the oil price at 45 $/bbl for their 2015-16 budgets.

4.3. The role of Saudi Arabia and their strategies

Saudi Arabia is one of the largest players in the global oil market: it produces more than a 10th of the world's oil output and owns a quarter of the world's proven reserves. The Kingdom is also a key OPEC member, typically playing a central role in OPEC's decision-making. Saudi Arabia's spare capacity is much larger than the aggregate spare capacity of the rest of the oil producers (Cristiana and Galo, 2015). It typically acts as a "swing producer" in the oil market, increasing its production in the face of supply disruptions in other producers or rises in demand, and reducing it in the opposite case (Anton and Galo, 2013).

The Saudi Arabian government is heavily dependent on oil revenues, with almost 90% of the government's revenues coming from oil and this income enables the regimes to provide their populations with a high standard of welfare. In other words, oil revenues translate into highly subsidized services and products. For example, the cost of one liter of oil in Saudi Arabia is 16 cents – less than the price of a bottle of water. The regimes are also the principal employers and the source of pay increments and bonuses, without charging any tax. On the other hand, residents can't exercise any political rights, and this de-fecto citizens-state contract is bound by the idea that the king takes care of its people while they accept non- intervention in the government. Hence there is a close nexus between oil revenues and regimes stability. The drop in oil prices will make it hard for the kingdom to maintain the momentum of development and higher living standards.

The recent fall in oil prices is likely to result in a higher government deficit and may result in lower government spending. This is bound to have a significant impact on job creation within the country, as most of the private sector jobs that are available are based on government contracts. Though in the short term the reduction in revenues due to low oil prices won't be an issue due to the fact that the Saudis can dip into their US$737 billion sovereign wealth fund for revenues, in the longer term Saudi Arabia needs around US $104 billion to balance its budget. The government ran a record deficit of about $98 billion, in 2015 around 15% of GDP. The International Monetary Fund – IMF estimates that the budget deficit will reach 20% of GDP this year, or roughly $140bn. If the Saudi economy does not diversify its exports and revenues, it will remain at risk. Far from retrenching, the Saudi government has launched a costly war against the Houthis in Yemen and is engaged in a massive military build-up - entirely reliant on imported weapons. With spending about $9.8 billion in 2015, the kingdom is now the world's largest importer of defense equipment.

But even after the drastic fall in oil prices, the Saudis have not cut their oil production in order to push oil prices upward. They stopped supporting prices and opted instead to flood the market and drive out rivals, boosting their own output from 9.7 mb/d (July 2014) to 10.6 mb/d (November 2015) as shown in Fig. 9. The reason why Saudi Arabia kept the price of oil down is largely motivated by its fear of Iran's regional ambition to become the region's hegemon. Most of the energy analysts believe that the Saudis are driving oil prices lower to inflict pain on Iran. Any collateral damage to US shale producers is a secondary or tertiary benefit. Though low oil prices hurt Saudi Arabia, they negatively impact Iran in a much greater way and it crimps Iran's ability to fund sectarian uprisings in Saudi Arabia's backyard. Essentially, they are forcing Iran to choose between higher oil prices and the economic prosperity that comes with it, and the desire to foment Shia uprisings in the Middle East. In essence we believe Saudi Arabia and Iran are fighting a war without tanks and jets but one with oil prices.

The other possible reason owing to which the Kingdom has refused to reduce its oil production is the global climate change accord agreed to by 195 nations in 2015 United Nations Climate Change Conference, held in Paris in December 2015. The parties committed themselves to reducing the consumption of hydrocarbon fuels in the 2nd half of this century to the point where their use produces no more carbon dioxide than can be absorbed by the world's trees. Each step they take toward reaching that goal diminishes the value of Saudi Arabia's vast crude oil reserves. The Saudis apparently figure that they might as well sell as much as they can now for whatever they can get, rather than leave it in the ground and see its value wither. As one American analysis of the climate pact noted, it "sends a strong message to the hydrocarbon industry that much of the global remaining reserves of oil, gas and coal must remain in the reservoir and cannot be burned." The Saudis have feared not that they will some day run out of oil but that they will run out of customers for it. They anticipate that electric vehicles, industrial efficiencies, bio-fuels and climate-change concerns will turn consumers away from oil.

The slump in recent oil prices and its impact on the Kingdom's economy have spurred the acceleration of efforts to diversify its economy as a long-lasting solution against the volatility of the oil market and for providing much needed jobs for the growing, young population. And indeed the industry that attracts most interest and investment is petrochemicals, which along with the plastics sectors is already robust. Saudi Arabia is one of the leading petrochemical producers in the world, accounting for around 8 per cent of total output, most notably through the public company Sabic (Saudi Arabian Basic Industries Corporation).

The Kingdom is determined to maintain its leading position and has earmarked $91 billion to be spent over the next 10 years to build new plants, expand existing ones and integrate refineries with new or existing petrochemical units. For example one of the major projects under way is led by Saudi Aramco, the national oil company, which is building a $19.3 billion petrochemical plant in a joint venture with American specialty chemicals giant, Dow Chemical.

The kingdom made considerable investments over the past decade to build world-class petrochemical facilities. Capturing the gas flows associated with oil production that were previously flared and instead channelling those flows into very low-priced feedstock for chemical production has made it possible to build an immense and highly profitable industry.

Similarly the Aramco new oil refinery at Jazan with production capacity of 400,000 bpd, would become operative in early 2017. The Jazan refinery is part of a $20 billion plan to develop an industrial city in Jazan in south-western Saudi Arabia, which would also include a 4000 MW (MW) power plant, a commercial port, and a refinery terminal. The city also includes the construction of world largest industrial gas complex at a cost of $ 2.1 billion. The gas complex for which the construction has started in July 2016, will supply 20,000 metric tons of oxygen and 55,000 metric tons of nitrogen to its Jazan refinery for 20 years.

The Kingdom intends to establish a 1,000 km-long canal linking the Gulf with the Arabian Sea, passing by the Kingdom to facilitate transport of oil, avoiding the Strait of Hormuz (Saudi Arabia to build largest artificial oil canal, 2016). According to the study (Saudi Arabia to build largest artificial oil canal, 2016), 10 nuclear power stations will be constructed along the new canals with a total capacity of 50 Gigawatt, which is the Kingdom's present electricity requirement. This will enable the Kingdom to avoid its dependence on traditional power stations powered by oil.

The government also plans to invest in refining and chemical plants outside the Kingdom. Under the deal, Aramco would gain full control of the 603,000 barrel-*per*-day Port Arthur refinery. For instance Aramco would gain full control of the 603,000 bpd (largest refinery in the U.S) Port Arthur refinery once the break-up of its joint venture with Royal Dutch Shell is complete. Port Arthur has great strategic value, especially given the American oil boom that has eased U.S. appetite for foreign oil. It will give the Saudis complete control over the refinery. They could then likely bring more of their own crude oil into the U.S. for refining and selling in the North American market.

The Kingdom has captured the world's attention with the announcement of an ambitious agenda, called Vision 2030, aimed at overhauling the structure of its economy. The plan would reduce historical high dependence on oil by transforming how the kingdom generates income, as well as how it spends and manages its vast resources. It is supported by detailed action plans, the initial implementation of which has already involved headline-grabbing institutional changes in a country long known for caution and gradualism.

In simplified terms, Vision 2030 focuses on three major areas, together with efforts to protect the most vulnerable segments of the population (El-Erian, 2016). First, the plan seeks to enhance the generation of non-oil revenues, by raising fees and tariffs on public services, gradually expanding the tax base (including through the introduction of a value added tax), and raising more income from a growing number of visitors to the kingdom. Second, the authorities want to reduce spending by lowering subsidies, rationalizing the country's massive public investment program, and diverting spending on arms away from foreign purchases. Third, the kingdom seeks to diversify its national wealth and, in the process, increase current investment income. For example, the plan would raise funds via the initial public offering of a small part (up to 5%) of Saudi-Aramco, the giant oil conglomerate, and invest the proceeds in a broader range of assets around the world.

The attention attracted by Vision 2030 is not surprising. The plan, after all, is about a lot more than fundamental economic reforms. If Saudi Arabia succeeds in transforming its economy, including reforming institutions and restructuring economic incentives, other countries that face similar challenges, in the region and beyond, will be inspired to follow suit (El-Erian, 2016).

4.4. The role of the U.S. dollar exchange rate

One reason for the muted demand response to the low price signal has been the increasing strength of the US dollar relative to other major world currencies. Oil is bought and sold in US dollars across the globe. When the dollar gets stronger (as it has over recent months), it makes oil more expensive to buy in countries outside the US. That, in turn, weakens worldwide demand and further puts downward pressure on oil prices. The decline in the value of the US dollar played a vital role in the oil spike of 2007/2008. The Euro rose 78% against UD dollar between January 2002 and July 2008. This corresponded to oil prices. An examination of the Fig. 13 reinforces the truth that the recent drop in oil prices has corresponded to a strengthening US dollar. The chart shows that the US dollar index has risen by more than 10% against major currencies in trade-weighted nominal terms since July 2014. Empirical estimates of the size of the US dollar effect cover a wide range: the high estimates suggest that a 10% appreciation is associated with a decline of about 10% in the oil price, whereas the low estimates suggest 3% or less (Zhang et al., 2008; Akram, 2009). To the extent that both the price of oil and the U.S. exchange rate depend on the evolution of the global economy, one cannot think of the exchange rate having an independent effect. For the recent oil plunge Baumeister et al. Christiane and Lutz (2015) claim that variation in the US dollar have no independent effect on the crude oil price.

5. Conspiracy theories and geopolitical strategies

The sudden collapse in crude oil prices launched all manner of conspiracy theories, even as the prices created unanticipated ripple effects throughout the global economy. There were those who said that Saudi Arabia in collusion with the United States, decided to allow the price of oil to decline by refusing to accept cuts in production in order to punish Russia for its support of Syria and its aggressive attitude in Ukraine. Others went even further claiming that Saudi Arabia wants to get rid of Assad to prevent the building of a pipeline from Iran to Syria running through Iraq to consolidate the so-called "Shiite Crescent" and give it an economic underpinning. The pipeline would deliver Iran's, Iraq's and Syria's oil and gas through Turkey and on into Europe.

Another entertains the idea that the Saudis are using low prices as leverage against Iran. The Saudis its Gulf allies know that Iran, dominated by the Shia Muslim sect, supports a resentful underclass of more than a million under-privileged and angry Shia people living in the gulf peninsula – a potential uprising is waiting to happen against the Saudi regime (Lucas, 2014). A more realistic explanation focuses on a "price war" between Saudi Arabia, shale oil producers in the U.S. and

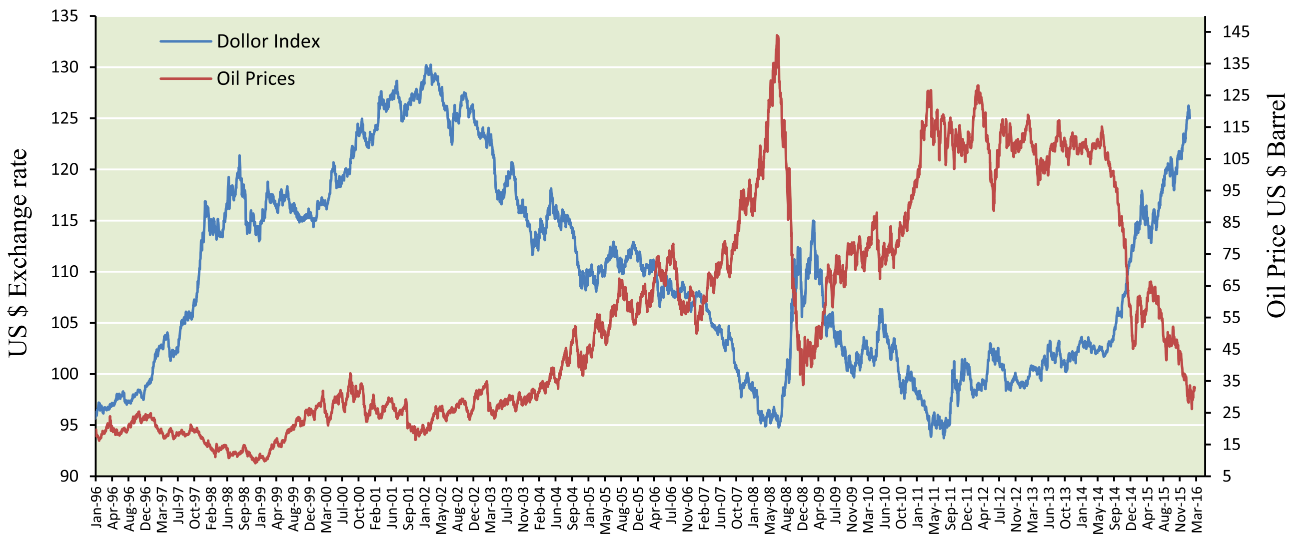

Fig. 13. Oil price versus US dollor index.

sand oil producers in Canada, by arguing that the Saudis are trying to protect their market share as they can accept temporary losses and force costly producers to bankruptcy (Bershidsky, 2015). Similarly in an interview with Harvard International Reviews (Oil, Prices, and Global Impact, 2016), Leonardo Maugeri (globally recognized expert on oil, gas, and energy) said that the major target of Saudi Arabia is the United States, their secondary target is Canada, and another secondary target is Iran - though more for political reasons. He mentioned that Kingdom is very preoccupied with the current state of negotiations between Iran and the United States about the nuclear issue.

But there are some skeptics. Denton Cinquegrana, chief oil analyst at Oil Price Information Service, says U.S. oil bust isn't a big enough threat to Saudi Arabia's global market share to spur this kind of painful price war.

Author Mike Whitney (Whitney, 2014) believes that the US and Saudi are purposefully conspiring to push down oil prices as a way to create further instability for these countries. The New York Times in their article (Mazzetti et al., 2015) has admitted that Saudi Arabia has been trying to pressure Russia to abandon his support for President Bashar al-Assad of Syria, using its dominance of the global oil markets at a time when the Russian government is reeling from the effects of plummeting oil prices. The Guardian's Larry Elliot (Elliott, 2014) thinks the US and Saudi Arabia are engaged a conspiracy to push down oil prices. He points to a September meeting between John Kerry and Saudi King Abdullah where a deal was made to boost production in order to hurt Iran and Russia. Even the government of Iran and Venezuela claimed that the low oil price has been engineered by the U.S. and its allies to harm Russia and Iran. However the Saudi government has repeatedly denied claims that the kingdom is involved in a conspiracy.

Saudis have used oil as a political weapon many times in the past to achieve their foreign policy objectives (Topf, 2014). It is abundantly clear that Saudi Arabia is a US client state that closely follows US's regional and global strategies (Afrasiabi, 2015). It's not autonomous or sovereign in any meaningful way. It's a US protectorate, a satellite, a colony. They do what they're told (Whitney, 2014). The idea that Saudis want to push down US shale oil production is absurd. We don't think that US would let Saudis fiddle prices in a way that destroyed critical US domestic energy industries, ravaged the junk bond market, and generated widespread financial instability without uttering a peep of protest on the matter? The fact that Obama has not even alluded to the shocking plunge in prices just proves that the policy coincides with Washington's broader geopolitical strategy.

Even the New York Times has readily admitted (without any reference to an oil conspiracy) that the US has harvested "huge benefits" from the oil price decline, including geopolitical gains against its adversaries such as Russia, Iran, and Venezuela (consistent with the US's post-cold war doctrine of preventing the emergence of a global rival at any cost) (Higgins, 2014). Similarly William Engdahl – a geopolitical analyst at Canadian based Centre for Research on Globalization stated in his article (William Engdahl, 2014) that the US-Saudi oil price manipulation is aimed at destabilizing several strong opponents of US globalist policies. Targets include Iran and Syria, both allies of Russia in opposing a US sole Superpower. The principal target, however, is Putin's Russia, the single greatest threat today to that Superpower hegemony. Then an article by Thomas Friedman at the New York Times (Friedman, 2014) suggested Saudi Arabia's policy – in coordination with the Obama administration – was aimed at hurting Russia by lowering the oil price.

The Russians have noticed this play before. The Russian newspaper Pravda published an article on April 3, 2014 with the headline, "Obama Wants Saudi Arabia to Destroy Russian Economy" (Lyulko and Ru, 2014). It said: "There is a precedent for such joint action that caused the collapse of the U.S.S.R. In 1985, the Kingdom dramatically increased oil production from 2 million to 10 million barrels per day, dropping the price from $32 to $10 per barrel. The U.S.S.R. began selling some batches at an even lower price, about $6 per barrel. Saudi Arabia did not lose anything, because when prices fell by 3.5 times Saudi production increased fivefold. The planned economy of the Soviet Union was not able to cope with falling export revenues, and this was one of the reasons for the collapse of the U.S.S.R." Many Russian believe that the full implementation of the plan began after a September 2014 meeting between US Secretary of State John Kerry and Saudi King Abdullah where a deal was made to boost production in order to hurt Iran and Russia (Titov, 2014). Adding credence to this theory, an article in the Wall Street Journal (Entous and Barnes, 2014), stated that it was during that meeting that a deal was hammered out between US and Saudi Arabia.

Almost all of the above mentioned conspiracy theories have very strong roots in the geopolitical importance of Syria and Yemen with respect to an energy gateway to Europe. Russia the dominant energy supplier to Europe, with 35% of its oil, 30% of its gas, 26% of its coal and 25% its enrich uranium imports originating from Russia. But Europe doesn't like being so reliant on Russia for fuel and has been trying to reduce its dependence. It's a move that is supported by the United States as it would weaken Russian influence over Europe.

Before the civil war in Syria, two competing pipelines put forward by Qatar and Iran aimed to transport gas to Europe through Syria.

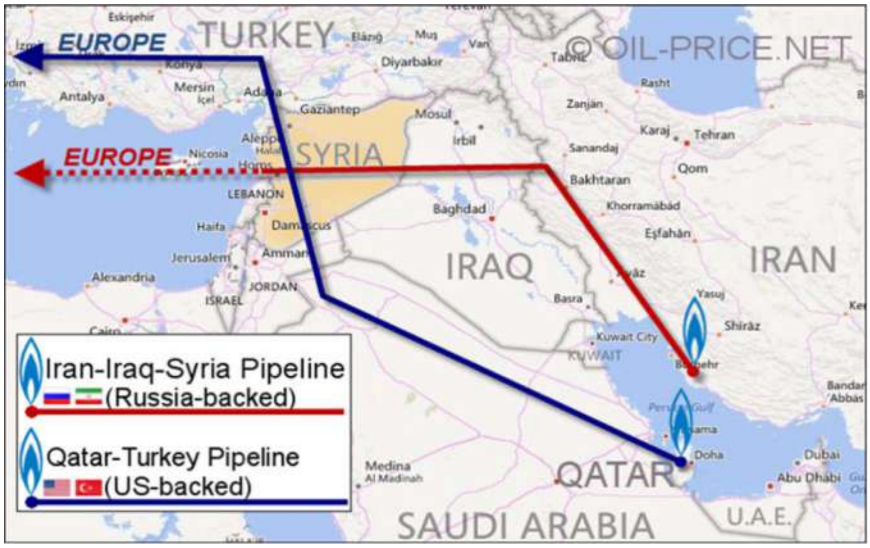

Fig. 14. The two rival proposed pipeline to supply gas to EU.

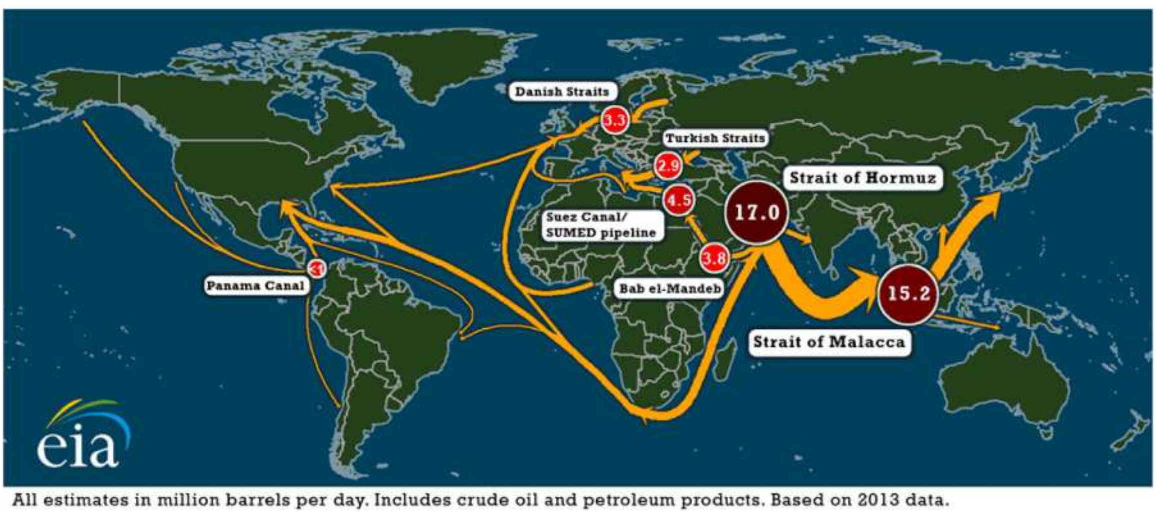

Fig. 15. World major maritime chokepoint for oil transportation.

Qatar's plans were first put forward in 2009 and involved building a pipeline from the Persian Gulf via Saudi Arabia, Jordan, Syria and Turkey. The gas field located 3000 m below the floor of the Persian Gulf is the largest natural gas field in the world. Qatar owns about two-thirds of the resource but can't capitalise on it fully because it relies on LNG to deliver it to other countries by tankers and this makes its gas more expensive than Russia's. President Assad rejected that pipeline and preferred one from Iran through Iraq to the Syrian coast and then to Europe under the Mediterranean Sea. Therefore as shown in Fig. 14 there are proposed options to deliver natural gas to energy-hungry European nations, the first one is US backed Qatar- Turkey pipeline US while the other one is Russia backed Iran-Iraq-Syria pipeline. Assad signed off on the Iran plan in summer 2011 and it was due to be completed in 2016 but it was ultimately delayed because of the Arab Spring and the civil war broke out in Syria. Syria's rationale for rejecting the Qatar proposal was said to be "to protect the interests of its Russian ally" and belived the real cause of Syrian civil war. Failed pipeline bidder Qatar is believed to have funded anti-Assad rebel groups by $3 billion between 2011 and 2013. Saudi Arabia has also been accused of funding the terrorist group (Entous and Barnes, 2014). In contrast Orenstein and Romer noted the successful pipeline bidder, Iran, was believed to be helping Assad by running the Syrian army, supplying it with weapons and even troops.

Major Rob Taylor, an instructor at the US Army's Command wrote in the Armed Forces Journal March 2014 that the rival pipelines could be influencing the conflict in Syria. He stated that the conflict in Syria is not a civil war, but the result of larger international players positioning themselves on the geopolitical chessboard in preparation for the opening of the pipeline (Rob Taylor, 2014). An Iran-Iraq-Syria pipeline is unacceptable in the Beltway not only because US vassals lose, but most of all because in currency war terms it would bypass the petrodollar. Iranian gas would be traded in an alternative basket of currencies (Escobar, 2015). Compound it with the warped notion, widely held in the Beltway, that this pipeline would mean Russia further controlling the gas flow from Iran, the Caspian Sea and Central Asia (Escobar, 2015).

The geopolitical significance of Yemen has also weighed heavily in the equation. Preventing US and Saudi rivals from gaining a strategic foothold over the Bab-el-Mandeb Strait and the Gulf of Aden is a major objective of the war on Yemen (Nazemroaya, 2015). Bab-el-Mandeb is a maritime chokepoint, which acts as a strategic link between the Indian Ocean and the Mediterranean Sea via the Red Sea and the Suez Canal. Most exports from the Persian Gulf that transit the Suez Canal and Suez-Mediterranean (Sumed) crude oil pipeline also pass through Bab el-Mandeb. As highlighted in Fig. 15, an estimated 3.8 million bbl/d of crude oil and refined petroleum products flowed through this waterway in 2013 toward Europe, the United States, and Asia. The Strait is 18 miles wide at its narrowest point and its closure could keep tankers from the Persian Gulf from reaching the Suez Canal or SUMED Pipeline, diverting them around the southern tip of Africa, adding to transit time and cost.

In conclusion, history shows that conspirators rarely show their hands and often the passage of time is necessary to uncover them and circumstantial rather than direct evidence must be used to prove a conspiracy.

6. Consequences of low oil prices

6.1. *Effect of low oil prices on us oil production and economy*

It has been a truism of the American economy for decades: When oil prices rise, the economy suffers; when they fall, growth improves. But the decline of oil prices over the last two years has failed to deliver the usual economic benefits. On the face of it, although the US seems to be a huge beneficiary of lower oil prices, deeper analysis shows the situation to be a bit more complex. While lower oil prices will benefit consumers in terms of increased savings that are likely to increase consumption and result in an uptick in the GDP, they are also likely to hurt U.S. shale oil producers in the long term – who according to estimates need oil prices to be above US $60 to break-even – and lead to lower associated investment. Lower oil prices will also negatively affect the profitability of US energy companies such as Exxon, Chevron etc. The US industry has so far proved surprisingly resilient in the face of low oil prices, which last month hit their lowest level since the global financial crisis. But the IEA report suggests the growing financial pressure on shale operators and the steep fall in the number of rigs drilling for oil is beginning to take their toll on production. Fig. 16 shows that the number of drilling rigs has fallen to 502 compared to September 2014 peak of 1930. Rig count is considered as a direct measure of the health of oil industry and oil production. Falling rig count lead to a decline in oil production, but why this is not the case in this downturn? Despite this significant rig counts declines, production cutbacks are relatively minor.

This is due to introduction of advanced technology as well as better and efficient ways of producing the oil. Many companies are now focusing on increasing efficiency and productivity of their wells. More cheaper and efficient well intervention and well completion technology, greater proppant use and targeting the most productive tracts. In the Eagle Ford (Texas) and Bakken (North Dakota) regions, new well productivity has more than doubled from less than 300 barrels per well in early 2012, to 785 and 712 barrels per well, respectively (Commodity Markets Outlook, 2016).

Another reason that explains the resilience of US shale oil is the fact that many operators who are still losing despite all the cost cutting measures prefer to take a loss and wait, because they know the oil market is boom and bust by nature and they expect things to get better soon. According to a report by Wood Mackenzie, given the cost of restarting production especially in large projects, many operators prefer to continue producing oil at a loss in hope for a rebound in prices rather than to stop production.

6.2. *Effect of falling oil prices on Russia*

Russia has by far been one of the countries that have been most adversely affected by the recent plunge in oil prices. Its oil revenues, which constitute more than half of its budget revenues and approximately 70% of its export revenues, have dropped significantly, with every dollar drop in the oil price impacts the Russian economy by US $ 2 billion loss in revenue. The recent crash in oil prices will not only test President Vladimir Putin's domestic support. It will upend Russian foreign policy, challenging the modernization of the country's armed forces while diminishing its influence in Asia and Europe.

So far Russia has been able to cope with lower oil prices by allowing the market to massively devalue the ruble, which has lost half its value against the U.S. dollar since summer 2014, when oil prices began to fall. Also, since oil and other commodities are sold in dollars, energy companies and the government earned more rubles for every dollar's worth of oil sold, offsetting the effect of the price fall and allowing the government to run a deficit of around 3% without borrowing or massive cuts to spending. The weak ruble transformed Russia's trade balance, since anything brought from outside the country suddenly became far more expensive. According to official customs data, the value of imports fell by 38% in the first 10 months of the year. This was another boon to the state, creating an expected current account surplus of more than $60 billion this year to help balance capital outflows and repayments to foreign creditors.

When oil prices began to fall in the summer of 2014, various economists predicted it would be a disaster for the Russian budget, which needed oil price of $110 a barrel in order to balance the budget deficit but 2015 proved that claim wrong. William Engdahl – a geopolitical analyst at Canadian based Centre for Research on Globalization stated in his recent article (William Engdahl, 2014) that US oil war strategy against Russia` is doomed to fail for several reasons, not just because Russia took some major strategic measures together with China and other Asians countries to search new markets for its vast oil and gas reserves and to reduce its dependence on the West. In fact the oil war is stimulating recent Russian initiatives to focus its economic power over national interests and reduce its

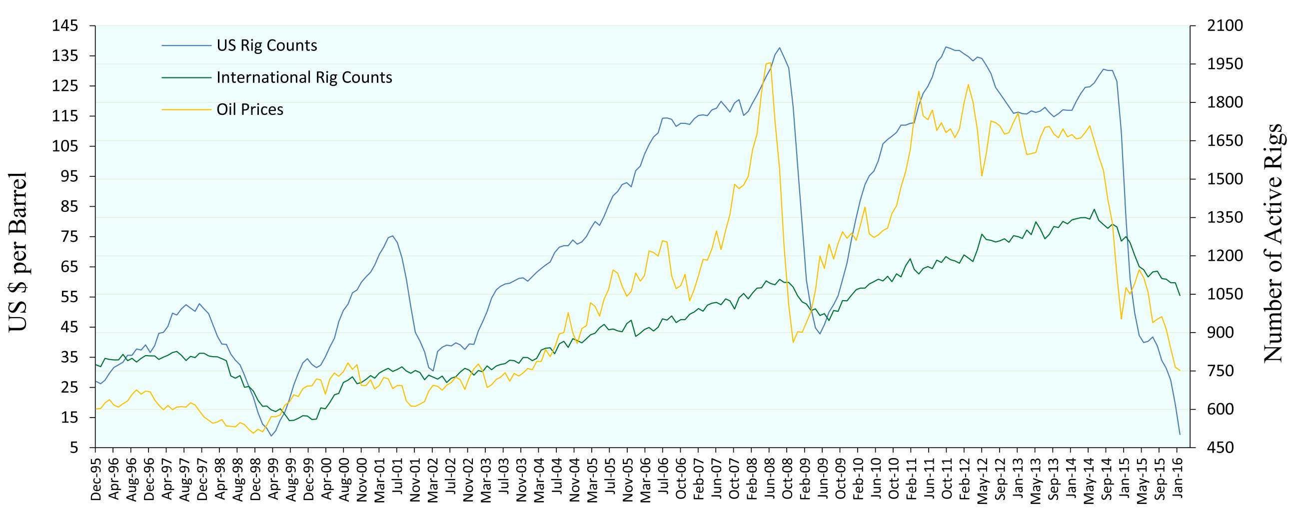

Fig. 16. Oil prices vs rig counts.

dependency on the Dollor system. If the dolor ceases being the currency of world oil trade, the US Treasury will face fiscal disaster (William Engdahl, 2014).

6.3. Economic and financial consequences

The development of oil prices is critically important for economic development. Crude oil is not only an important resource for production, but also accounts for a large proportion of the expenditure of private households. Crude oil has an impact on both production costs and the purchasing power of private sector incomes. The recent plunge in oil prices is having significant economic consequences around the world. In past large increase of oil has caught widespread concern about its impacts on macroeconomy, especially those major oil importing and developed countries (Lee et al., 2001; Chang and Wong, 2013; Gronwald, 2008; Oladosu, 2009; Ismaél et al., 2009; Rumi et al., 2011; Sajjadur and Apostolos, 2012; Tiago and Tovar, 2013; Fan et al., 2007; Du et al., 2010). Oil prices decline in global oil markets are supplemented by substantial real income transferals from oil exporting economies to oil importing economies. However the ultimate impact of low oil prices on each country depends on a several factors, including share of oil in their export, their cyclical positions, their dependence on the oil sector for tax revenues and their financial policy room to respond. Although the negative Impact on the oil exporters is immediate.

Theoretically the recent decline in oil prices should bring positive impacts on economy of oil importers. The savings from the oil imports bills in the oil importing countries can ease the government's budgets deficits. In many developing and emerging economies, the Pre-tax subsidies on the oil which arise when the end consumers pay less than the supply cost of oil, are high (Clements et al., 2013; Keith et al., 2015). In such countries authorities can take advantage of the drop in the oil price to remove costly fuel subsidy without having to suffer a spike in domestic fuel prices. India, Indonesia and Malaysia are examples of countries that have slashed their fuel subsidy lately. Fiscal resources freed up from the reduction in fuel subsidies can also be reallocated toward more productive spending, such as infrastructure. A A decline of 10% in oil prices could increase economic growth in oil importing countries by value of 0.1–0.5% depending on the contribution of oil imports to GDP (Tang et al., 2010; World Bank, 2013). But the recent oil plunge is not following this economic principle. One of the chief economic surprises of 2015 is that the magnificent decline in crude oil prices did not provide a major lift to global economy. Despite the sharp plunge in the oil prices, from over 112 $/bbl in June 2014 to 38 $/bbl at the end of December 2015, most macroeconomic models reveals that the impact low oil prices on global growth has been less than expected.

In theory a long period of low oil prices should benefit the global economy. The world is both a producer and a consumer: what producers lose and consumers gain from a drop in prices sums to zero. For instance lower oil leads to cheaper gasoline, which leads to more income for consumers to spend. The additional spending would also boost corporate profits, thereby increasing the demand for workers (and/or technology), and push the unemployment rate down. Cheaper oil is especially beneficial to companies that spend a significant amount on transportation such as shipping, airlines and trucking companies. Lower transportation costs should help reduce the price of retail products and put downward pressure on inflation. Less expensive products should also result in an increase in consumer and business spending. But on actual grounds despite decline of over 70% in oil prices from their 2014 peak, the economic benefits are unnoticeable (Domanski et al., 2015). Lower oil prices could also conduce to significant drop in the other commodity prices. For example the lower oil price will likely result into lower natural gas prices in European Union countries and LNG prices in Asian countries. As shown in Fig. 17 LNG prices in Japan already dropped 52% since June 2014.

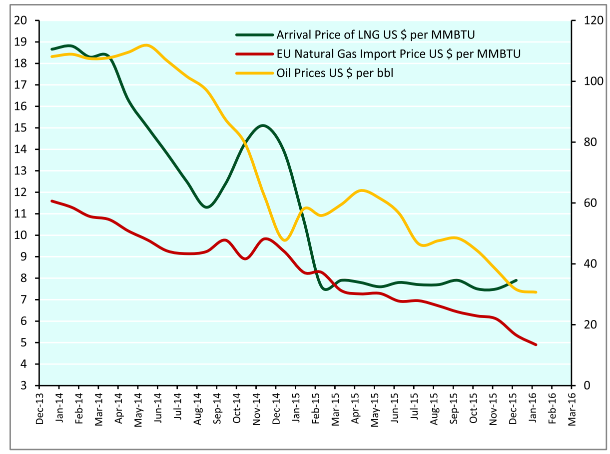

Fig. 17. Oil prices vs LNG and EU natural gas import prices.

Similarly falling oil prices has significantly affected the European Union natural gas prices, and so far a drop of 50% has been recorded since June 2014.

There will be, however, a big dent in the earnings of giant integrated oil companies like Exxon, Conoco, Shell, Amoco, and Chevron because they have to sell their petroleum products at cheaper prices. In reaction to low prices, some of these companies plan to drastically lower their investment and many others may do the same in the future. The hardest hit will be taken by the shale oil companies that are already in financial stress because the breakeven price for them is $60 a barrel and hence they cannot make a profit unless the price is above this amount. Their existing wells may continue to operate, however, they may eventually downsize their operation by ceasing to invest in new ones. The negative effects on the oil-rich southern states are especially problematic. Likewise, oil-exporting countries like Iran, Russia, Venezuela, and Saudi Arabia whose economies depend heavily on oil revenues stand to lose big. For example, a drop in oil prices creates a massive revenue shortfall for the Iranian government that needs at least $100 per barrel to balance its budget.

The price drop plunged the oil industry into crisis, with major international oil companies and small independents cancelling billions of dollars worth of projects planned for 2015 and 2016. Across the industry, some 400 US $ bn in expected investment has been canceled or delayed (Adams, 2016). Wood MacKenzie, a consulting firm, identified 68 large oil and gas project worldwide, identified 68 large oil and gas projects worldwide, with a combined value of $380 billion (Deferred upstream projects tally reaches 68, 2016; Scheck, 2016a), that have been put on hold around the world since prices started coming down, halting the production of 2.9 million barrels a day. It is estimated that the global investment in oil production and exploration has fallen by $150 billion in 2015 (The Oil Market Abnormally Normal, 2015). The U.S. Energy Information Administration estimates that lower oil prices and lower investments could see US crude oil production fall by 7% in 2016. Barclays estimates that investments into the oil and gas industry would fall by 15% in 2016. It fell by 23% in 2015. The ambitious investments in LNG, deep-water exploration and Canada's oil sands are becoming increasingly scarce. North American oil and gas companies are expected to cut their capital spending by 27% in 2016. However, Middle East oil and gas companies are expected to increase their capital spending in 2016. So, this suggests that Middle East oil producers are winning the battle. The mammoth fall in oil and gas investments would curb oil production activity and eventually, this will feed back into prices, but only slowly and gradually.

The low prices will also affect the world proved oil reserves. According to the 2015 BP Statistical Review of World Energy (BP Statistical Review of World Energy, 2015), in the past 10 years global proved oil reserves grew by 334 billion barrels to reach a global total of

1.7 trillion barrels. To put that in perspective, Saudi Arabia's proved oil reserves stood at 267 billion barrels at the end of 2014. That means that the global proved oil reserves added to the books in the past decade were equal to one and a quarter of Saudi Arabia. Was that much new oil actually discovered over that time frame? No. Further, we can anticipate that a big fraction of the proved oil reserves that were added in the past decade will have to be removed from the books at the end of this year. To understand why, it's important to understand a few things about oil reserves.

An oil resource describes the total amount of oil in place in a formation, a country or even the world. Most of the resource typically can't be technically and/or economically recovered. For example, it is estimated that the Bakken Shale centered under North Dakota may contain several hundred billion barrels of oil (the resource). However, what is technically and economically recoverable in the Bakken has been estimated at less than 10 billion barrels (< 10% of the resource). The portion that is technically and economically recoverable at prevailing oil prices may be classified as proved oil reserves. Because of the requirement that the oil be economically recoverable, proved reserves are a function of oil prices and available technology. This is an important qualifier. Thus, as oil prices rise, oil resources that may have been discovered decades ago can be shifted from the category of resources into the category of proved reserves.

One of the major consequences of the current oil plunge is the drastic effect on the oil and gas related job sector. As the price of crude oil continues to slip down, the oil companies are cutting jobs to survive the business. The collapse in oil prices has so far claimed more than 250,000 jobs worldwide according to Houston consultancy Graves & Co (Scheck, 2016b). The Canadian Association of Petroleum Producers (CAPP) estimates the energy industry downturn has led to 35,000 layoffs in Alberta's oilpatch so far this year. The fall in drilling activity impacted oilfield equipment and services companies like Schlumberger, Halliburton, Baker Hughes, Weatherford, National Oilwell Varco (NOV), FMC etc. Schlumberger, the world's largest oilfield services company, has laid off 30,000 employees representing 23% of their workforce since June 2014. Similarly Halliburton the 2nd largest oilfield services company, total headcount has been reduced by 29,000 since 2014, resenting 34% of its global workforce. The falling oil prices causing the sharping decline in the income oil exploration and production companies and they now reacting to the low oil prices in the jobs cut. An E & P company, Royal Dutch Shell has become the latest victim of the oil price rout after it confirmed 10,000 jobs would be axed amid its sharpest decline in income in 13 years (Cunningham and Ambrose, 2016). Table 1 shows the number of jobs laid off by Oil companies since 2014.

6.4. *Effects on downstream industry*

However for many companies in the downstream sector, the current low-oil-price environment has been a blessing. With the plunge in oil prices, their feedstock costs have fallen materially. Simultaneously, demand for their products has risen, propelled by a pickup in economic growth triggered by the decline in oil prices. These companies' margins have widened proportionately.

Table 1
Major layoffs.

S.No.	Company	Type	Jobs Layoff
1	Schlumberger	Service Company	30,000
2	Halliburton	Service Company	29,000
3	Weatherford	Service Company	20,000
4	Baker Hughes	Service Company	13,000
5	Shell	E & P Company	10,000
6	BP	E & P Company	7,000
7	Chevron	E & P Company	7,000

For instance, the Reliance India, operator of the world's biggest oil-refinery complex having combined capacity of 1.24 mbd, reported its highest quarterly (April–June 2015) profit in seven and a half years as lower crude costs boosted earnings from fuel sales (Shanker and Chakraborty, 2015). During that quarter, the profit margin of company was $10.40 for every barrel of crude turned into fuels, compared with $8.70 a year earlier. Moreover, the company is investing $12 billion to boost its petrochemicals capacity and build facilities to import ethane from the US. A further $5 billion will be spent to complete the refining and petrochemical cracker and downstream projects. Similarly the profit margin of crude oil processing refineries in USA rose by 20 – 30% during 2015 (Rey, 2016).

However, the effects of low oil prices on downstream companies vary by segment and, within some segments, by region. On the supply front, some refining projects will be postponed, as the fall in oil prices poses a financial burden for most national oil companies in Asia and the Middle East, likely forcing some to reduce downstream capital expenditures. Kuwait Petroleum International, for example, has canceled a planned $1.4 billion investment in its (88,000 barrel bpd) Rotterdam refinery and may sell it. In the U.S., low oil prices have already led Marathon Petroleum to defer a final investment decision on the planned expansion of its residual-oil upgrader at the company's 522,000 bpd refinery in Garyville, Louisiana (Marathon cancels Garyville refinery upgrade, 2015). In China, Sinopec, Asia's biggest refiner, recently announced that it would cut capital expenditures by 12% as a result of cash constraints and declining growth in domestic demand for oil (Marten, 2015). Petro-China has canceled two grass-roots refinery projects that represent a total of 400,000 barrels per day of production capacity (Marten, 2015).

In sum, for many downstream companies, the current environment offers attractive opportunities for revenue and profit growth. However in long term, if a sufficient number of the industry's investments are canceled or delayed, it could produce negative effect the economic growth.

7. Oil prices in future

There are lots of projections for the oil market, yet no one predicted or got anywhere near close to the steep price fall in August 2014. Especially the people whose business it is to track the price of oil hadn't the slightest idea this was coming. An exception to these projections is the paper, "Oil: The Next Revolution" authored by Belfer Centre (Harvard University) energy expert Leonardo Maugeri In 2012, was the only who boldly predicted today's oil glut in his paper, "Oil: The Next Revolution (Maugeri, 2012). Crude oil is one of the hardest markets to predict by far because there are so many conflicting crosscurrents that affect its price including supply and demand, geopolitics, and the global monetary and regulatory environment.

The Wall Street Journal's 2014 economic forecasting survey found that the economists surveyed expected oil to end 2014 at about $95 a barrel, up from about $92 at the time of the survey (Zweig, 2014). A big miss to be sure, but they were not alone. The U.S. Energy Information Administration July 2014 outlook gave itself a very wide margin for error, projecting oil prices to average $110/bbl in 2014 and $105/bbl in 2015 (Short-Term Energy Outlook (STEO), 2014). Similarly The IMF World Economic Outlook of October 2014 forecast that the average price of oil will be $103 a barrel in 2014 and $99 a barrel in 2015 (World Economic Outlook. International Monetary Fund (IMF), 2014). Medium-term Oil Market Report 2014 published by International Energy Agency estimated that oil prices will average 108 and 103 for 2014 and 2015 respectively (Medium-term Oil Market Report, 2014). The estimate of World Bank was also far away from the real market. World Bank Commodity Markets Outlook, July 2014 report stated that the average oil prices per barrel are expected to $106 in 2014 and $104 in 2015 (Commodity Markets Outlook, 2014). In the same manner World Oil Outlook 2014 issued by Organization of the

Table 2
Oil prices forecasted for 2016 & 2017.

S.No.	Organization	Report Date	Forecasted Price		Report Date	Forecasted Price	
			2014	2015		2016	2017
1	Wall Street Journal	Oct–14	95		Feb–16	39	
2	U.S. Energy Information Administration (EIA)	Jul–14	110	105	Feb–16	38	50
3	International Monetary Fund (IMF)	Oct–14	103	99	Oct–14	50	55
4	International Energy Agency (IEA)	Jun–14	108	103	Jun–14		
5	The World Bank	Jul–14	106	104	Jan–16	37	48
6	Organization of the Petroleum Exporting Countries (OPEC)	Jun–14	110	110	Jun–14	50	55

Petroleum Exporting Countries (OPEC) assumed nominal price of $110/b for 2014 and 2015 (World Oil Outlook, 2014). Forecasted oil prices of all mentioned organization at level along with their current estimated are summarized in Table 2.

Low oil prices are predicted to remain in place for the foreseeable future, based on signs a global oversupply will continue. Interestingly, two contradictory oil price forecasts have appeared in the past few days, Goldman Sachs predicting that prices would remain “low” for fifteen years, while OPEC does not see oil prices returning to triple-digit territory within the next 25 years it has argued that the price should recover to $80 a barrel by 2020. According to recent estimate of February 2016 by US EIA, Brent oil prices will average $38/b and $50/b in 2016 and 2017 (Short-Term Energy Outlook (STEO), 2016). In the recent scenario almost every forecasting organization are slashing their projection for oil prices e.g. a recent survey of 13 investment banks in February 2016 by The Wall Street Journal foresees Brent crude, the international oil-price benchmark, averaging $39 a barrel this year, down $11 from the survey in January 2016 (Kantchev, 2016).

Looking ahead, shale oil supplies are likely to continue to be a highly elastic source of oil supplies (Kaushik and Sri, 2015). But as output from shale oil wells declines rapidly, falling by some 70% or more in the first year and more than 80% in the first two years (Commodity Markets Outlook, 2016). This requires substantial drilling to offset the shale's rapid declines. While efficiency gains and technical innovation are expected to continue, future improvements may be more difficult (Commodity Markets Outlook, 2016). The US shale oil industry has so far proved surprisingly resilient in the face of low oil prices, but the IEA report suggests the growing financial pressure on shale operators and the steep fall in the number of rigs drilling for oil is beginning to take their toll on production. On other hand, it is also quite possible that Libya and Iran will add significant amounts of oil to the market, up to 2 mb/d, in the next couple of years, and Iraq (including Kurdistan) could meet as much as one-third of global demand growth for years to come.

Oil prices forecasting have major connection to supply and demand market. On the supply side, the three important features of oil industry are exploration, development, and production. Exploration is very sensitive to projected prices of crude oil. With prices now dropping, new exploration activity will decline. Development is the process of sinking more wells in a field that has already been proven by exploratory drilling. Development also includes building the local pipelines and terminals required to get the oil to a transportation facility. Development expenses are often worthwhile even at lower prices. For example, suppose that the all-in cost of oil from a brand new field is $80, of which $30 per barrel constitutes exploration. That means that development and production only costs $50 a barrel extra. If the exploration costs have already been paid, then companies will continue with development even at today's $60 price. Production is even cheaper. Traditionally, production costs were very small compared to exploration and development, but wells that are fracked have higher production costs that old-fashioned wells. Nonetheless, once the exploration and development have been paid for, it almost always makes sense to keep the wells pumping. Therefore supply-side question for the future is *not* whether it's profitable to find new oil at today's low prices. The question is how long we can enjoy the new oil supply that has been discovered in the past ten years. Some expert believe the answer will range in 5 to 10 years.

On the demand side famous oil prices analyst Michael Lynch think that without a strong economic revival in China, it will be difficult to develop enough demand to absorb likely increases in OPEC production (Lynch, 2015). He believes that a long-term price is more likely to be $50–60 a barrel by 2020 [Michael Lynch]. The confusion around the demand issue is that there are times that demand growth slows, and that is often mistranslated into “falling demand.” For example, the International Energy Agency – IEA (Medium-term Oil Market Report, 2016) has forecast that demand growth will slow to 1.2 million barrels per day (bpd) for 2016, but this follows very strong demand growth of 1.6 million bpd in 2015. Nevertheless, this year's forecast of 1.2 million bpd of new demand growth is still above the average growth rate of the past 30 years, and is certainly not a decline in demand.

In conclusion the only certainty about oil market is that prices will be uncertain and likely volatile in next couple of years.

8. Conclusion

(1) Both long- and short-term factors contributed to this plunge, including a surge in oil supply due to the shale revolution in the U.S. and Canada, robust production in the Middle East from Saudi Arabia and Iraq, change in OPEC policy objectives, a slowdown in the Chinese economy that has diminished expectations of future demand, and a rapid rise in the value of the dollar relative to other currencies. The exact contribution of each of the factor is difficult to quantify. It is estimated that the supply counts for 30%, demand for 20%, Dollar 0–3% and the balance can be linked to the hidden sources.

(2) It is observed that the supply and demand haven’t changed enough to create a 72% plunge in oil prices. It means that the major fall in oil prices since June 2014 may be about a shift in trading (most probably due to changing role of oil pricing reporting agencies –PRAs), rather than a change in the fundamental supply and demand equation. PRAs play an important role in assessing the prices of benchmark crudes such as WTI, Brent, and Dubai and these assessed prices are then used by oil companies and traders to set the oil prices contracts.

(3) While U.S. shale oil producers will struggle to stay profitable amongst low oil prices, their rise has significantly changed the economics of global oil production. The very fact that Saudi Arabia and other OPEC members chose not to cut production in order to boost oil prices because they are wary of losing market share suggests that a future oil embargo like that of the 1970s is unlikely. Any attempts to cut production and limit the supply to the rest of the world will quickly revive shale oil production in order to fill the supply gap.

(4) One of the implications of the recent oil revolution is that U.S. production can play a significant role in balancing global demand and supply, and this in turn implies that the current low oil price

environment could be persistent.

(5) Some high-cost shale production is closing, but once wells are drilled, it usually makes sense to keep pumping, even at a loss. It is better to make a little money rather than none. And the shale revolution is marching on.
(6) The huge fall in oil prices launched all manner of conspiracy theories, which says that the oil prices are down purposefully by US and Saudi to destabilize several strong opponents of US globalist policies.
(7) Politics and the tussle between the sole super power and countries that continue to challenge that status quo of the sole supremacy will determine the future of oil crisis that currently exists. Therefore it is not a game of pure supply and demand. It is also a game of reigning supremely: politically, economically and militarily that will determine the future volatility of oil prices.
(8) Falling oil prices for the economy as a whole, brought both positives and negatives effects. Low oil prices offers advantages to net oil importers by making them to cut their costly and expensive fuel subsidy program and diverting the same funds for much-needed infrastructure and other growth projects. On the other hand, in oil exporting countries, the sharply lower oil prices will weaken the fiscal position and shrink economic activities.
(9) Job losses and investment decline in hydrocarbon related industries and more oil consumption are just a few bad side effects.
(10) It is very difficult to make firm projections about the future oil prices, as there are several contradictory variables that that affect oil prices, from supply and consumption, technological development, global financial environment and geopolitics (which is inherently unpredictable), but it is important to be conversant with some factors that have a high probability to force the oil prices lower for next couple of years.
(11) Over the medium term the volatility in oil prices and consequently uncertainty in the world of Energy, Politics and Economics will continue to prevail for a couple of years due to an unavoidable relationship between the three elements.
(12) The only certainty here is that oil prices will be uncertain and likely volatile in 2016.

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Annexure-G

Khan, M.I., 2017. Identifying and addressing barriers for the sustainable development of natural gas as automotive fuel. International Journal of Hydrogen Energy, 42(40), pp.25453-25473.

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Identifying and addressing barriers for the sustainable development of natural gas as automotive fuel

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ABSTRACT

In recognition of the risks associated with climate change, governments around the world have tried to develop and define policies to address greenhouse gas emissions with transport recognized as one of major sources of greenhouse gases and air pollution. Apart from climate change, there is another side to this coin, and that is the risks surrounding energy security and future oil supplies. Vehicle manufacturers are increasingly recognizing their role in contributing to the goal of decarbonizing the economy and reduce dependence on oil. Out of available alternate fuels compressed natural gas (CNG) is the one which is meeting the maximum needs of countries worldwide, who want to switch over to alternate fuels. However, despite the fact that CNG are often seen as a panacea by policy-makers, there are a number of barriers to their widespread market penetration and diffusion. This study aims to identify an approach to strategic framework for addressing the barriers to widespread adoption of compressed natural gas as transportation fuel. Besides assessing the barriers to natural gas vehicles, the study attempts to identify how they can affect various stakeholders. The paper systematically examines natural gas vehicles (NGVs) adoption patterns and the evolution of pertinent market structures throughout the world but majorly concentrated on eleven countries:, China, Iran, Pakistan, Argentina, India, Brazil, Italy, United States, Germany, Sweden and South Korea. The underlying paper set out an objective of presentation of the framework for supporting policy makers in aspects including; identifying and assessing qualitative aspects of the barriers and consequently defining measures for their resolutions.

Introduction

World total primary energy consumption remained 549 quadrillion Btu in 2012, of which 72 quadrillion Btu shared by road transport sector [1]. Road transport predominantly relies on a single fossil resource, petroleum that supplies 96% of the total energy used by this sector. It is well evident in the literature that high fossil fuel usage and consumption in transportation, increases emission of pollutants causing serious negative externalities and environmental degradation [2]. It is found that road transport sector produced 5.0 $GtCO_2eq$ of direct GHG (greenhouse gas) emissions in 2010 and hence was responsible for approximately 10.3% of world GHG emissions, which is the leading cause of global warming [3].

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Since the past few years, attention has been focused upon alternative fuel vehicles (AFVs) within the context of greenhouse gas emissions [4]. The policy developers must realize the importance of transportation as part of a socio-economic development of a nation. It is essential for them to establish policies which are not only environment friendly but also sustainable. Transport demand must not be restrained by the controversial change in behavior measures like the planning restrictions, road pricing congestion charges or the carbon taxes. Their policies must include opportunities for job creation, economic growth and supply security enhancement like domestic biofuel production incidents.

Throughout the world markets, there are various kinds of AFVs available like ethanol, methanol, natural gas, fuel cell or hydrogen, biodiesel and electric or hybrid electric. Of these, compressed natural gas (CNG) fuel is the most popularly used alternative fuels being used in the world where alternate fuels are being preferred [5]. CNG has a clean combustion nature thus it is considered as the most appropriate fossil fuel substitution solution [6,7]. World-wide, this fuel is considered as environment friendly [8,9]. The following aspects have enhanced the use of natural gas being used as transportation fuel:

i. Wide availability
ii. Eco friendly
iii. Conventional SI and CI engines compatibility
iv. Low operational cost.

Although share of natural gas in today world road transport sector is slightly above 1%, but according to recent report of US Energy Information Administration, IEO2016, global natural gas consumption is expected to increase @1.9%/year. Abundant natural gas resources and robust production—including rising supplies of tight gas, shale gas, and coalbed methane - contribute to the strong competitive position of natural gas. In addition, 50% of bus energy consumption is projected to be natural gas in 2040, as well as 17% of freight rail, 7% of light-duty vehicles, and 6% of domestic marine vessels.

Determination of innovative fuel for transportation is limited by elements in the social as well as the economic surroundings that also have technology as an integrated element; hence, becomes a years' long and considerably ambiguous process [10]. Implications of a complex environment in which a policy is to be implemented and made is when ignored, it resultantly causes failure of the policy [11]. Therefore, it is important to analyze environment for policy.

Yeh et al., 2007 [12] studied mitigation policies of greenhouse gas from the transport sector, including a transition policy to NGVs, by using a bottom-up MARKAL model. The study compared NGVs usage in eight countries that are Argentina, Brasilia, China, India, Italy, New Zealand, Pakistan, and United State. The study investigates main policies in order to promote NGV usage, instrument for policy implementation and factors that influence NGV usage. The major findings of the study can be summarized as follows:

- The availability, modern technology and gas fuel vehicles component are important for the acceptance of gas fuel vehicles on customer side, compared to the existence of OEMs (original equipment manufacturers).
- The main strategies of NGV success are having a retail selling price of gas fuel as much as 40%–50% below gasoline & diesel price, and also giving incentive to receive payback period for 3–4 years or below.

Collantes et al., 2011 [13] analyzed Argentina's experience in implementing CNG program. Methods that have been used in the analysis are through interviews with stakeholders and analyzing Argentina's economical data to determine the main reason in fuel usage in the views of economic, politic etc.. Based on analysis result, regulation to determine fuel prices is decisive factor that significant with CNG usage. Main points of the study that need to be highlighted on NGVs development are:

- Determine and implement the effective standards and codes;
- Cost prediction and financing mechanism from fuel switching transition;
- Cooperate with the stakeholders;
- Determine economical price for consumers;
- Bi-fuel CNG vehicles can relax the close coupling of vehicle adoption rates and infrastructure expansion rates that constrains the deployment of dedicated NGVs.

Janssen et al., 2006 [14] analyzed the introduction of NGVs in Switzerland. Stakeholders' analysis and dynamic modeling technique were used to describe the system. The analysis identified barriers and chances in penetration process of cars market with gas fuel in Switzerland. Referring to elements of "Balanced Scorecard" approach, it will produce better performance on implementing fuel gas vehicles in Switzerland. The recommendations of the this study are as follows:

- CNG fuel station ratio is 1:300 NGVs;
- NGV conversion done by local mechanic caused higher emission level and greater fuel usage compared to NGV from OEM. Thus, it eliminates most of the gas fuel usage benefit;
- The NGVs Payback period is a maximum of four years in order to attract customer, therefore lesser tax from government is needed;
- Subsidy for the purchase of NGVs is important in order to give customer attraction.

The former president of CNG Fuel Systems (a Canadian organization), Flynn [15] states in his 2002 paper analysis regarding the mid-1980s (1984–1986) commercialization failures of the NGVs in Canadian market. Various factors which leads to the failure of vehicle adoption are mentioned which includes the present refueling stations lower level profitability for their increased investments. Additionally, he states that vehicle conversions would have low level sales, conversion dealers would be subjected to excessive parts markup, economic and environmental advantages increased claims and promotional activities inefficient design.

Wang H et al. [16] analyzed the enabling factors and barriers to China's NGVs development. Important outcomes of their study can be summarized as:

- Relatively low natural gas price promotes NGV development.
- Coordinated development of refueling stations and NGVs is important
- Policies that encourage private NGVs development should be adopted
- Middle-income and medium-sized cities are more suitable for developing NGVs

In a recent article Ogunlowo O et al., 2015 [17] studied the NGVs implementation approaches and outcomes in seven countries with diverse experiences in order to gain an understanding of the barriers to the NGV market development in Nigeria. Their results can be summarized as:

- The use of legislative mandates helps deepen NGV penetration.
- Aligning stakeholder interest is critical to NGV adoption.
- Making national interest a priority ahead of regional infrastructure is a critical success factor.
- Government support drives participation.

von Rosenstiel et al. [18] used a case study procedure by integrating quantitative data with perceptions of the multi industry expert panel extracted through in-depth interviews. Additionally, the civil society, government and industry experts were also interviews to understand the aspects leading to the low growth level of German CNG sector and market failure. According to the research, the most prominent factors leading to the failure of the NGV functioning market are complementary market coordination failures, information is imperfect, consumer rationality is restricted and issues related to principle-agent.

Wiedmann et al., 2011 [19] explored and analysed the aspects limiting the market development for NGVs in Germany. Analysis included determination of the aspects that negatively influence the purchase pattern and in turn causes limitation in the development of market. Financial risk factors such like cost and payback period; driving range being performance aspect; associated danger or physical risk; and time required for adapting to a new technology constitute major risk factors.

However, despite this increased interest from scholars and policy-makers little systematic and comprehensive work linking the drivers and barriers to actual adoption at national level has been done. It is important to note that earlier studies [12,17] based on the statistical data reported by IANGV (International Association of Natural Gas Vehicles). However there is a significant disparity between the data of IANGV and actual market data. For example, number of NGVs reported by IANGV for the countries: China, Iran and Pakistan (top 3 NGVs countries) for year 2010 were 550,000, 2,070,930 and 2,850,500 respectively. While the actual data reported by the concerned ministry of the respective country for the year 2010 were 1,088,879 [20], 2,467,862 [21] and 2,590,200 [22] for China, Iran and Pakistan respectively. In this study the data were collected from state-owned official NGVs authorities of the concerned country e.g. HDIP (Hydrocarbon Development Institute of Pakistan), IFCO (Iran Fuel Conservation Organization), China's Ministry of Transport, GAIL (Gas Authority of India Limited), US AFDC (Alternative Fuels Data Center), Secretarıa de Energıa (Secretary of Energy) Argentina, Ministry of Environment, South Korea etc.

Research objectives and methodology

Most studies examining NGV market penetration and the role of economic and policy factors have been limited to single-country analyses [15,18] or provide only a snapshot of comparisons across countries [14,23] without considering socio-economic condition of the case countries. This paper systematically examines NGVs adoption patterns and the evolution of pertinent market structures throughout the world but majorly concentrated on eleven countries. The eleven countries are divided into two groups:

Developing Countries: Those countries having GNI per capita less than $12,475 as specified by World Bank [24]. The selected courtiers are China, Iran, Pakistan, Argentina, India and Brazil.

Developed Courtiers: Those countries having GNI per capita higher than $12,475 as specified by World Bank [24]. The selected courtiers are Italy, United States, Germany, Sweden and South Korea.

These countries representing the top NGVs countries in their respective group with respect to number of NGVs. The selected countries were divided in the above mentioned two groups because the adoption of any alternative fuel technology has a strong connection with socio-economic status of the end user. For example as shown in Fig. 1, NGVs have shown significant penetration in the Asian road transport. However, despite substantial public and private investment of more than 2.5 billion Euros, NGVs have been adopted far slower in most OECD markets than expected. Moreover these countries represent the top NGVs countries in their respective group. The countries have wide range of market experience, spanning early development (India, Argentina, Italy), sustained growth/high penetration (China, Iran, Pakistan), and low penetration (US). Specifically, this paper examines the barriers to the NGVs market development. The objective of this paper is to present a framework, which can be used by policy-makers to identify and qualitatively evaluate these barriers as well as potential policies that might be implemented to address these barriers.

The paper uses the personal data collected during several years of experience with Pakistan CNG industry, secondary data from academic literature, published reports by a variety of international agencies, expert presentations, and grey literature comprising of government publications, reports, statistical publications, news-letters, fact sheets, working papers, technical reports, conference proceedings and policy documents.

World NGV market

Number of NGVs are increasing at such fast pace that there are no information sources which are consistent. However, as

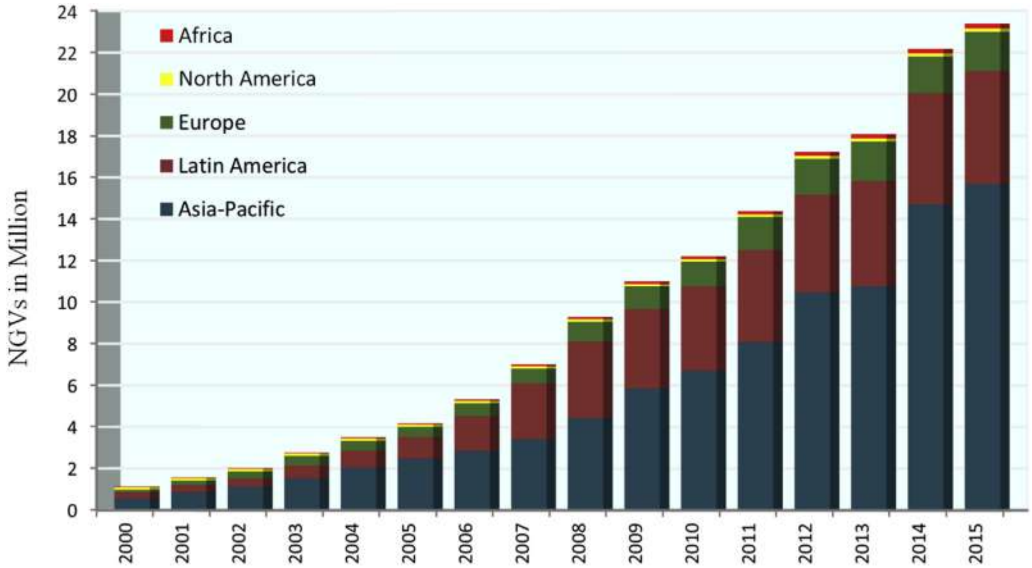


Fig. 1 – Worldwide NGVs growth by region.

per the existing reliable sources, currently there are over 23.5 million NGVs and over 22,000 CNG refueling stations distributed through 85 countries worldwide with major concentrations in Asia and Latin America regions [25]. The majority (93%) of CNG vehicles are light duty car and commercial vehicles. Fig. 2a shows the top 6 NGVs countries from developing economies while Fig. 2b represents the top 5 NGVs countries from the list of developed countries.

NGV market's participants

Investors, general consumers, associated businesses, and other fleet owners from public and private sectors constitute the main stakeholders for NGVs market. Hence, understanding of their respective viewpoint is critical in determining the aspects of limiting growth of NGVs market. Broadly three categories, public fleet owners, private fleet owners and general consumers constitute have much variation in their respective purchase decision. According to the survey results, vehicle performance and design style have 82% and 65% role in individual's car purchase decision [26]. Another survey (Fig. 3) shows 24 factors having different weightage which are considered by LDV consumers when opting a vehicle. Performance and style do not attain vital importance since the fleet buyers are not the drivers. These buyers are interested in lifecycle costs, prices, serviceability and vehicle suitability during purchase decisions [27]. Operation specifications and requirements for public and private fleet buyers also have variation. For example, budget is the major guiding principle of public fleet buyers. They are restricted in moving investment (or capital) fund to the operational (or maintenance fund).

NGVs market's another major stakeholder and buyer category including vehicle manufacturers. The said category is large in size and has been in the conventional vehicle manufacturing business for good long time; while, have

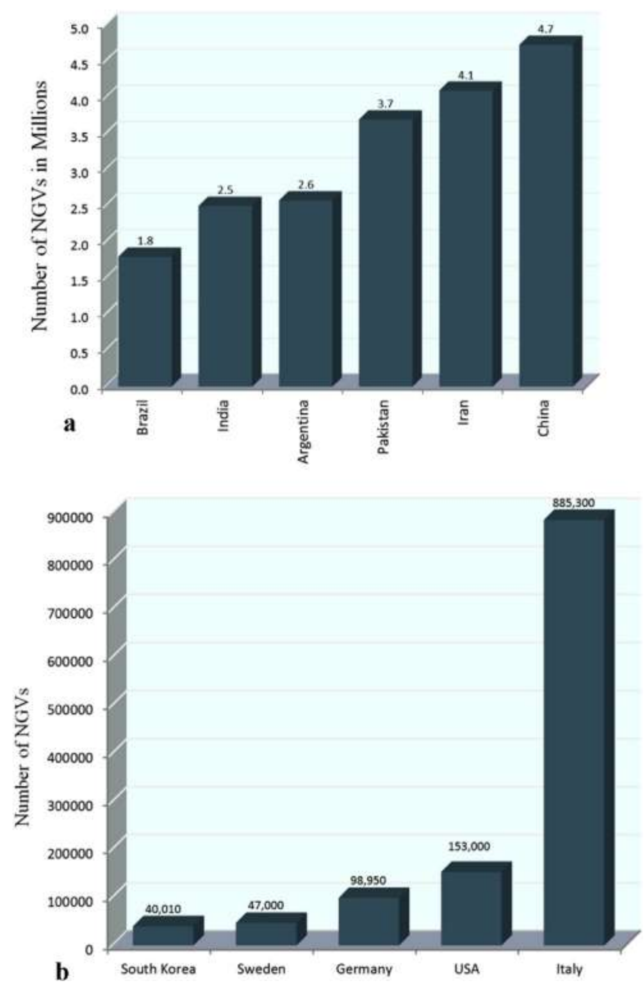


Fig. 2 – a. Top NGV Countries (from developing economies). b. Top NGV Countries (from developed economies).

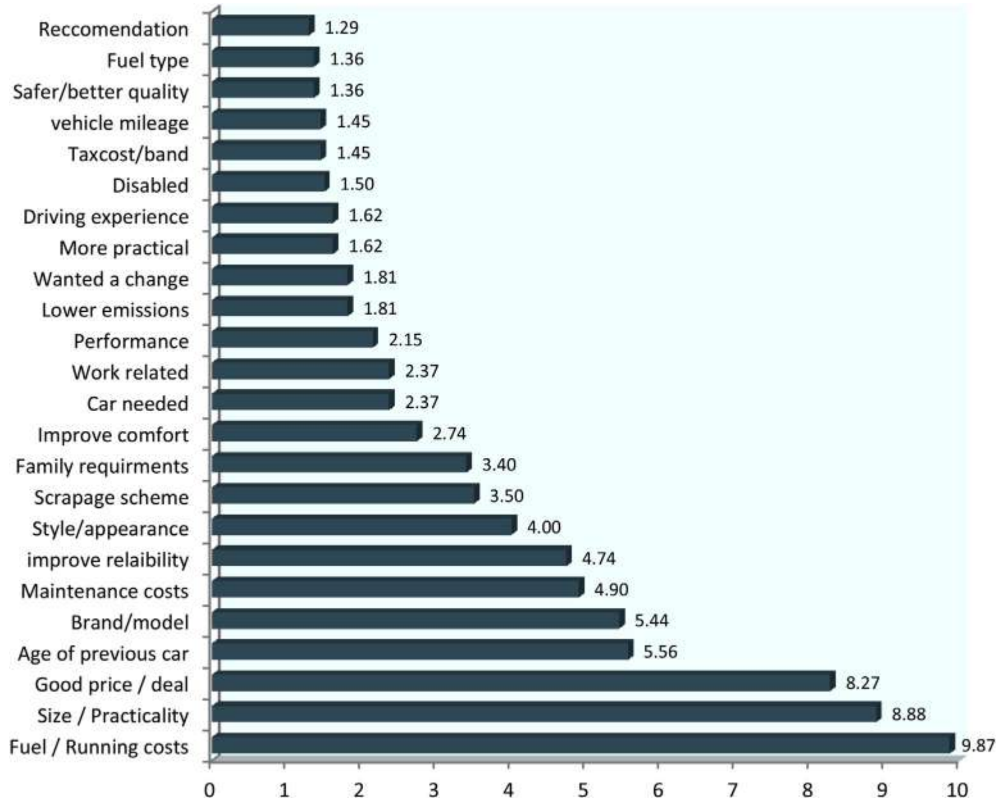


Fig. 3 — Weightage of consumer preferences while selecting a vehicle.

recently started adding NGVs to their offerings and product line. For instance, in 1998 Honda started production of Civic GX first factory-built car fueled with CNG in the US.

Air quality requirements and fuel economy standards both contributes to growth of the NGVs market. CNG buses are often first introduced in cities that can otherwise not attain ambient air quality standards imposed by government environmental protection authorities.

Another set of stakeholders include fuel suppliers who have core interest in establishing infrastructure related to fuelling stations for NGVs. They also include companies with focus in production and sales of natural gas. Additionally, infrastructure providers are also stakeholders in NGVs market. These type of stakeholder face strict restrictions on the investments they can make as the distribution and sale of natural gas is regulated by the government in most of the regions. Widely this set of stakeholders constitutes government, which meets the initial investment needs related to development stage followed by usage stage.

Barriers to NGV adoption

Identification of the challenges that is limiting the pick of the natural gas for meeting fuel needs regardless of fact that it offers considerable cost saving benefit can be a starting point. Resulting suggestions for the resolution of identified issues can be made. It is important that the key stakeholders which are government at different levels can take up the responsibility of determining and resolving such barriers.

In particular, the barriers to alternative fuel vehicles can be classified in financial, political, regulatory and legal, technological, public acceptance, and market availability [28,29]. But there are many differences between CNG and other type of alternative transportation fuel, owing to which the barriers identified in the literature can't be implemented to CNG industry without considering the features associated with CNG industry. As a first step in identifying promising solutions, it is critical to understand the fundamental barriers to NGVs deployment, as well as specific barriers to NGVs finance.

By studying the CNG industry of various countries, we have identified the following barriers (Fig. 4):

i. Financial barriers, which include additional costs to consumers, capital and operating costs for investors and resource constraints on public finances;
ii. Technical or commercial barriers, which might limit market availability and commercial feasibility;
iii. Institutional and administrative barriers;
iv. Public acceptability;
v. Legal or regulatory barriers;
vi. Policy failures and unintended outcomes;
vii. Physical barriers;
viii. Information-related barriers to NGV purchasers and fueling infrastructure providers;
ix. Barriers to private investment in NGVs and fueling infrastructure;

Fig. 4 – Barriers to the adoption of CNG as Transportation Fuel.

x. Information-related barriers to private investment;
xi. Legal and regulatory barriers to private investment;
xii. Coordination failure in complementary markets.

Financial barriers

The main financial barriers for the NGVs consumers include: (a) the additional cost of OEM NGVs purchase relative to conventional technologies; and (b) modification costs of converting gasoline vehicle to bi-fuel CNG vehicle. The capital cost of the NGVs tends to be higher than the alternatives, and prospective users of gas powered vehicles will only use such vehicles if the overall lifetime cost is less than the alternatives. The consumer belong to lower income class having limited available funds for down payment tends to opt for the fuel related cost saving in future [30]. In general, most consumers will only opt for alternative fuels if they are price competitive with mineral fossil fuels and environmental considerations tend to be overshadowed by price and availability. The additional cost associated with the purchase of new OEM or retrofitted NGVs varies from region to region.

The heavy-duty NGVs cost over $30,000 than the equivalent diesel vehicle and $6500 to $10,000 is the cost of the new OEM light-duty NGV as compared to the gasoline vehicles [31]. The price depends on the fuel-tank capacity and whether the vehicle is purchased from a dealer or is an in-service vehicle that has been converted. The maintenance and operation costs of NGVs are similar to those of their gasoline or diesel counterparts.

One of the major problems with the development of CNG refueling infrastructure in the developed countries is the requirement of relatively much investment for the construction of CNG stations. A fast fill station in the developed countries may cost anywhere from $1.2 to $1.8 million [32,33]. While on other hand cost of constructing same size of CNG station in the developing countries ranged between $120,000 and $200,000 per station. For example in Pakistan the country having the highest number of CNG station after China, the average cost of constructing a CNG station is comparatively much low and amounting to $150,000 [34]. Whether this is due to lower labor costs in the developing countries or different regulation stringency, the fact of the matter is that the payback period for refueling station investment is relatively very high. Moreover being having gaseous nature, the operative cost of CNG refueling station is high in contrast to conventional refueling station. Fig. 5 shares the survey results as presented by Seidinger et al., 2012 [35], a comparative data between the diesel/petrol and CNG refueling stations in European countries. The survey included the direct costs such as equipment and fuel transport or grid connections (for the CNG option) and indirect cost such as land and buildings. Important to mention is the fact that refueling hold most significance among factors. According Seidinger's survey analysis a dedicated CNG station would need an annual capacity of around 1 million Kg of CNG (equivalent to around 1.46 million liters of diesel) and would need to achieve sales volumes of at least 30% of maximum sales capacity to be efficient. Contrarily, a dedicated petroleum station in Europe reports to have output of around four million liters annually while has a benchmark cost of operations approximating €200,000.

Given the likelihood of slow build-up of CNG sales, co-location with existing facilities is clearly the most cost effective option though the cost of grid connections could still be a very significant additional item.

To minimize the initial investment required for construction of dedicated CNG refueling stations, states and provinces can also encourage communities, counties and municipalities to provide land designated for CNG station sites. This would

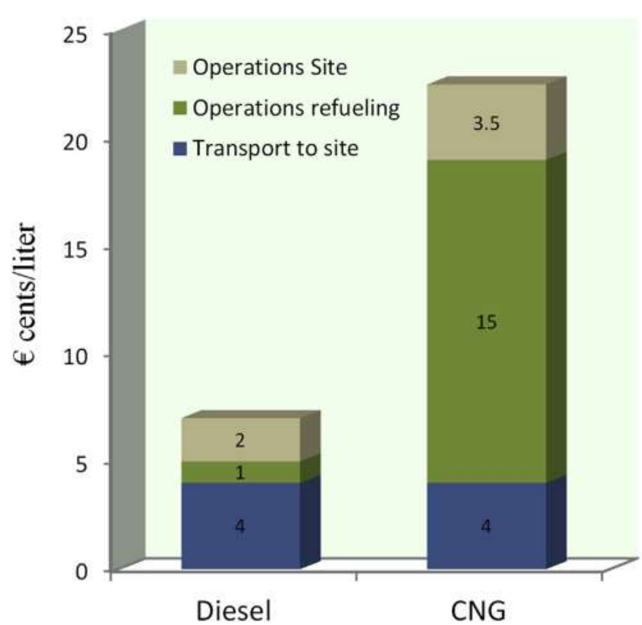


Fig. 5 – Refueling Station Cost of CNG vs Diesel.

reduce capital expenses for infrastructure development and send a signal to communities that CNG deployment is a priority. Land along highways or at rest stops, or land co-located with other fueling sources, would be ideal.

In case of developed countries, the annual capital costs could be calculated as follows:

$$C = P \times \frac{(1+i)^s \times i}{(1+i)^s - 1}$$

where:

C = investment costs/year (depreciation and interest)
P = purchase price of CNG-station
s = service life of CNG-station (20 years)
i = notional interest (10%)

In line with the above discussed assumptions, approximate annual cost is amounted to US$ 35,200. Spreading the cost over the output of the gas on an annual basis is a way for recovering cost. Therefore, annual sale of 1.6 million cubic meters CNG still requires the gas prices to be pulled up US' 2.2 per every cubic meter sale (annually) for meeting the cost of investment. Considering an undeniable role of the operating cost such as salary, maintenance, and other energy costs etc., the price will ultimately have to be increased to US' 4.0 for every cubic meter sale of CNG. The competitiveness level of gas as against the fuel and diesel will be driven by the recovery of initial investment in full and for this, it is critical to have a contribution from the government. The contribution from government does not need to be initial investment only; instead, government can contribute by reducing imposed taxes and other low interest loans for making capital investment. For instance, before mentioned statistics at affect, the cost of CNG (per cubic meter) can be reduced by US' 1.0 just by lowering the interest rate to 3%. It has been observed that once subsidies for fueling stations and NGVs customers run out, the expected profitability of new CNG filling facilities is no longer attractive enough. In e.g. Canada, reducing investments in fueling stations retarded the conversion sales. Investment in new refueling facilities stalled because existing stations did not buildup sufficient load to make them profitable. Interestingly, it shows that the lack of refueling infrastructure can also be attributed to minimal consumer demand due to the limited number, and higher price, of CNG vehicles available from automakers. Hence, for elevating the CNG consumption in a country by adding its supply infra-structure it is evident that the government has to play certain prominent role. As a matter of fact, in case government makes contribution in the initial investment and development costs, the future prospects for the country are considerably positive. Some benefits include reduced spending on oil imports and its financial and economic impacts on the budgetary conditions with sustainability. As the consumption of NVGs will take-up in the country transport sector, the needed contribution from the government will be reduced.

Fuel price ratio

The most essential aspect which motivates users to switch to the NGVs is the price difference between CNG and the other conventional fuels like diesel and gasoline [14]. There are significant fuel cost savings that can be made using CNG. In most regions refueling with CNG is around half the cost of conventional fuels i.e. diesel and gasoline that have had successful NGVs penetration. Fig. 6a and b shows the trend of fuel ratio of CNG to gasoline in developing and developing courtiers respectively. Interestingly it can be observed that there is no significant difference between CNG fuel price ratio policy in developing and developed economies with the exception of USA and Sweden where low fuel price difference between CNG and gasoline (0.75:1) can be a contributing factor towards the slower growth rate of NGVs in these countries. The relative pump price of gasoline and CNG depends on two factors: the inherent pre-tax difference in cost between oil and natural gas and the social stimulus provided by variable taxation or direct grants.

The fuel cost savings could be gained by businesses that are heavily reliant on transport. Trucking companies are the obvious beneficiaries of lower fuel costs, but companies such as Courier services companies, waste collection trucks operated by local councils, and other companies which rely on road transport to distribute their products around the city also stand to gain.

If the price difference is high, the NGVs drive will save on fuels and consumers would be motivated to switch. However, economic advantages are weakened by high CNG prices as the fuel cost savings are unable to offset the low engine power inconvenience. NGVs development in most nations is hindered by the low price advantage of natural gas when compared to gasoline. For instance the one of the major contributing factor for the well establish NGVs market of Argentina is the low CNG prices [13]. A similar situation can be observed in Sichaun (a major NGVs area in China) where fuel cost of NGVs per Km is nearly half of driving a gasoline vehicle [36]. With this price advantage, NGVs share 17% of total vehicle fleet in Sichaun while for the rest of the China the NGVs share to the total vehicle fleet is 4%. In another study of Chinese NGVs market, Hao H et al., 2016 [20] found that at a ratio below 0.5:1, adoption was strong, while with a ratio of 0.75:1, relatively few opted to adopt NGVs. Overall, we found that in countries with high NGVs market penetration, the price ratio of natural gas to gasoline is usually between 40% and 60%. There are examples from across the world where governments are enforcing regulation for encouraging natural gas consumption or discouraging the diesel consumption. Such as in Pakistan's government offered price benefit on natural gas while government in India banned using diesel in the buses running in metropolitan cities.

Payback period

The NGVs Investment Pay-Back Time expresses how fast the extra purchase cost for an NGV are compensated with lower fuel cost, for the main consumer segments. Large number of factors produces an influence on the payback period. Some factors, though not limited to, include, technology required for NGVs and conventional fuel vehicles, price variation, impact on vehicle efficiency, and miles coverage etc. When vehicle operators and owners make a choice regarding their fuel, the crucial variable is payback period of the additional investment made to convert the gasoline vehicle into running on the CNG

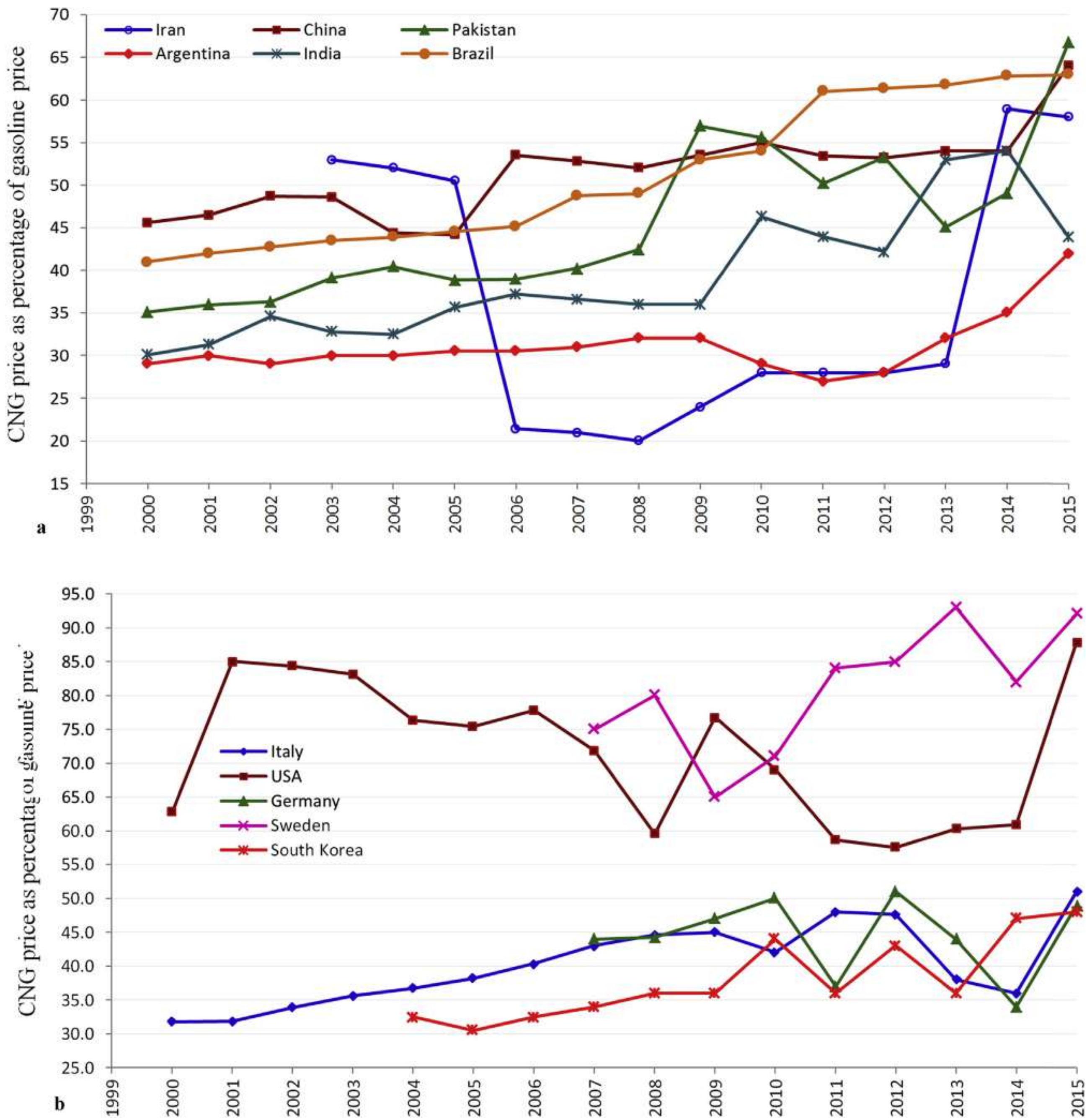


Fig. 6 – a. CNG to gasoline fuel price ratio in developing case-study countries. b. CNG to gasoline fuel price ratio in developed case-study countries.

or to purchase the OEM vehicle with higher price as compared to the new diesel or gasoline vehicle. The payback period has to be sufficiently short to justify the investment and to compensate for the inconvenience associated with CNG, notably the loss of space in the boot/trunk and the more limited availability of refueling stations in some countries and regions.

The reduced fuel prices are considered to the central benefit of NGV by the main users or customers. However, consumers tend to overestimate the extra costs of NGV relative to the advantages of the cheaper gas. Therefore, keeping in view the trend of NGVs market growth in the case courtiers suggest, the customers can be attracted if optimally investment in NGV is recovered within a period of two years while can go to four years at most. This duration is considerably less than the car's life-time. It is also advised that benefit of reduced oil price is less than the cost benefit at the time of NGV purchase. Example from Argentina states that taxis (service cars) shows a 50 days payback period while using CNG and covering 120,000 km/a. While, medium drivers covering 20,000 km/annum have a potential to have payback period of 10 months. Contrarily, New Zealand reported a payback period to be 18 months when the industry of NGVs was in growth period [37]. Bluestein L et al., 2014 [38] conducted a case study of 70 heavy-duty refuse trucks fueled with CNG (dedicated CNG engine) operated by three fleets from very different types of organizations in USA. On average, each refuse trucks traveled about 23,335 km per year. The average incremental cost per CNG vehicle in the study was $38,200 and the average fuel cost saving as compared to diesel was 50% (approximately $0.62 per Km). The study revealed that incremental cost could be recovered within three years, which is well within the vehicle's full useful life of 10–15 years.

Consumers making investment in the fuel economy demand considerably low payback period of three years, research claims [39,40]. The said duration is much lesser than the life-time of the almost all passenger vehicles; hence, imply that the consumers deploy considerably high rate for discounting when making investment decision pertaining to technology. Greene et al., 2005 [39] stated that there is not much evidence about the aspects the consumers' value fuel efficiency in their investment analysis in car purchase. Nevertheless, the considerably reduced time for the payback period leads to an underestimation of economic advantages of such investment. Energy models estimating the technology adoption trends and patterns for AFVs penetration by deploying bottom-up (technology-rich) strategy gives considerable weight to assumption regarding the payback period.

The conversion costs of gasoline vehicle to bi-fuel CNG vehicle are about five times higher in the developed countries than in developing countries (Fig. 7). This is due to lower labor costs in developing countries, lower duties and different regulation stringency. Because of high incremental cost of dedicated NGVs or conversion cost of current gasoline vehicle, the payback period in the developed countries (given average driving, fuel prices, and fuel efficiencies) is approximately six years; about the same number of years consumer in these markets tend to keep their vehicles.

In developing countries the low cost aftermarket conversion of gasoline/diesel vehicles to bi-fuel CNG vehicles, is more attractive to consumers than originally manufactured CNG vehicles, with high additional cost. Normally, the regions where retrofitting of CNG vehicles is encouraged have relatively larger CNG vehicle fleets. In contrast, NGVs growth is not very dynamic in regions where CNG vehicle retrofit is prohibited. In China factory built bi-fuel CNG vehicles cost 9%–20% (1000$ - 1500$) more than comparable gasoline version of the same model. While the conversion cost of vehicle retrofit from conventional gasoline vehicle to bi-fuel CNG vehicle is only 550$–1000$ per vehicle [16,20]. At this price, the payback period for converting a gasoline taxi to bi-fuel CNG taxi is ~2–3 months while the payback period for CNG heavy truck is ~1 year. In India, it is estimated that a taxi or individual LDV can recover its conversion cost after 30,000 km. Similarly in Argentina time to obtain return on investing in the CNG conversion kit is ~4 months, (assuming that a taxi covers 200 km a day and saves US$ 15 a day on fuel) [41]. As shown in Fig. 7, the cost difference between developed and developing countries of acquiring an NGV is very high, but it is noteworthy that in the developing countries most available light duty NGVs are based on bi-fuel CNG technology while in developed countries the NGVs are normally have dedicated CNG engines. Dedicated CNG are more expensive but have the advantage to avail comparatively high compression ratio by utilizing the high octane value of CNG. Incidentally bi-fuel CNG vehicles will not have the advantage of a high octane value of CNG as the compression ratio will be set to the level required for gasoline.

Information related barriers

Information failures have led to the low existence of consumer demand and alternative transport fuel resistance [42]. The lack of information in terms of being verified or independent would cause market confusion regarding the vehicle availability when using a specific fuel along with alternative fuel vehicle characteristics or vehicle availability. Surveys demonstrate that most consumers' knowledge of NGVs is

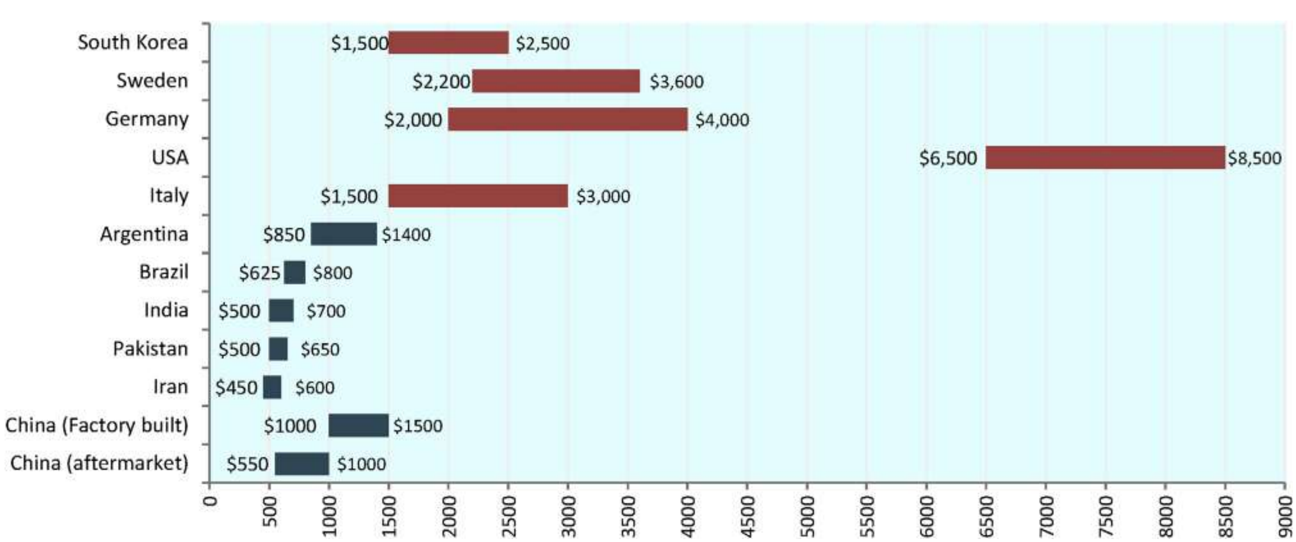


Fig. 7 – NGVs conversion in case-study developed and countries in US $.

minimal and often inaccurate and that many are waiting to see large numbers of NGVs on the road before they will consider purchasing one.

Usually information on CNG technology tends to be published by fuel suppliers, rather than independent economic and environmental performance information sources. In many cases, information is not based on local conditions and in some cases, conflicting information is available for the same or similar claims. Government can play effective role to enhance the consumer beliefs in the available information. Governments are regarded as unbiased providers of information in the vehicle and fuel market arenas, and this neutrality is important to end-users [43].

The key information barriers which are usually associated with the development of NGVs market include: vehicle total cost of ownership; uncertainty for vehicle buyers over costs and durability; and uncertainty around fueling needs. Aligned with above discussion, the down payment requirement for NGV vehicles is much higher as compared to conventional cars; hence, becomes a leading barrier in adoption. However, accounting for the incentives on fuel and cost of maintenance, the overall cost of NGVs tend to reduce significantly. For example, Chevrolet Silverado 2500HD truck can save around $6000 to $10,000 in the operating cost with respect to fuel expense across three years' time when ran on CNG as compared to conventional fuel. According to waste management, for heavy-duty trucks, they managed to save around $30,000 annually under fuel and cost of maintenance when drove on CNG. A financial model considering fuel consumption and vehicle cost as one of aspects for overcoming the overall ownership cost problem. For example, a pay-per-mile model has a potential of offering higher cost assurance on investment and maintenance of vehicle making it feasible for individuals and fleets consumers in realizing the benefit of savings from AFVs. Ambiguity regarding the operating cost as well as durability of NGVs is another information barrier for potential investors. The most critical ambiguity regarding NGVs is related to the future natural gas price, despite fact that EIA claims it to remain considerably low for many years. Lack of availability of real data produces lack of trust in contrast to available options of testing and anticipating the durability and cost savings from the NGV technology.

Addressing information gaps

Hence, it is important to have a well thought out and comprehensive research that is capable of dealing with the intended market for bridging the knowledge gaps and changing in the vehicle market. The suggested strategy needs to have a top-down approach implemented in form of a main website for all customers in general and the tailoring content for the domestic clientele. It also needs to have a bottom up approach for featuring a domestic network for support for the final clientele while defining reach to the workshops as well as case examples for the domestic fleets.

Target audiences

The NGVs market of the 11 case-study countries identifies 14 key target audiences that can be organized into the following five categories: 1) end-users, 2) vehicle supply chain, 3) authorities and regulatory bodies, 4) industry, and 5) general interest.

End-users. This category includes fleets for the public as well as private sector including municipal transit, industrial, school bus, short and long distance delivery vehicles. It is important to focus on the basic knowledge for this category in addition to outreach for covering the knowledge holes regarding NGVs. This would include fleet managers with little as well as out-dated basic information about NGVs. Such people intend to acquire knowledge pertaining to the fuelling aspects such as sources of natural gas and its prices; in addition to technology availability in vehicles and differences in their price, information about other users' operating experiences, codes that are applicable including region wise standards, information related to equipment as the suppliers of fuel, and environment related and other similar benefits of acquiring and investing in an NGV.

CNG and conventional fuel prices at filling stations are usually labeled in different units complicating an easy comparison of prices. To address this information gap energy content of CNG need to be disseminated to consumers. For example, Gas Technology Institute, USA, surveyed 6811 samples of natural gas nationwide in US and concluded that the average natural gas in the US had energy content (lower heating value) of 923.7 BTU/scf, and a density of 0.0458,172 lbs/cubic foot. Hence the equivalent gasoline/diesel liter of CNG can be determined as:

$$1\ \text{Kg of CNG} = 1.475\ \text{Liter of Gasoline} = 1.323\ \text{Liter of Diesel}$$

or

$$\begin{aligned}1\ \text{Kg of CNG} &= 0.390\ \text{Gallon of Gasoline}\\ &= 0.349\ \text{Gallon of Diesel}\end{aligned}$$

To clear the understanding of consumers towards the economics of CNG, all retail CNG dispensers need to be labeled with the above conversion factor in terms of kilograms or pounds. The label should be permanently and conspicuously displayed on the face of the dispenser. Labeling fuel prices in energy instead of volume and mass units would increase the visibility of CNG cost advantage for customers.

Vehicle supply chain. OEM dealers with the limited information and experience about NGV are included in this group. The information needs of this groups knowledge for convincing the NGV target market for the investing decision. The information needs of this group include, though not limited to, information related benefits that NGV offers for environment suitability of using natural gas, range coverage, weight as well as dimension of the NGV etc., for helping meeting the information needs of investor of NGV.

Authorities and regulatory bodies. Authorities, regulating parties and responders in emergency, constitute this set of category and the role of these audiences will have to reduce as the market picks up. However, they have a prominent role in the beginning states of market development. Their role includes setting standards and abiding regulation related to the acceptance, development, and operating phases of NGVs related project like refueling stations etc.

Industry. Companies in the up, down, and middle level streams of natural gas are included in this category and include organizations such as equipment manufacturers, research developers and consultants for NGV. Their role is prominent in dealing with the final consumer in creating acceptance for NGV; hence, requires information related to the decision making and distribution process. Further they ensure an effective implementation that is capable of meeting needs of the target audience.

General interest. This category includes the public, media, and environmental groups. The target audiences in this category, especially the media, play a role in forming the opinions of others, so they need to have accurate information at their disposal. This could also involve, for example, setting a target that a certain percentage of car-related advertising in the national media should be related to NGVs in stock.

In some cases, it is possible that even with appropriate information available; some consumers may continue to lack confidence in NGVs. This issue can be mitigated to some degree by improving consumer knowledge through demonstrations of the uses and benefits of CNG under local conditions so it is directly relevant to users.

Fig. 8 depicts the process plan going to end-users who are fleet managers and considering investment in medium- and or heavy-duty vehicle. The vehicle decision making process is subject to information acquisition from many related sources. Any limitation and gap in this information acquisition will

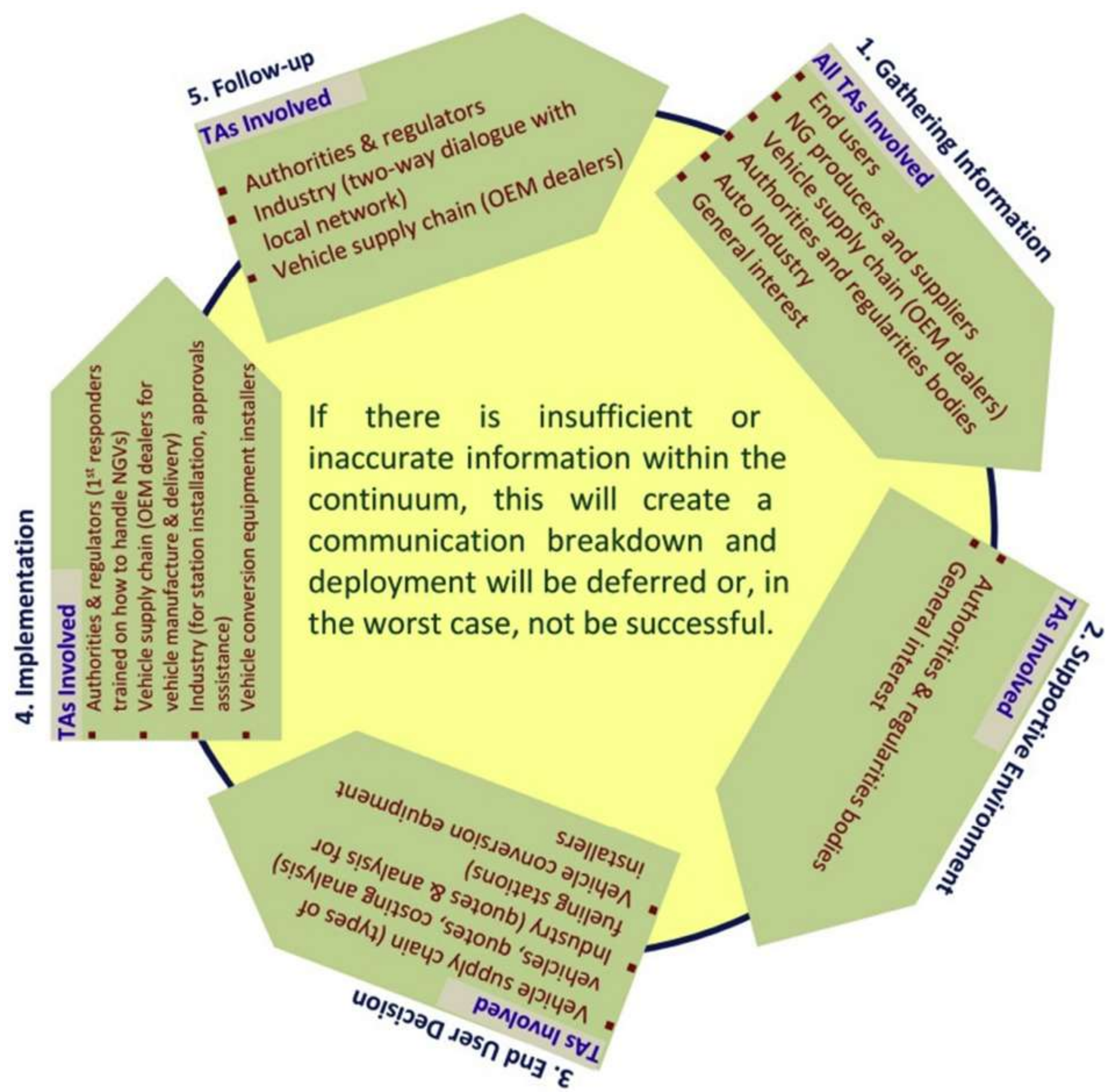


Fig. 8 – Generic Process Continuum for Deploying NGVs (to be modified as per regional conditions).

create communication gap, which consequently leads to halting NGV purchase decision.

Step 1: Information collection is the first step for the end user. The stage involves all target audiences because every channel has to offer certain information for cultivating the desired response from users.

Step 2: Use of NGVs demands support from the government in form of positively influencing regulations while incentives for user. Further, it is required that media should their play their role in creating awareness in the target audiences.

Step 3: For investment decision, it is important that investors conduct a complete cost benefit analysis. The cost benefit analysis must then account for aspects such as vehicles, refueling stations, and fuel cost impact in addition to the payback period analysis.

Step 4: Industry incumbents are required to take proactive measures for approvals required for vehicles and refueling stations. Timely delivery from dealers and emergency support service is also important. Front end emergency respondents must be given complete desired training and awareness related to NGVs.

Step 5: A constant process of interaction for updates must sustain among industry, end users, and vehicle supply chain regarding vehicle/station performance, maintenance, product updates and warranty issues. Additionally, regulators must also be followed for changing certification and inspection requirements.

Coordination failure in complementary markets

NGVs and the corresponding fuel infrastructure are complementary goods. In addition, large investments are required by the respective industries to create a market. Both factors raise the need for coordination as otherwise investments are perceived as too risk. In many countries the markets for NGVs are often incomplete because car OEMs, fuel companies and refueling station operators do not coordinate sufficiently to render vehicles and the corresponding infrastructure attractive for consumers.

Barrier to private investment in NGVs and refueling infrastructure

Private investment and other related financial products are crucial in overcoming demand barriers for NGV. Major areas of contribution include support in down payment for both infrastructure developers and buyers, limiting information risk for end-users, and monetizing tax compatibility [44]. Private investment in financial contribution with expectation of positive returns and channelizing private investment for crafting financial product specifically become important as financial techniques are useful in operational savings mainly from fuel side; hence, overcomes the higher down payment required for vehicle or even infrastructure like for fuel. Loans, debt instruments, asset and loan securitization, and leasing are some examples from a wide range of financial products available to NGVs buyers and infrastructure players. Such tools have already been deployed for green technologies and energy efficient measures in different sectors. Potential of coming up with an innovative form of financial tool and payment system such as tool that combines complete ownership cost including capital and operational cost, are also possible.

Major contributors to the private investment's barriers

While innovative investment tools can help deploy more NGVs and related infrastructure, private investment faces its own set of barriers including:

Information failures. Lack of credible, reliable information about new technology and future market demand for NGVs limit interest in private sector financial solutions.

Liquidity risk. NGV market is much affected by the illiquidity concerns where target audience are not clear about the benefit and cost involved; hence, considering it risky venture. Liquidity and financial regulations also force financial institute to have enlarged safe results while investing in the presumably illiquid assets.

Information related barrier to private investment

Information limitations related to product, investment and return possibilities are among key barriers to a cheap capital and financial vehicles in picking up NGVs. Almost all stakeholders are affected face this limitation [44]. Further demand in market along with fuel accessibility form the key concerns of investors for NGVs. The anticipations are significantly dependent on the consumer interests, fuel prices, and policy matters decided for public by regulators.

Scale barriers

The economy of scale factors that leads to reduction in cost with increase in the output is present in the private finances like manufacturing. Investors in manufacturing and institutions for it are key beneficiaries and affected ones of scale impact. In private financing, capital in the total amount in dollars is units while costs refer to the cost of transaction for acquiring financial instrument. The higher interest rate charged is for recovering the initial investment values at a much higher pace and it can be seen when the cost of transaction for loan or a deal amount become much higher than total value of loan. Per unit cost has a chance to reduce in cases where increase in the number of high value projects or projects with standardization come into market. Hence, the role of standardization is critical in controlling the scale and cost limitations.

By standardizing the processes, there are ample chances that scale relates challenges can be dealt with. The cost of capital increases significantly for financing range of unique business plans. For instance, the cost rises to $ one million or higher for a single CNG fuelling station under the ownership of a third party. However, spreading the legal fees applicable to a single project can be spread across few similar projects and resulting reduced cost benefit can be gained. Furthermore, the liquidity of the financial products for such projects will increase with increase in trading as the market for CNG stations picks up. Resultantly, the financing cost will reduce considerably and consequently will curtail the consumer's financing cost. Hence, a continuous cycle come into effect where increase in customers for the product that are large in scale and have limited liquidity spread across that in turn reduces the overall cost. Carrying an impact from such spread to a wider range of people reduces the overall cost associated with the infrastructure deployment. The net impact for such measures comes out to be the rise in the demand and market pick up for NGVs.

Technical barriers

Technical barriers can occur at the corporate or systemic level and can be classified broadly as:

a) technological barriers;
b) infrastructure barriers; and
c) uncertain raw material availability.

There are barriers related to technology as well where an assessment of the commercial viability of the new technology is conducted. It is reviewed if the project can actually be moved to the full scale mass production from the concept development in theory and industry prototype. For instance, technologies related to the specific innovative or niche markets. One of the major technological barriers associated with the market diffusion of NGV is the perception of inferior performance associated with bi-fuel CNG vehicles. Several experimental studies have shown that gasoline vehicles retrofitted to CNG are subjected to a 15%–20% loss in total brake horse power while running on natural gas [25]. However, all of the AFVs highlighted above face technological barriers to some extent. For example, due the high viscosity of biofuel, the engine thermal efficiency may be diminished, leading to a perception of inferior performance associated with vehicles operating on biofuels [45].

Moreover, light-duty NGVs will have to compete with improved efficiency conventional vehicles (such as clean diesel or plugless hybrid electric vehicles, HEVs), as well as other alternative fuel vehicles (AFVs), such as plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), or E85 flex-fuel vehicles (FFVs). Many of these powertrains also face similar challenges to NGVs. Thus, in order to gain significant market share, NGVs must therefore be an economically viable alternative to the established and more efficient gasoline-fueled car, and also a more attractive option than other AFVs.

Another important technological issue pertinent to both dedicated and bi-fuel NGVs is the driving range. The driving range the vehicle has a defined ability to travel a specific distance before it is refueled. When considering volume, 1.1 L of diesel or 1.0 L of gasoline makes up 1 m^3 of natural gas approximately. The natural gas has lower energy density when compared to diesel or gasoline. It occupies storage space that is 3–4.5 times as compared to diesel or gasoline, hence, the vehicle range is reduced. As a transportation fuel, the CNG growth and development is vitally affected by the Driving Range. The cargo space loss is another technological issue associate with light duty NGVs specifically. Usually, the CNG cylinders are large thus they need much storage space to be placed in the car trunk. As compared to a conventional vehicle, the cargo space is significantly reduced by nearly 50%. However, the issue is managed as the CNG vehicle includes 2 or 3 cylinders which are under the vehicle to avoid loss of luggage space.

Institutional and administrative barriers

Institutional stakeholders including manufacturers, importers, fuel suppliers and retailers, policy regulators, as well as media are also expected to show resilience. The core institutional resistance comes in the traditional pattern where investors who have already sunk cost in the existing technology show resistance to new ones to the market. Such stakeholders show resilience to take up further investment in a unique technology especially when the market development is still vague. Resultantly a circular movement (chicken and egg dilemma) comes into play in the energy sector specifically in the initial stages where the transition is comparatively slow mainly when movement is towards the energy sources that are less polluting. Investors' reluctance also intensifies in cases where the output has costly and riskier while policy, customer demand trends, political arena, and media support all are limited and uncertain. New fuel introduction is a comparatively less usual, ambiguous, and time consuming process mainly due to the pace difference between the policy to technological adoption. The impact is further increased when the technology is expensive to invest and requires longer payback period. Resultantly, it becomes dependent on the development between the chicken and egg relationship between institution and technology. Unruh et al., 2002 [46] noted about the embedded role of 'carbon lock-in" where fossil fuels are integrated in the current business system are actual hurdles in a way of policy development. Therefore, a midway is required allowing flexibility for current systems to adapt to the new processes in future.

Public acceptability

Public acceptability or preferences are a critical factor in the development of successful alternative fuel vehicles [47]. Generally five different factors influence the public acceptability of NGVs: (a) AFV technology must offer higher and improved performance when compared to conventional fuels and vehicle technology; (b) access to maintenance, refueling stations, and other necessary infrastructure to overcome the range limitation, must be there; (c) the higher the affordability the greater will be market demand; (d) must be a safe option and should not have flammability concerns associated; and (e) perception of the offering should be of a favourable product.

Consumers while reviewing new options have perception scales related to the reliability, comfort, and performance and demand better or competitive performance of the new offering as compared to the currently used one. Consequently, resistance and sceptics in masses and groups arise due to the conventional attitudes, cultural compliance and limited public face, and most importantly limited knowledge about improved benefits as compared to costs. Hence, when models are introduced in the market with focus on the certain class, it is then perceived as something for the niches and not the mass market. Studies shows that while unlike experts in the field that are able to rely on technical knowledge, the general public simply rely on experience, emotions, media and other non-technical material [48]. This may require industry and stakeholders to inform and educate as well as ‘selling the benefits’ through awareness campaigns.

Consumer myopia is accompanied by a tendency of consumers to be skeptical about technological innovation [49]. A large body of literature shows that resistance towards innovations increases with the extent to which consumers perceive them as risky in physical, economic, functional and respect. With respect to NGVs, the reluctance of consumers is driven by anxiety about practicality and safety. Survey conducted by gas companies show that the majority of consumers are not convinced that CNG-specific components (e.g the technology of string gas at pressure of 200 bar and interface between filler neck and fuel nozzle) are as reliable as those gasoline power-trains similar, as consumers have a high preferences for safety in terms of fuel supply. These safety concerns have negatively preoccupied the public consciousness over its benefits. However, awareness campaigns, robust safety systems, vigilance or specialized training can help resolve these issues like for public transport operators.

Most consumers can be described as being economically rational, in that they respond to price and given identical options will pick the cheaper of the two, and environmental pragmatists, who are willing to switch to an environmentally friendlier fuel so long as it does not force them to alter their behavior. In advanced countries attitude towards environmental benefit is expected to be influence consumer behavior and green purchase intention but environmental concern is not considered to be positive by everyone [50]. The motivational factors identified in the CNG markets of 11 case-study countries for opting the CNG technology are listed below:

- Opportunity to pay less for fuel
- Other government incentives
- Tax credit
- Permission to drive in high occupancy vehicle lane
- Unaffected by fuel price fluctuations
- Awareness of climate change and global warming
- Exemptions from ‘Bad-Air’ day traffic bans
- Decreasing natural resources consumption
- Preservation of the environment
- Reduction in pollution level
- Being a trendsetter of pro-environmental technologies
- Being part of socially responsible activities
- Attracted to new technologies
- Educating others about a new type of vehicle
- Being a pioneer in the technological sphere
- Sharing technological knowledge
- Sharing a common ideology within the community
- Independence of oil producers

Regulatory or legal barriers

Barriers related to the regulatory environment include regulation updates, trade limitations, expected legal implications, and planning restrictions. Such gaps result when there is vacuum or silence regulating avenue about the government's policy direction and incentives. Even often the policy regulations can also higher growth of the market when policies conducts are inconsistent that negatively influences the consumer and investors' confidence. Ambiguity in the policy stance has much potential to cause failure of NGVs as it restricts the mass diffusion and acceptance of CNG technology.

Importantly, heavy duty CNG fueled vehicles e.g. trucks demand considerable trade-off about available space. The tanks for CNG occupy much more space as compared to the space used by the liquid fossil fuels that in turn reduces the available space for carrying freight than otherwise available in case of diesel vehicles. Such vehicles also get heavier. What complicates the matter is the restriction on the length of CNG trucks; hence, such trucks then have to benefit from limited carrier space that in turn reduces their economic benefit irrespective of the other benefits they bring. A weight credit or “allowance” for the additional weight of CNG fuel tanks would eliminate the concern and financial impact of a diminished payload. In countries where regulation restrict the weight for CNG fueled trucks, the regulation should allow for additional weight and/or length of a CNG vehicles over and above its diesel equivalent. Such schemes have been introduced internationally and allow fleet operators to maintain a payload that matches a diesel equivalent. For example the US congress has recently passed a bill about NGV weight exemption that allows heavy-duty NGVs to exceed the federal weight limits up to 82,000 pounds to compensate for the additional weight of natural gas fuel systems and tanks [51].

Physical barriers

In some countries the access to CNG refueling station is limited by physical barrier, e.g. the dispenser is located in secure area open during limited hours of operation and/or requiring pre-approved access key or gate code, or by administrative requirement, e.g., dispenser requires pre-approved fuel card or billing code to activate. Generally, transient customers are prohibited and cash and/or credit card sales are not available. Examples: utility or government public works fleet yards USA where a limited number of pre-approved “guest” fleets are authorized to use “host” fueling site. Some public stations require card key access or that customers call ahead. Some require users to complete special training or enter PIN codes. However these physical barriers are now becoming less common.

Safety standards and regulations

There must be set internationally acceptable standards for gas quality, garages, engine manufacturing, NGVs, conversion kits, gas dispensing units, refueling stations and gas cylinders. Additionally, the standards must be enforced through an appropriate inspection and monitoring system. Due to gaseous and pressurized nature of CNG fuel, the general the public would likely have concerns about the safety of CNG vehicles and related infrastructure. For this reason, particular emphasis should be given to develop sound safety standards. Our interviewees confirmed that, at the beginning, consumers are indeed concerned about safety. It is common for people to believe, for example, that vehicle collisions could lead to explosions. Our investigation found reference to only few serious CNG-related accidents mostly in Pakistan (for detail see our paper at Ref. [52]), all of them due to blatant deviations from recommended practices by end users. Similarly, in 1999, a group of media consisting of 3 main newspapers, 8 weekly magazines and 25 monthly magazines, conducted Italian NGV Campaign and surveyed 800 vehicle drivers (85% gasoline, 8% diesel, 5% LPG & 2% CNG), representative of the Italian drivers population. To answer one of survey's questions "why do you think CNG is not attractive", 19% drivers considered CNG as dangerous fuel (Fig. 9).

Reliable standards and codes must be produced by policy makers after integrating with industry associates. The standards must be related to storage, distribution, production and the demonstration program development using green procurement to help enhance awareness. In this context a "safety codes and standards" working group should be established to collaborate with existing concerned National Standards Association's technical committees to address gaps and issues in existing codes and standards identified during the roadmap process. An umbrella committee would be needed to ensure that codes and standards for NGVs are coordinated and comprehensive. The committee would develop and deliver appropriate training materials for stations, vehicle repairs, and NGVs fleet operations, as well as for cylinder inspection.

Infrastructure barriers

Successful diffusion of NGVs is difficult and complex for several reasons. Drivers will not find NGVs attractive without ready access to fuel, parts, and repair services, but energy producers, automakers, and governments will not invest in CNG technology and infrastructure without the prospect of a large market the so-called chicken and egg problem.

In case of a mature fuel, such as gasoline, the "invisible hand" of the marketplace regulates the profitability of the infrastructure. Competition prevents excess profits from damaging the market, and opportunity induces new investment because of the overwhelming demand for the fuel. This is not the case for a new fuel like CNG, and those who would promote the CNG fuel need to resist the temptation to be absorbed by technological challenges and opportunities. Rather, they need to focus on and ensure that the infrastructure to support the new fuel emerges and is profitable, without excess profits at the expense of users of the new fuel, since infrastructure is far more important to existing and prospective customers than future improvements in technology.

The main infrastructure barrier to NGVs market growth include (a) lack of NGVs and service centers (b) lack of refueling station.

NGVs and service centers

NGVs will be best served by a mix of OEM supply and competent aftermarket conversions by large-scale suppliers who can address warranty and service. OEM is only likely to occur if certain countries, that are major auto design and manufacturing centers, support the CNG through public policy. Aftermarket product is also needed because OEM sales are too low to build a profitable load on infrastructure, especially refueling. Aftermarket sales can target areas where refueling facilities are in place and build fuel demand quickly.

Aftermarket vehicle conversion centers should not be based at a dedicated facility. Alternatively a network of trained installation dealers using existing conventional

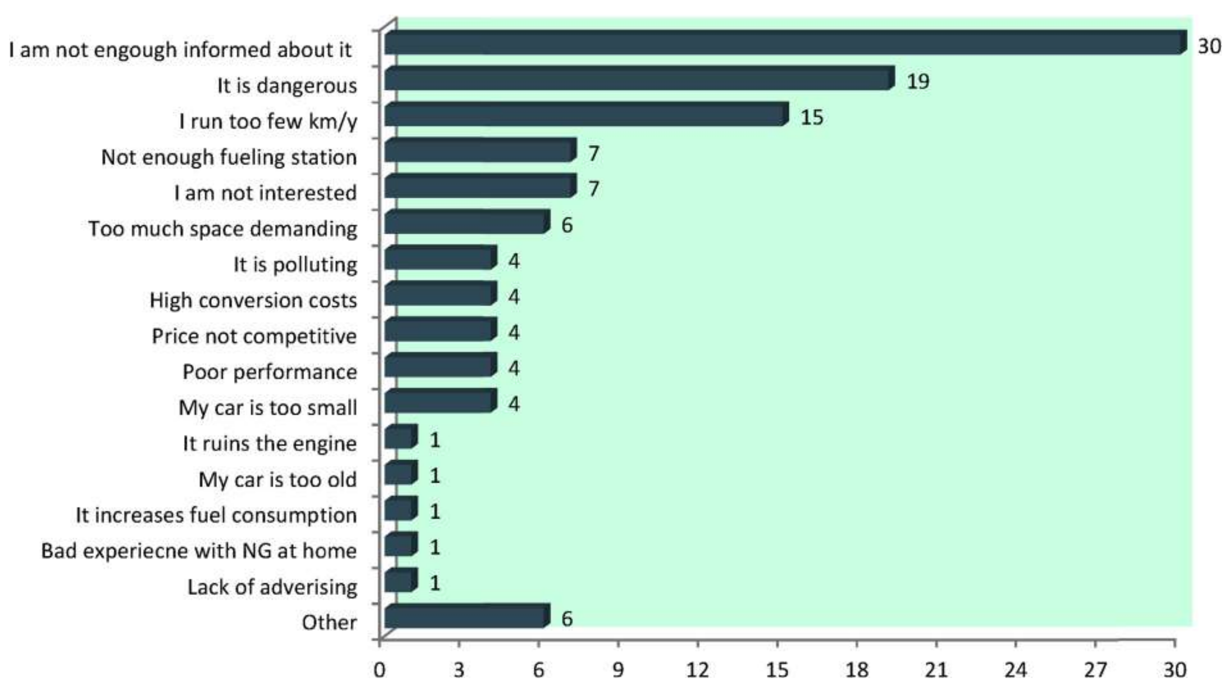


Fig. 9 – Results of 1999 Italian NGV Survey [Source: The NGV market in Italy, Flavio Mariani (ENI) as presented at the 2002 Bayernqas Symposium].

vehicle service centers could be developed. This is the prevailing practices in major NGVs markets in developing countries e.g. Pakistan, India and China where after-market conversation of conventional gasoline vehicle to CNG is significantly low as compared to conversation cost in developed countries e.g. USA, Italy, and Germany. For instance one of the major reasons for the Canadian NGVs market failure during 1983–1985 was the creation of dedicated NGVs conversion centers in four major metropolitan areas in Canada to install conversions and service vehicles. This was an economic disaster, since conversion sales were too erratic to keep the shop busy and many conversions were too distant to be installed or serviced at the facility.

Lack of refueling stations

Usually, the purchase decision of the consumers is based on the availability of refueling stations near their homes or workplace. For instance, in Canada, as the refueling station development progressed rapidly, the NGVs market reaped benefits initially. However, soon the investments reduced leading to a flat market decline of the Canadian NGVs. Similarly very recently, a lack of refueling infrastructure stalled CNG light commercial vehicle development in the UK [53]. Maintaining an overall context, it can be stated that an automatic NGVs development would not occur if more refueling stations are built. Each station profitability declines when the ratio of refueling stations to NGVs is high. At times, some stations may go out of business. Surprisingly, despite having less than 100,000 NGVs, Germany has a wide network of CNG refueling stations of 922; only 140 fewer than Italy, which has nine times (885,300 NGVs) as many NGVs on the road. Therefore, achieving a balance between the rate of development of NGVs and refueling stations is essential.

Vehicle-to-refueling-station index (VRI). As stated consumer often base their purchasing decision partly on whether there is sufficient number of refueling station around their home or place of work. The number of CNG refueling stations can have a significant impact on the development of NGVs. An oversupply may result in lower return on investment, which makes refueling station less profitable and could damage the interest of investors; while an undersupply may lead to unwillingness of potential NGV owners in purchasing NGVs. Therefore, a vehicle-to-refueling-station index (VRI) has been introduced as an indicator to reflect the balance between supply (refueling stations) and demand (number of vehicles). In their survey of NGVs penetration worldwide between 2003 and 2004, Janssen et al., 2006 [14] found a VRI value roughly equal to 1 (i.e., 1000 vehicles per refueling station) for countries with a large number of NGVs, including Argentina, Brazil, India, Italy, and Pakistan. They concluded that this is the optimal balance between profitability for fueling stations and convenience to NGVs drivers.

Refueling station density has an additional measure which is the ratio of the gasoline refueling stations to the relative numbers of alternative-fuel refueling stations. Travel time/distance simulations and consumer preference surveys are techniques used by Nicholas et al., 2004 [54] and the results indicate that mature markets need minimum of 10–20% of alternative-fuel refueling stations as compared to conventional gasoline stations. If the number is higher, the consumers would not consider fueling stations as a hindrance for adopting AFVs.

The VRI requires proper analysis of vehicle, refueling stations, and utilization modeling with appropriate optimization function to balance the availability of CNG refueling stations while ensuring the profitability of those stations. Measuring the VRI aggregated to the national level suffers from variations within and across countries and adds additional unevenness and uncertainties due to several factors, for example:

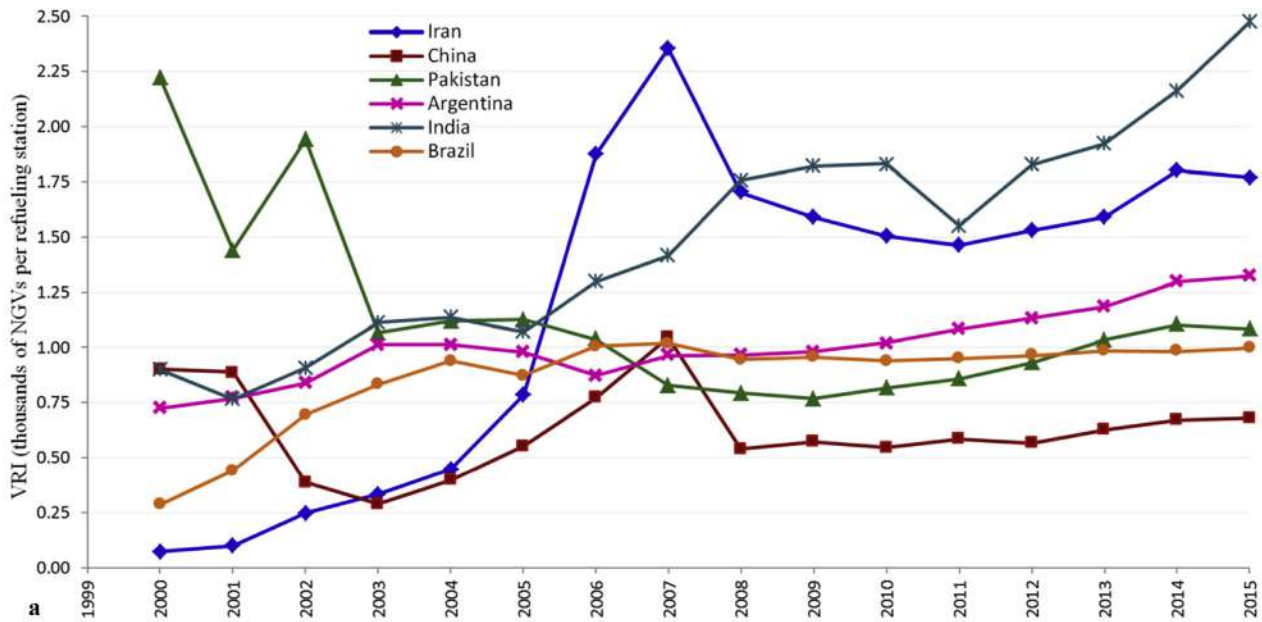
- Spatial characteristics and socioeconomic differences.
- Consumer sensitivities to incremental increases in driving distance or waiting time for refueling.
- Capacities of fueling stations.
- The number of public versus private refueling stations.

The optimal VRI cab be described as ‘‘chicken and egg’’ dilemma that mainly depends on infrastructure availability.

The refueling station distribution and design are another important factor for optimized transportation performance. It is possible to have CNG refueling stations as integrated with gasoline stations or installed separately. Factors that affect the optimization of CNG fueling stations include the following: accessibility, investment, environmental, and user preferences. In order to optimize the performance of NGVs, it is important to analyze all operational parameters involved, which include the following: fueling station facility parameters, operation hours, accumulative total trip distance for vehicles, piping expansion costs, environmental impact costs e.g. social cost of CO_2 emissions.

We calculated the VRI values for each of case-study countries and the results are highlighted in Fig. 10a and b. In the developing countries, the VRI for India, Iran and Argentina is high than 1 which means that the refueling stations are operating with good margin. For Pakistan the VRI is approximately 0.82 which little below the optimal level of 1. Although this value keep the refueling stations well above the minimum profitability threshold to operate stations but refueling stations in Pakistan are facing gas shortage problems. Due to gas curtailment to NGVs sector, CNG refueling station are now open only for 3 days a week, which not only affect the profit margin of refueling station but also encourage the consumers to switch back to conventional fuels. China is only developing country included in the list of case-study countries NGVs have maintained VRI value well below than 1 (0.60) for the last eight years. Due to low labor cost and low CNG station machinery cost in China, the VRI value of 0.60 strongly supports the operation CNG stations in China. This make the basis that the optimum VRI value of 1 suggested by Janssen et al., 2006 [14] and Yeh et al., 2007 [12] could go well below the value of 1 depending upon the capital and operating cost of CNG refueling stations.

Fig. 10a shows that Iran commenced their CNG program with VRI value of less than 0.08 and maintained a level 1.7 within 5 years. The underlying reason for this high VRI value is that government provides substantial financial incentives to NGV consumers but due to current low price of CNG, the business of CNG refueling station is not attractive for private



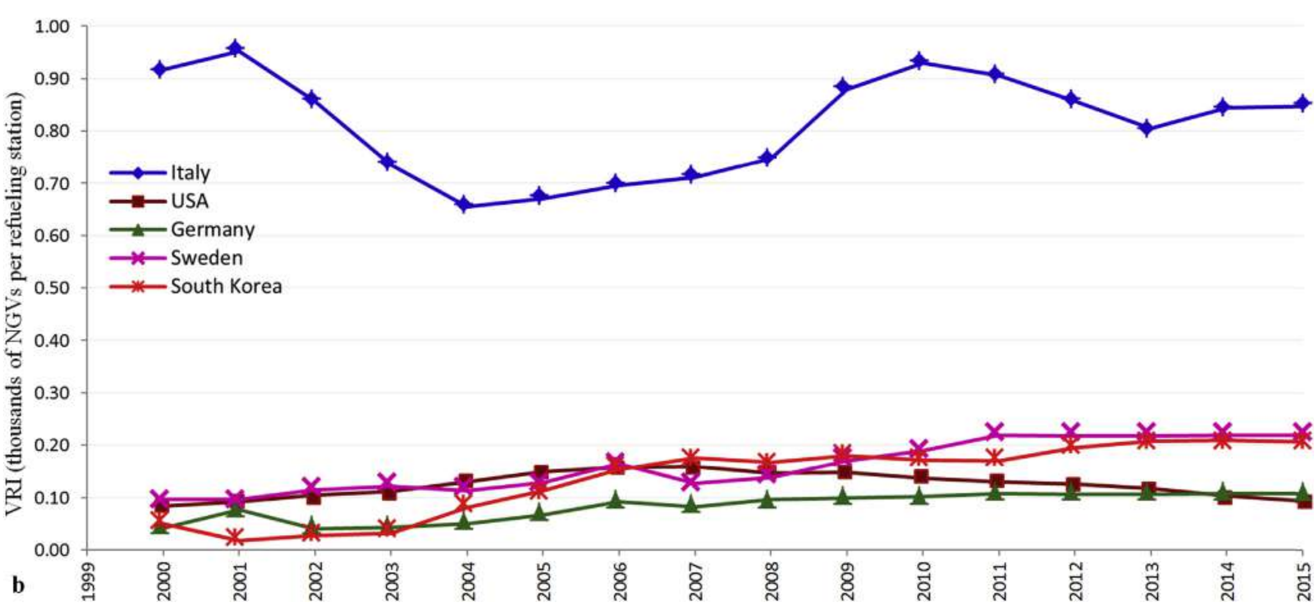
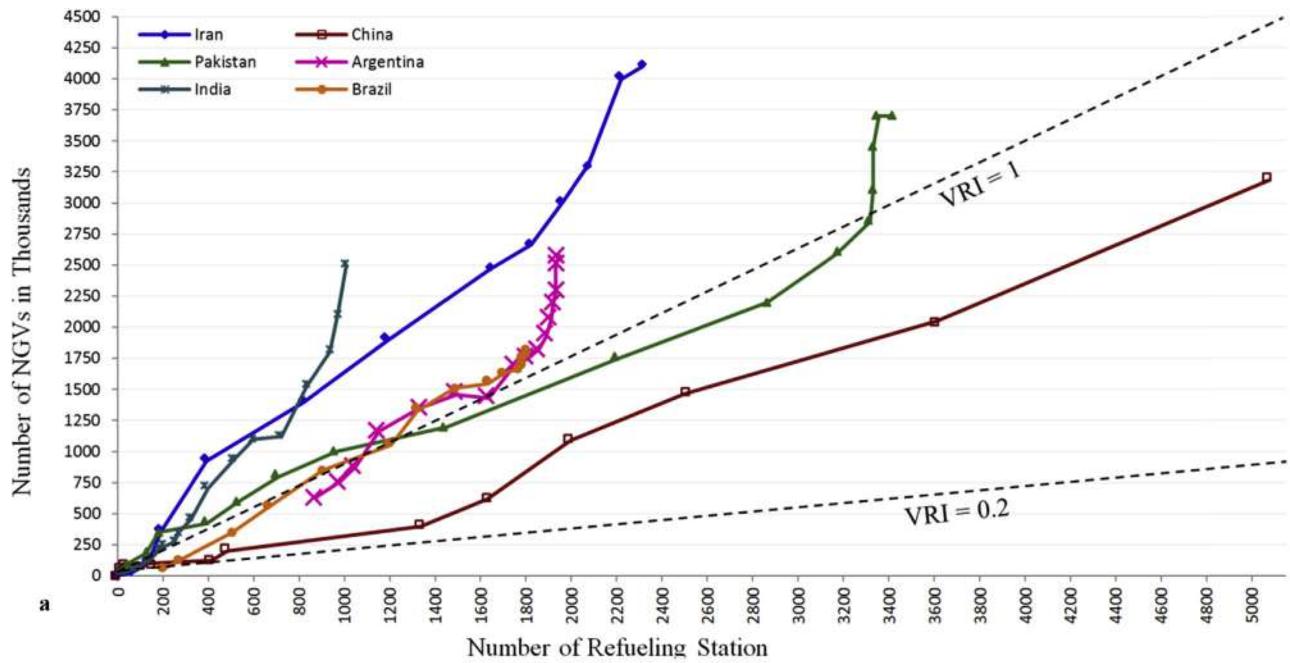


Fig. 10 – a. Natural gas vehicle-to-refueling-station index (VRI) in developing case-study countries. b. Natural gas vehicle-to-refueling-station index (VRI) in developed case-study countries.

investors. Therefore there is less participation from private sector in refueling stations and out of total 2268 refueling stations, 2233 stations are owned and operated by government. Owing to high VRI value, the drivers have to wait for hours in long queues to get their tanks filled. To avoid long lines for refueling in the countries having very high VRI values, Fig. 10a suggest an upper limit for VRI of 1.25–1.5.

Fig. 10b illustrates the VRI value in the case-study countries belongs to the category of developed countries. In contrast to developing countries the VRI values are very low in the developed countries. There is not a single country approaching the value of 1. The average VRI value of all case study countries except Italy is close to 0.125 or 125 vehicles per station. In Italy, where NGVs have successfully maintained a mature market for decades, the VRI remains nearly 0.85.

The low VRIs (0.185) for the developed countries examined here, indicate a much lower utilization of CNG stations. Keeping in view the economic conditions of case-study developed countries, a minimum VRI of 0.2–0.4 is usually necessary for gas companies to profitably operate a filling station, depending on various external factors like commission-fees, costs for connecting filling station to the gas grid, and gas prices. The fact that filling stations in these countries (where VRI < 0.2) operate on less than half of the



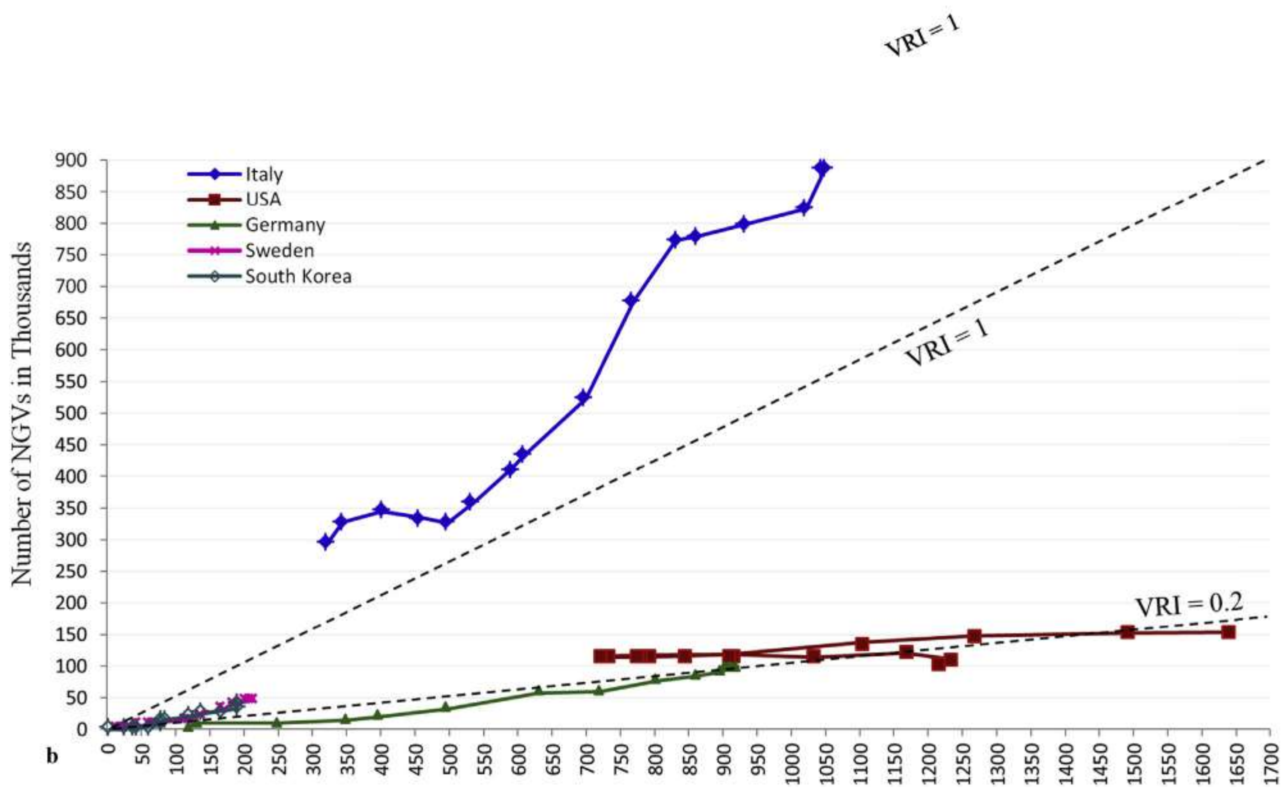


Fig. 11 — a. Number of NGVs versus number of CNG refueling stations in developing case-study countries. b. Number of NGVs versus number of CNG refueling stations in developed case-study countries.

profitable minimum can partly be explained by fact that most of the CNG stations in these countries are owned and operated by government.

However, it is important to note that the optimal number of refueling station in a region is not only determined by the potential number of NGVs, but also depends on the type NGVs associated with the refueling station. The optimal VRI value of 1 suggested by Janssen et al., 2006 [14] and Yeh 2007 [12] assumed the light duty NGVs in their estimation. Off course heavy duty vehicles e.g. Buses consumes much more fuel due to high engine capacity and mileage as compared to personal cars. This can be well implanted to South Korean CNG industry, which although having VRI value of 0.18 but can be considered optimal VRI value as more than 80% of Korean NGVs fleet comprises of heavy duty transit buses.

Plotting the NGVs numbers with the refueling stations shows an indirect relationship between the NGVs and VRI that restricted to 1 or 0.2 and even lower (Fig. 11a and b); in other words, countries either seem to break away from the "chicken and egg" phenomenon and form relatively sustained networks, or continue to struggle. The underlying reasons for this are not clear, and it needs some future work which can provide some explanation for the observed VRI bifurcation in Fig. 11a and b. Some results of bifurcation were found in the work of Struben et al., 2006 [55] that noted about the diffusion point of tipping after which AFVs adoption rate are sustained. This in turn implies that increased barriers related to long life of a fleet as well as social and economic implications demand that subsidies and other similar benefits must stretch at-least to the point of diffusion tipping. Based on the above discussion it can be safely stated that except Italy, no other developed economy is expected to achieve the self-sustained NGVs market provided government withdraws subsidies.

Concluding observations

Despite their economical and environmental benefits, NGVs still face formidable market and non-market barriers. Each of these barriers can be overcome but this will require concerted action by all stakeholders, including governments and industry. In particular a comprehensive communications strategy will be needed to overcome a lack of awareness, understanding and confidence on the part of stakeholders. Key lessons includes:

- The role of user related economic is profound in driving people towards CNG conversion and removing barriers for its adoption. It is important that notable saving in terms of direct operational cost can convince them to move from the routine usage system to the new CNG system. Furthermore, profitability of the CNG refueling station is important for business continuity. Failure of providing benefit of any of the two can lead to a program failure. Hence, is important that price differential between the CNG and conventional fuels is lucrative, so to convince users and infrastructure providers for making other adaption relation expenses.
- All stakeholder groups need to be involved. Reduce the key barriers affecting each stakeholder group whose actions are essential to policy success.
- Vehicle owners require a payback of their conversion investment within two years at the most if they are to change to using an alternative fuel. Government should aim to provide financial incentives that result in a payback period of 2–3 years or less.
- In developed countries, technical and performance related issues, refueling stations and public perceptions are viewed as potential barriers to market growth. Similarly initial purchase price is perhaps the most salient for new NGVs buyers in these countries. Although the motivations of NGVs buyers are complex, purchase price and operating costs are generally the most important considerations. Financial incentives should be designed to be readily understandable by consumers and their availability should be well publicized. Lack of awareness, unfamiliarity and the perceived risk of purchasing a CNG technology appear to be the most important non-financial barriers to NGVs adoption in developed countries.
- In developed countries the government needs to encourage the aftermarket conversion of gasoline vehicle to bi-fuel CNG vehicle. This move will not only avoid the lack of CNG infrastructure that constrains the deployment of dedicated NGVs but would also decrease the incremental cost associated with NGVs.
- In developing countries like Pakistan, India, Brazil and China the availability of natural gas for CNG station is the major hurdle for NGV growth.
- In developing countries economic factors such as fuel costs weigh more heavily in most consumers' purchase decisions than environmental attitudes, therefore establishing retail CNG prices of 30–50% below gasoline and diesel prices are the keys for wide adoption of NGVs in the case-study countries.
- To improve the consumer and industry confidence, the government should establish and enforce codes and standards. Adequate training and certification must be provided, either by the industry or national education systems, for all mechanics, technicians and inspectors involved in an alternative fuels industry.
- To overcome the high cost associated with the construction of CNG refueling station, government should allow modular additions to the existing conventional liquid fuel stations. This lesson has been derived from CNG market of Pakistan where CNG refueling station infrastructure expand very sharply due the fact that over 50% of CNG refueling station has been established by upgrading the existence gasoline/diesel station facilities to offer CNG.
- In developed countries, the low ratio of vehicles per refueling station is a critical challenge to balancing NGV growth.
- The review of VRI values suggests that successful NGV markets have the tendency to gravitate toward VRI of 1.1 in developing countries while settle to 0.2 in most developed economies. In developing countries, the series of VRI graphs suggest an upper limit of 1.25–1.5 and lower limit of 0.5–0.6. At VRI >1, refueling stations increase at slower rates than the number of NGVs and the drivers have to wait for hours in long queues (e.g. Pakistan, India, Iran) to get their tanks filled.

Nomenclature

AFV	Alternative Fuel Vehicles
BEVs	Battery Electric Vehicles
CNG	Compressed Natural Gas
EIA	Energy Information Administration
HEVs	Hybrid Electric Vehicles

LDV Light Duty Vehicle
NGVs Natural Gas Vehicles
OEM Original Equipment Manufacturer
PHEVs plug-in hybrid electric vehicles
VRI Vehicle-to-Refueling-Station Index

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Annexure-H

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Policy options for the sustainable development of natural gas as transportation fuel

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ABSTRACT

In much of the world, compressed natural gas (CNG) has been a long recognized alternative transportation fuel due to the fact that it is domestic, one of the cleanest burning and most affordable alternative transportation fuel available – directly addressing three key issues of the countries: national security, global warming & air quality and the economy. However, due to the complex adoption dynamics and diffusion processes, most endeavors to introduce and build sustainable demand for natural gas vehicles (NGVs) have been underachieved. This paper analyzes a wide range of policies to promote natural gas vehicles in new as well as in mature markets. In this paper, several success and failure factors for the introduction of natural gas vehicles (NGVs) are examined and compare the government policies for the adoption of natural gas vehicles (NGVs) throughout the world but majorly concentrated on twelve countries: China, Iran, Pakistan, Argentina, India, Brazil, Thailand, Italy, United States, Germany, Sweden and South Korea. The paper examines the transition road map to CNG technology implantation and identifies lessons that could be useful to developed countries in their efforts to deploy natural gas vehicles.

1. Introduction

The development and application of alternative fuels for the internal combustion engines use in transportation motivated by economic and strategic advantages offered by these fuels over petroleum fuels. Recently, environmental concerns to oil combustion have stimulated an interest in addressing the tailpipe emissions problems of vehicles, and discovering the potentials of alternative fuels. Several alternative transportation energy sources are identified as having potential for generating overall lesser exhaust emissions in contrast to conventional diesel and gasoline vehicles. Compressed natural gas (CNG) has been identified as leading candidate fuel for road transportation applications due to its lower environmental impact (Khan et al., 2015; Sexton and Eyer, 2016), easily available at an economical price and depending on technologies already well-established (Askin et al., 2015; Yeh, 2007). Worldwide significant research is being carried out to explore that CNG is good for the consumer and environment while enhancing the energy security of the country. A growing number of economies around the world are jumping on the bandwagon to adopt CNG, due to its various advantages. Besides being in abundant worldwide supply, natural gas is simple to process and deliver to the customer (once pipelines are established) and can be purchased at retail prices that are often half that of an equivalent amount of gasoline or diesel.

CNG as a transport fuel is not a new story. With over 23.5 million natural gas vehicles (NGVs) on the roads worldwide by 2015, the industry is well-established, challenging perceptions about how all forms of transport are powered. The Asian countries leads the world with 15.7 million natural gas vehicles, followed by Latin American countries with 5.4 million NGVs (Fig. 1). In addition to increased supplies – thanks to the US shale revolution – the change towards gas has been further incentivized by regulatory, economic and environmental imperatives.

However, due to the complicated process of adoption subtleties and diffusion practices, most efforts to introduce and build sustainable demand for natural gas vehicles have been disappointing (Janssen et al., 2006). For most parts, the acceptance by individual consumers for this green fuel is still missing (Yeh, 2007). There is a need of comprehensive government leadership to develop comprehensive and attractive policy tools for energy-efficient solutions to be economically attractive to both consumers and enterprises.

Abundant research discussions on NGVs have been conducted with

Abbreviations: AFV, Alternative Fuel Vehicles; AFV, Alternative Fuel Vehicles; EIA, Energy Information Administration; EU, Europe Union; GHGs, Greenhouse Gases; GNI, Gross National Income; GWP, Global Warming Potential; ISO, International Organization for Standardization; IC, Internal Combustion; IPCC, International Panel Committee on Climate Change; LDVs, Light Duty Vehicles; NGVs, Natural Gas Vehicles; OECD, Organisation for Economic Co-operation and Development; OEM, Original Equipment Manufacturer; SMEs, Small and Medium Enterprises; VRI, Vehicle-to-Refueling-Station Index

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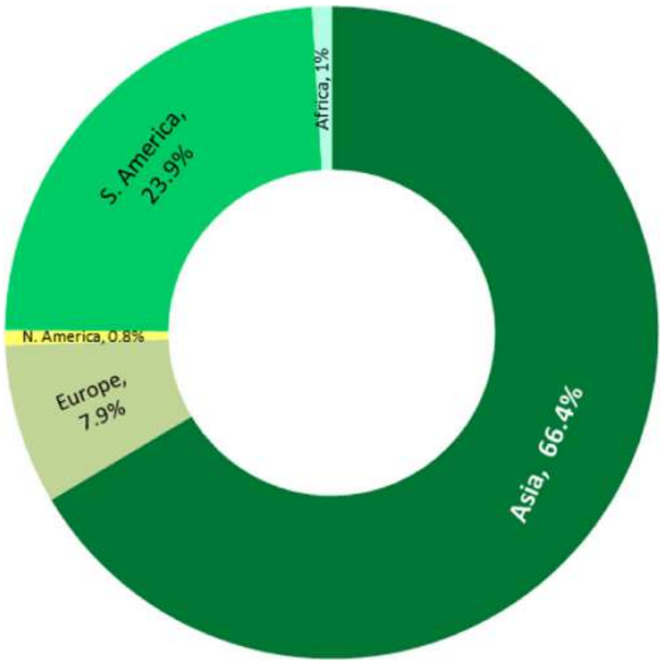


Fig. 1. Regional distribution of NGVs.

views on sustainable development focusing on: regional experiences with NGVs, economic aspect of NGVs (Collantes and Melaina, 2011; Wang et al., 2015; von Rosenstiel et al., 2015); CNG engine's design, control and performance (Khan et al., 2016a); combustion and fuel injection characteristics of CNG engines (Khan et al., 2016b); CNG/diesel dual fuel operations (Khan et al., 2016a), Hydrogen enriched CNG and environmental aspect of NGVs (Khan et al., 2015), safety aspect of NGVs (Khan et al., 2016c). However, there are limited numbers of studies focusing the policy framework for development of compressed natural gas (CNG) fueled vehicle in new markets as well as mature markets.

2. Research objectives and methodology

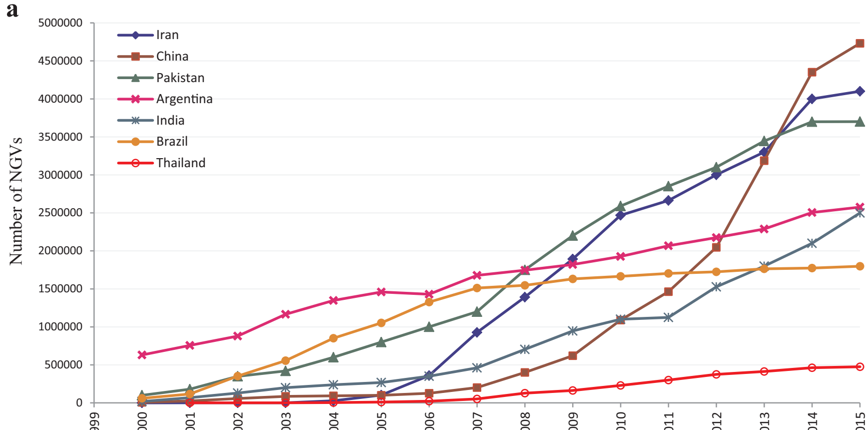
This paper aims to examine the policy measures for eradicating the barriers of transition to CNG and promoting CNG as a transportation fuel without limiting the evaluation to a particular national system boundary. The principal research question of this study revolves around "how can the country adopt CNG as a road transportation fuel source to build a more sustainable transport system" The objective of this research is to find the answers to the following questions: (i) Who are the stakeholders in the adoption of CNG as domestic transportation energy source? (ii) What will they gain from it? (iii) What strategy can be adopted to balance the stakeholders' interests and adopt CNG as an energy source for domestic transportation? (iv) How will this strategy be implemented and how long will it take?

The paper is based on the policy measures of twelve countries which are grouped as follow:

2.1. Developing countries

Those countries having GNI per capita less than $12,475 as specified by World Bank (World Bank Country and Lending Groups). The selected countries are China, Iran, Pakistan, Argentina, India, Brazil and Thailand. In recent years, countries such as Colombia, Uzbekistan, Bolivia, Armenia and Bangladesh, have demonstrated strong growth in the

a



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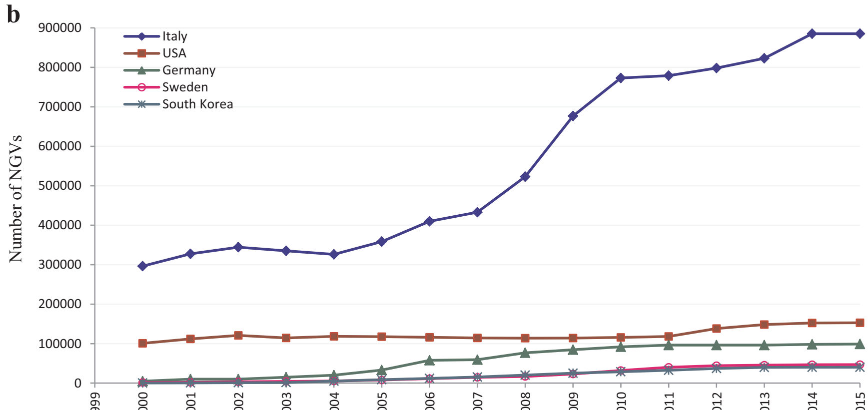

Fig. 2. a). Growth of NGVs in case-study countries (developing countries). b). Growth of NGVs in case-study countries (developed countries).

adoption of NGVs but discussion about these countries is beyond the scope of this study.

2.2. Developed countries

Those countries having GNI per capita higher than $12,475 as specified by World Bank (World Bank Country and Lending Groups). The selected countries are Italy, United States, Germany, Sweden and South Korea.

Fig. 2a and b illustrates the growth of NGV markets in the above mentioned case-study developing and developed countries respectively.

3. NGVs transition challenge

Successful diffusion of NGVs is difficult and complex for several reasons. As a first step in identifying promising solutions, it is critical to understand the fundamental policy issues to the sustainable development of NGVs. Alternative transportation fuel like CNG is still dependent on the respective infrastructure that is not compatible with the IC engines. The two sided impact come from where users will not opt for it unless it provides the accessibility to fuel, spare parts, and other support services while the investors (e.g. automakers, gas suppliers and government) will not invest in CNG technology and refueling infrastructure unless the sound estimation and confirmation for market development is there, the so-called chicken and egg problem. Hence, for the sustained conversion to Alternative Fuel Vehicles (AFVs) analysts make recommendation for the various measures. But there are many differences between CNG and other type of alternative transportation fuel, owing to which the lessons identified in the literature for other type AFVs (e.g. electric vehicles, fuel cell vehicles) can't be implemented to CNG industry without considering the features associated with CNG industry. For instances few of the analysts suggest for the subsidies program to consumers, automakers and fuel providers for breaking the chicken and egg connection of dependency (Farrell et al., 2003; The Hydrogen Economy, 2004). However, there are concerns from the failure of the initial subsidies arrangements in leading the NGVs market to pick up (Flynn, 2002). This means that failure to duly understanding the critical factors, policies intended to stimulate the NGVs program may actually hinder large-scale adoption. For instance, during 1980s, the Canadian government offered subsidies on vehicle conversion and grants to CNG refueling station installer for developing the NGVs market. Despite an attractive immediate response showing 15,000 vehicles conversion and around 80 refueling station within a period of five years, it then failed because the future challenges were not anticipated. Investors attempted to remain in business; however, failed in achieving anything more or around breakeven that in turn resulted in the serious backlash regarding CNG settings. For example, "exaggerated claims have damaged the credibility of alternate transportation fuels, and have retarded acceptance, especially by large commercial purchasers" (Flynn, 2002). Once deemed a failure, technologies do not easily get a chance to rebound e.g. diesel cars failed to pick up in USA market despite fact they were doing great well in European part of the world during 1970s (Moore et al., 1998).

3.1. Conditions for transition

There are number of conditions that need to be considered as prerequisites for implementing CNG as alternative fuels for road transport. These include:

- The availability of sufficient indigenous (or import) natural gas reserves required to fuel the natural gas vehicles. This is a very important point which needs much deliberation before adopting CNG as alternative transportation fuel. As a sample case of Pakistan with over 3.7 million NGVs, where owing to gas shortage problems, currently the government is not in favor of further expansion of CNG sector in the country. The government is struggling with the difficult task of trying to turn back the strategy and to ablactate vehicles back onto gasoline to divert the natural gas to industry and power plants (Khan and Yasmin, 2014). The questions such as either to supply natural gas for cooking meal for poor on costly fuel or fueling vehicles of the wealthy people on inexpensive fuel are becoming increasingly prominent in the country. Similarly the inadequate supply of natural gas can be considered as a major cause for slow growth rate of NGVs diffusion in the Brazilian CNG market. As shown in Fig. 2a, the significant growth of the Brazilian CNG market from 2000 to 2007 resulted in conversion of 1.5 million NGVs. But after 2007 the growth rate was not impressive and only 286,000 vehicles were added to the NGVs fleet in the following years (2008–2015). The shortage of gas for CNG sector subsequently reduced the investments in natural gas distribution network and CNG refueling stations. Besides some reduction in the price difference between CNG and conventional fuels, the Brazilian government's preferential option for natural gas usage in power generation and industries was the major contributing factor.
- The existence of, or commitment to, a gas distribution system on a scale that will provide good opportunities for construction of CNG refueling stations in the locations of interest. The countries having already natural gas infrastructure in place can make economic transition to CNG technology. Pakistan, taken as a case study, has a wide network of gas transmission and distribution. The country's network has an extensive unused capacity that can be used for moving natural gas as a fuel for transportation. This will save country from investing in the pipeline or gas recovery except domestic connections for natural gas to CNG refueling stations. Hence, in such situation, CNG project can be defined as a marginal project. Moreover, the countries considering CNG for road transportation and not as a marginal contributor need to account for the additional cost of the gas pipeline network must also be considered when calculating the economic advantage associated with the CNG conversion at a large scale.
- Availability of vehicles that are candidates for conversion to CNG on a scale that will result in the establishment of a viable commercial market.
- Development of CNG system that is safe also along with being financial viable under the clear regulatory framework.
- A government that is ready to perform a prominent role in the form of introductory force at the very least, to be a strong supporter.

3.2. Drivers

It should be established at an early stage that there are convincing reasons, or drivers, for introducing CNG. These are usually one or more of the following,

- Reduction of local air pollution and health effects (e.g. Indian CNG program),
- Reduction of GHG emissions (Chinese and South Korean CNG program)
- Enhancement of energy security and national self-reliance (e.g. Iranian CNG program),
- Import substitution (e.g. Pakistani CNG program),
- Economic opportunity value of the natural gas (e.g. New Zealand CNG program),
- Mobilization of an available domestic energy resource (e.g. Venezuelan CNG program),
- Employment creation (e.g. Canadian CNG program).

One or more of these factors should be strong enough to attract the government attention and its quest to introduce alternative automotive fuels as part of national energy policy.

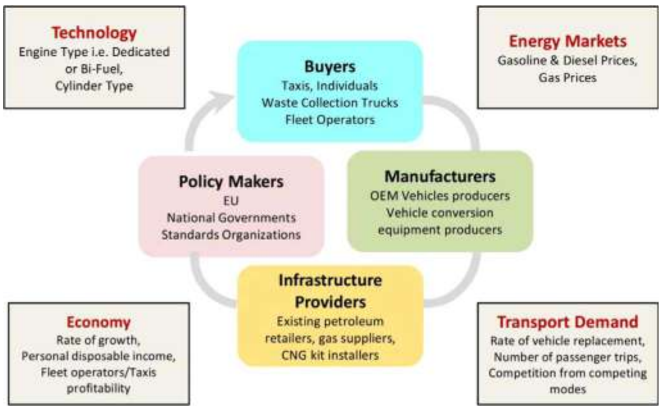

Fig. 3. Key external factors and stakeholders.

3.3. Program management

It is essential and key task for the early establishment of a program coordinating committee with representation from both government and pertinent stakeholders. There are four groups of stakeholders:

- Vehicle Owners;
- Manufacturers (OEMs) and distributor of vehicles and CNG equipment – this could also include maintenance service providers;
- Infrastructure providers – i.e. owners/operators of the refueling stations;
- Government and other policy makers (e.g. EU, ISO, national agencies etc)

A representation of both factors and key stakeholders is shown in Fig. 3. Clearly some stakeholders will have a role in shaping or influencing the external factors. For instance, government will shape the industry with regulation while close analysis of the upcoming technologies will fall within the role of manufacturers. The role of government remains prominent as they provide resources for the initially defining and analysing the feasibility structure of the business along with implementing. Scenario planning and defining ventures setting among stakeholders including vehicle manufactures, importers and other service providers are deemed to be necessary steps for the coming up with the strategy of transition. The steps also account for the anticipating options, guiding maps, and reverse engineering for determining the potential growth and challenges aspects in the process (Van der Vleuten and Raven, 2006).

The coordinating committee consisting of four groups of stakeholders will:

- Support the implementation of the Roadmap's recommendations and assess progress against key milestones;
- Provide recommendations to stakeholders regarding how the NGVs community could respond to future developments, such as changes in market conditions and technological innovations;
- Act as an umbrella organization for the local support network for end-users; and
- Serve as a forum for stakeholders to discuss issues pertinent to the NGVs community.

3.4. Feasibility studies

At the very initial level it is important to determine pre-feasibility analysis for establishing the existence of the CNG program, its economic feasibility, and potential implementation options. Favourable outcomes can then direct to setting a full fledge feasibility study and defining a clearly defined outcome and plan to the government for desired actions.

The feasibility must cover following aspects:

- The location availability and the structure for ownership related to gas reserves necessary for the CNG program.
- The price setting for CNG specifically for offering price advantage over conventional fuels.
- The configuration of the existing and future transport fuel distribution system and how it might accommodate the introduction of CNG.
- The CNG dissemination plan along with sites and arrangement for refueling points.
- Description of the current as well as future vehicle fleet including ownership, type, motive power, patterns for general traffic and estimation of vehicles likely to be converted to CNG,
- Assessment of the domestic and international exhaust and GHG emissions, inclusive and exclusive of CNG
- Review of CNG influence on the environment with specific attention to its production, dissemination, and consumption. GHG or Global Greenhouse gases have association with global emission. Hence, a comparative analysis of well to wheel or GHG emission must be assessed considering the complete fuel cycle emissions at the point of well to vehicle operations' causing emissions, most importantly and the global warming potentials of non-CO_2 greenhouse gases. The conclusions are usually depicted in total CO_2-equivalent emissions that deploy using global warming potentials for converting total non-CO_2 emissions to the mass quantity of CO_2. In accordance with the Third Assessment Report (2001) of IPCC, Methane contains GWP of CO_2 in a multiple of 23.
- Review of current regulatory scenario leveraging support for the safe development and sustainability of the CNG mechanism such as refueling stations along with the determination of the institutions related infrastructure, in case if any required.
- The assessment of the presence of the commercial environment for promoting nascent industry by importing equipment, investment by banks, local and foreign investors as well as effective workforce.
- The determination of the possible champion supporting the CNG system which is usually the government.

The feasibility is then required to ascertain the rate at which CNG uptick is the expected in terms of the vehicle conversion and refueling points. Determination of support from the governing bodies and other commercial stakeholders that is present and required for the industry. The results level will ascertain the viability of stretching feasibility work from city to country or even regional level. Such instances happen when say the natural gas is only present in the certain region or may be if the launch of the project to be only applicable at local level (for controlling domestic pollution level).

3.5. Implementation plan

If a decision is made to proceed, an effective implementation plan needs to be developed. This will consist of the guidelines on how the CNG program is to be established. The plan will cover:

- The production, distribution, compression and storage of natural gas,
- The target vehicle fleet,
- The system and network for CNG refueling.
- The standards, industry codes of practice and regulations required and the institutional infrastructure needed, including inspection and enforcement capabilities,
- Industry benchmarks, principle codes and regulations needed infrastructure along with institutional infrastructure required including inspection and enforcement capabilities;
- Staff training, capacity management, and defining R & D necessities.
- The arrangement and setting for the government as well as industry

inducement for encouraging and motivating initial level set-up.

- Financial backing for the CNG stations.
- The financing of aftermarket conversion or purchase of factory built NGVs,
- Mechanisms for provision of government support and involvement of all appropriate government agencies,
- Marketing plan for promotional campaigns including advertising and public relation management.
- Targets for the implementation of key elements of the CNG technology.

The sketch of an implementation program must be brought forward completely to the government and its relevant key departments for review. The review by government and other necessary stakeholders is aimed at coming up with the final plan whose key components are already discussed and approved for implementation by the involved parties.

3.6. Stimulate cooperation between key stakeholders

The most important factor in this equation is the partnership and understanding between the NGVs stakeholders, primarily OEMs, gas supply companies, petroleum retail companies (integrating CNG in retail mix), transportation companies and governments (local, regional, national). The well-organized German stakeholders market can be used as an exemplary model for the development of NGVs. The involvement of stakeholders i.e. the gas industry, government and the vehicle manufacturers, who have individual as well as mutual interest in vehicle and fueling station growth, is one of the main reason for the success of the German NGVs market.

It is important that the car producers as well as fuel providers decide and agree on points for breaking the circle (chicken-and-egg problem) as they have done in Germany and Italy. For convincing customers to convert their vehicles to CNG, it is important that a wide geographical coverage across the area while multiple models for NGV are introduced. Models suiting to the customer needs tend to spur hike in sales. It remains in the hand of a government to contract with different associations belonging to stakeholders for making their respective contribution for the success of ventures:

- Government should at least commit to measures that keep the price of CNG at a competitive level for a fixed period and possibly offer incentives to reduce the price of CNG vehicles and the costs of CNG infrastructure.
- Fuel providers should commit to the construction of a number of CNG pumps that jointly offer a good geographical coverage.
- Car manufacturers should commit to the introduction of CNG vehicle models that jointly cover a significant number of vehicle segments.
- The gas distribution companies are key actors. It is extremely important that they believe in the business and communicate that they are willing to invest. That gives argument for OEMs to deliver vehicles and is a clear signal to the market. If gas distributors are not pushing the market initially with concrete actions no one else will. Gas distributors need to push OEMs as OEMs will not push gas distributors. It is a fact. It's absolutely essential that the gas companies are involved in the CNG business to motivate customers and break the chicken and egg problem.

3.6.1. Alignment of stakeholder's interests

This experience originates from strategy or business choices executed in Argentina adopt CNG as a substitute fuel to replace the traditionally used gasoline/diesel fuel and provides the basis for policies and business plans to adopt CNG as an energy source for domestic transport. In the beginning, the oil companies did not show much interest in the CNG business or establishing CNG refueling stations. Oil companies were encouraged to invest in this business by removing restrictions by the government like the minimum distance between stations, on conditions that new stations offered CNG. This move aligned the interests of petroleum companies with those of the government. The certification and inspection right of CNG refueling stations were deputized to the natural gas distribution companies by the federal government, these companies had interest in development of these stations. The certification and inspection process became more efficient as a result.

3.7. Program initiation

The coordinating/steering committee recommended in Section 3.3 should be given the task of program implementation either by deploying their own resources or outsourcing different tasks to experts. For ease and effectiveness of project initiation, three elements need to be commenced at a very early stage. These are:

- Vehicle and refueling system demonstration trials,
- Institutional requirements,
- Industry policies and incentives.

All of these are vital to the successful implementation of CNG program and all take considerable time to reach fruition.

3.7.1. Demonstration trials

Policy-makers should work with industry partners to develop demonstration programs through green procurement to increase awareness (Farrell et al., 2003; Dougherty et al., 2009). There should be one or more demonstration trials designed to provide a platform for study and evaluation of issues such as:

- NGVs drivability, performance characteristics, durability, CNG consumption,
- CNG fuel distribution and handling requirements,
- NGV refueling and refueling station requirements,
- Consumer satisfaction.

It is important to endorse the program by giving demonstrations to the sponsors about the process progress. Such measures, in addition to the information development, provide investors assurance about the accuracy of their investment decision. Also the mass target audience is given with the idea about the operational conduct of the CNG sector. For generating maximum results from the demonstrations, it is important that design, plan, and implementation is planned and scheduled at the very initial level. Different program may run consecutively or parallel.

3.7.2. Institutional framework

Second element that must be determined at the very initial stage of development is the benchmark and standards setting for the industry. Such codes become a source of unified guideline for all, including all stakeholders. No doubt regarding fact that standard industry guideline are time requirement component for their implementation. However, it is also equally important that stakeholders are assured that the set out plan and guideline will be following in full. It is critical in giving investors and other stakeholders about the certainty of the future of the industry which carries high risk at beginning level.

3.7.3. Early adopters

The early adopters of NGVs will likely be fleet operators that can establish their own infrastructure, such as government fleets, taxis, and delivery vans. Semi-state companies and public bodies, including local authorities (e.g. municipal waste collection trucks), should be encouraged to include NGVs in their fleets. Individual light duty vehicles (LDV) consumers are far less focused on lifetime ownership costs compared to fleet owners, and therefore only consider a few years worth of costs in their purchase decisions (Eppstein et al., 2011).

4. Policy options to promote NGVs

The significant and sustained lower relative cost of natural gas compared to petroleum-based fuels provides a strong incentive for fleets operators and individuals to shift to NGVs. Yet those who seek to make such a switch face two significant obstacles: the higher upfront cost of NGVs, whether automobiles, vans, or light, medium, or heavy-duty trucks, compared to diesel or gasoline powered vehicles; and the lack of a comprehensive fueling infrastructure for either CNG vehicles. The measures and policies to optimize the wider adoption of NGVs are classified into following categories:

i. Market based instruments
ii. Innovative financial mechanisms
iii. Command and control measures
iv. Information, Education and Technical Assistance Programs

Though each of the above categories of policies is capable of handling various problems effectively, it is widely accepted that a combination of the above measures is required to remove various barrier to NGVs. Table 1 provides an overview of the policies tools used by case-study countries to promote adoption of CNG technology.

4.1. Market based instruments

The role of market based instruments have historically been significant for the adoption of AFVs (Hackbarth and Madlener, 2013; Adler et al., 2003) but are also fundamental for the introduction of NGVs as such procurements of NGVs are considered unsafe, unfamiliar and costly compared to conventional vehicles. Countries that have experienced strong NGV market growth, such as Iran, India, Pakistan, China, Italy and Brazil have offered monetary incentives to end users and equipment suppliers. Market based incentives comes in variety of forms includes tax discounts, grants for compensating the initial high investments, and loans.

4.1.1. Tax incentives

In case of conventional fuel vehicle technology e.g. diesel or gasoline, one has to pay taxes at many steps while buying a car such as registration tax, periodic tax payable in connection with the ownership of the passenger car (annual road tax), fuel taxes, and other taxes such as VAT, insurance taxes, registration fees and road tolls. Therefore tax incentives has proved to be the most effective tool in encouraging the investors to invest in CNG refueling stations and fleets operators as well as individuals for purchasing CNG vehicles. Reduction in taxes is going to encourage all stakeholders of the CNG industry value chain like equipment suppliers, vehicle manufactures, fuel sellers, and refueling station owners.

4.1.1.1. Vehicle taxes. Reduction in the costs involved in buying an OEM vehicle or in the converting of an existing conventional fuel vehicle is the most common way to provide incentives; this may be done by providing grants or tax credits. Many taxes are involved when one owns a car, starting from registration taxes, annual circulation taxes (road tax) and a surcharge on income taxation when company cars are used for personal use. Every country has laws for circulation taxes e.g. In Germany, the tax is based on the calculation of engine size and CO2 emissions while in other countries vehicle registration tax is based on the price or engine capacity.

4.1.1.2. Fuel taxes. These actions lessen the payback period for acquiring an NGV or converting the existing one and also attract the public attention of the potential cost savings associated with the use of CNG fuel. All type of transportation fuels are taxed with a certain extent which is varying from country to country. For example in OECD countries, fuel tax rate on diesel varies from 0.4% to 64% (average 42%) while gasoline the figure varies from 17% to 72% (average 56%) and for CNG the tax range is 5–51% (average 18%).

One problematic aspect of introducing CNG in gas deficient countries can be their cost (excluding taxes) that can be equal or slightly higher than the conventional fuel i.e. diesel/gasoline. For example in Germany the cost of CNG before taxation is about equal to that of conventional fuels. Fuel tax incentives can therefore be a very effective tool to change the ‘playing field’ for CNG and conventional fuels. In many countries, taxes on fuel contribute to a significant proportion of the prices paid at the pump. In Australia, for example, 38c in fuel excise duty is charged for every liter of gasoline. Lower tax rates on CNG reduce the price gap with petrol and diesel. For example in South Korea CNG is exempted for VAT and environment improvement tax which resulted in significant price differential between CNG and gasoline/diesel thereby making conversions economically viable.

A lower CNG price is a prime incentive for consumers to switch to CNG. The regions where the natural gas is notably cheaper than petroleum, such as in top 10 ten NGVs the drivers with highest VMT (vehicle miles of travel) demonstrate the highest adoption rates. The more miles traveled, the greater the cost savings by switching to natural gas and the more rapidly initial purchase cost differences are paid off.

As fuel taxation constitutes a significant part of government revenues, hence it needs to be reviewed once the NGV sector gains significant penetration in the transport market. Alternatively to neutralize the revenue loss resulted from CNG fuel tax subsidy; environmental improvement tax can be charged on conventional fuel e.g. in 2008 Indian government has introduced a scheme of Air Ambience fee of Rs. 0.25 per liter on sale of diesel fuel in the city of New Delhi and cess of 2.5% on diesel cars. Revenue from this fee goes to a dedicated fund called Air Ambience Fund. This fund is now available for many of the clean transportation subsidy.

4.1.1.3. Tax credits. Some countries offer tax credit incentives to address the incremental cost of NGVs. Not all consumers, however, are able to use these tax incentives. For instance, the US federal government currently provides income tax credit covering 80% (nearly $6400) incremental cost for purchase of a new NGV and tax credit of up to $ 0.5 per GGE CNG. Similarly Austrian government offers a tax exemption on fuel consumed by AFVs up to €800 per annum. If a vehicle buyer is a nonprofit or public entity or does not owe enough in taxes, they will not directly benefit from an NGV tax credit. Likewise, the tax credit is not refundable, meaning that individuals that have less than $6400 in tax liability could not take full advantage of the credit. Tax credits can also confuse consumers and can be overlooked in the overall purchase incentives.

4.1.2. Custom and excise duty

Custom duty plays a vital role in the early development of NGV market. For example, one of the major stimulant for the sharp growth in Pakistani CNG industry was exemption of custom duty on the import of CNG refueling station machinery and vehicle conversion kits/cylinder. Similarly, the Government of Iran, Korea and Thailand is providing an exemption of customs duty on CNG converter kits/cylinder imported into the country. In India, the exemption of import duty has resulted in a decline in the price of a converter kit by about 15%.

Exemption/reduction of excise duty on the sale CNG is not very common. There are few countries that are providing exemption/relief in the excise duty. For instance the Government of Thailand levying excise duty on CNG that is roughly half that of diesel and a third of gasoline. Similarly China, Australia, Canada and Japan are providing some relief in the excise

The evaluation of the applicability of excise duty on sale of CNG is crucial for the adaptation of NGVs. To increase the storage capacity of

Table 1
Review of NGV policy measures in case-study countries.

Status	Country	Market based incentives	Non-monetary incentives
Developing countries	Iran	■ Compensating the entire incremental cost for factory built bi-fuel CNG vehicles and 90% cost for after-market conversion. ■ 35% concession in import duty for CNG Cars. ■ Exemption from import duty and sales tax on import of CNG machinery, equipment, kits and cylinders. ■ Providing loans up to $0.4 million with low to zero interest rate to private companies for constructing a refueling station. ■ Setting price differential gap of 80% (on the basis of energy content) between CNG and gasoline (but CNG cost is 20% above diesel).	■ Government placed a mandate on OEMs to reserve 25% of their annual production capacity for NGVs.
	China	■ Setting CNG energy equivalent price to 54% and 68% of gasoline and diesel prices respectively. ■ Exemption of excise (consumption) tax and reduction in VAT on CNG.	■ Allocation of land for CNG refueling station. ■ Giving high priority to NGV/AFV in lottery plate licensing system. ■ Mandating the conversion of public taxis to CNG or other alternative fuels by several cities. ■ Ensuring the control of CNG price.
	Pakistan	■ Setting price differential of 50% (on the basis of energy content) between CNG and gasoline/diesel prices ■ Exemption from import duty and sales tax on import of CNG machinery, equipment, kits and cylinders. ■ Loan on soft terms to setup CNG station.	■ Establishing predictable profit margins to influence refueling station investment decisions. ■ Liberal approvals to obtain license for CNG refueling station. ■ Priority of natural connection to CNG station. ■ Permit import of used and refurbished CNG compressor.
	Argentina	■ Increased tax on gasoline as a replacement policy measure for subsidy on Natural gas. ■ Provides lines of credit to cover the incremental cost of acquiring an NGV or the conversion of a conventional vehicle, allowing CNG consumer to pay back the loans with fuel savings. ■ Setting CNG energy equivalent price to 28% and 60% of that of gasoline and diesel prices respectively.	■ Exempted the minimum distance for the construction of new conventional diesel/gasoline refueling stations on conditions that new stations offered CNG.
	India	■ Exemption of customs duty on the import of CNG conversion kits and cylinders. ■ Exemption of 12% sales tax on CNG vehicles. ■ Exemption of VAT on CNG while charging 25% and 16.6% VAT on gasoline and diesel respectively. ■ Setting CNG energy equivalent price to 42% and 55% of that of gasoline and diesel prices respectively.	■ Allotment of land for CNG stations and pipelines on priority basis. ■ Exemption of NGVs from Odd-Even day traffic rule in New Delhi.
	Brazil	■ Reduction in sales tax on NGV compared to conventional vehicles. ■ Provides loans for aftermarket conversion of conventional gasoline taxis. ■ Provides long-term interest free loan to refueling station investor cover over 70% expenses of gas and electric as well as civil costs. ■ Up to 75% reduction in annual vehicle registration fees. ■ Setting CNG energy equivalent price to about 50% of gasoline.	
	Thailand	■ Exemption of NGVs from any taxes except VAT. ■ Levying excise duty on CNG that is roughly half that of diesel and a third of gasoline. ■ Pricing CNG at 30% of diesel and 25% of gasoline price. ■ Loans with special low interest rate and long term repayment for taxi conversion. ■ Tax exemption/reduction on the engines and equipment relating to NGV and refueling station. ■ Reduction of import duties on CNG kits and cylinders.	■ Setting NGVs as the first priority for natural gas use, especially gas from onshore fields. ■ Allocation of land for NGVs service stations. ■ Controlling CNG retail rate through a fixed distribution margin.
Developed countries	Italy	■ Provides a subsidy of €1400 ($1938) to purchasers of a NGV and €600 ($900) for aftermarket conversion. ■ Charging 19% fuel tax on CNG in contrast to 59% and 55% fuel tax rate for gasoline and diesel respectively. ■ Reimbursement of 50–70% cost of a new CNG filling station in some cities e.g. Liguria, Lombardy, and Piemonte. ■ Pricing CNG at 45% of diesel and 43% of gasoline price.	■ Allowing the entrance NGV to sectors where conventional vehicles are not permitted. ■ Exemptions from 'Bad-Air' day traffic bans or limitations in four cities.
	USA	■ A tax credit for up to 80% of the incremental cost of buying a natural gas vehicle, with a maximum value ranging from $7500 for a light-duty passenger vehicle to $64,000 for the heaviest trucks. ■ An infrastructure tax credit of $0.5 per GGE of CNG ■ Income tax credit of $30,000 (increased to $50,000 in 2009) for installation of a CNG refueling station. ■ Setting CNG energy equivalent price to 67% and 61% of that of gasoline and diesel prices respectively. ■ Rebate (upto 20%) on insurance premiums for NGVs.	■ Allowing NGVs to park in areas designated for carpool operators. ■ Allowing NGVs to use HOV lanes. ■ Allowing NGV user to park their vehicles without the payment of a parking fee at certain times in certain public parking lots, parking areas and metered parking zones. ■ Allowing heavy-duty NGVs to exceed the federal weight limits up to 82,000 pounds ■ Exemption from annual emissions control inspections
	Germany	■ Charging 80% and 65% less fuel tax on CNG than those for diesel and gasoline respectively. ■ Setting CNG energy equivalent price to 55% and 60% of that of gasoline and diesel prices respectively. ■ Providing grant vary from €200 to €2000 for the purchase of NGVs.	■ Granting free parking for NGVs. ■ Allowing NGVs to use bus lane.
	Sweden	■ Providing relief on the energy tax for NGVs. ■ Providing subsidy of €1000 to NGV purchaser. ■ 40% reduced rate of taxation on NGVs.	■ Priority lanes for dedicated CNG taxi-cabs at airports, railway stations, and ferry terminals ■ No-Wait' taxi zones for dedicated CNG taxi-cabs at airports & train

(continued on next page)

Table 1 *(continued)*

Status	Country	Market based incentives	Non-monetary incentives
		■ 40% reduction in income tax paid for the use of a CNG car typically worth €900 annually in tax savings. ■ Exempt NGVs from annual road tax for first 5 years after registration. ■ Low fuel tax on CNG ■ Setting CNG energy equivalent price to 80% and 85% of that of gasoline and diesel prices respectively.	stations (i.e. Goteborg & other Swedish cities) means much reduced time waiting for a new passenger and thus higher earnings. ■ Free municipal parking permits for NGVs in many cities (value of parking permit/year is €700). ■ Giving priority to NGVs by municipalities when ordering taxi cabs or other transportation services. ■ 10 Swedish cities have introduced free parking for NGVs, value of parking permit/year is 700 Euro.
	S. Korea	■ Set CNG price at one-third to gasoline and diesel fuel. ■ Exemption from the corporation tax (3%) for installing a refueling stations ($12,500/station). ■ Exemption of VAT (10%) and environment improvement charges (4%) on CNG buses. ■ Offer 30% discount for electricity charges to refueling stations. ■ Exemption from customs duty for importing CNG kits and cylinders. ■ Low interest loans for installing a CNG refueling station ($0.6 million/station) at conditions: 5 year deferment, 10 years amortization ■ Subsidy on purchase of CNG buses ($33,000/bus). ■ Empty running cost (in the case of more than 4 km distance from the nearest gas station, grants for empty cost of up to 22 km). ■ Gas station operation expanse (grants for the loss of the services of less than 31 NGVs in a station with the service capacity of 100 NGVs per day).	

the CNG changes are brought to its mass density by the process of compression. Hence, use of compressed natural gas as a transportation fuel should not be included in the manufacturing infrastructure, and hence exempting it from the excise duty.

4.1.3. Taxation regime

The differential taxation provides long-term sustainability of NGVs growth in comparison to the short-term benefits achieved from direct subsidies. The former enables the market to be flexible to the cost of transformation and provides the sustainability that not collapse like some of the older global programs. Let us consider New Zealand, where the government provided generous financial incentives both for conversion and establishing refueling stations, for growth of the NGVs industry, so that the number of NGVs doubled every year. However, the new government withdrew the financial incentives for the CNG industry and consequently the public lost their confidence in the NGVs industry, which was still developing. Car owners stopped converting their cars into CNG and assumed that the lack of government support indicated the failure of the NGVs industry. The country now has only 201 NGVs, almost negligible as compared to the peak of 135,000 and 530 refueling station in the past. Fig. 4 shows the effect of incentives on New Zealand NGV program 1980–1986. It can be observed that conversions per month were sharply affected by government incentives. When incentives occurred, market share increased. On other hand when incentives were removed, market share dropped significantly. Therefore, for the long-term sustainability of any clean fuel program, it is important to design differential fuel taxes instead of direct subsidies. For example, the Argentina government instead of direct subsidies offered the incentive for fuel switching in the form of high taxes on gasoline.

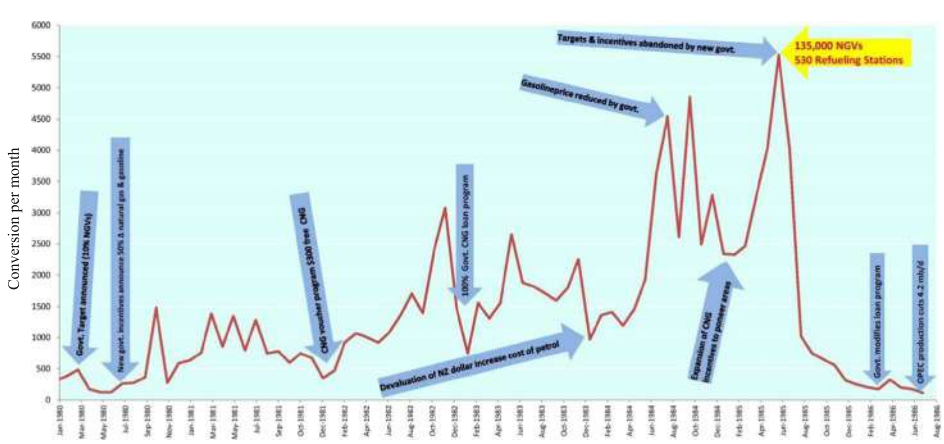

Fig. 4. Effect of incentives on New Zealand NGV program 1980–1986.

4.2. Innovative financial mechanisms

Role of private investment has much role to play in the picking up growth of the AFV market along with the infrastructure required for the purpose. Here, financial products tailored for the purpose gains immense important. Innovative financial tools have helped overcome similar barriers faced by other clean energy technologies, such as renewable energy or energy efficiency upgrades. Therefore, deploying those financial models designed for other technologies can be used for channelizing the process of private investment in CNG technology.

4.2.1. Loans and leasing

Soft loans on NGVs are exercised as an effective instrument to promote CNG as transportation fuels in various countries like Iran, Argentina, South Korea, Pakistan, Thailand, Brazil and India. The loans can be for vehicle purchases, conversions, and construction of public refueling facilities. The loans can also be provided to assist entrepreneurs interesting in the establishment of local equipment manufacturing capabilities e.g. kits and cylinders. Similarly various leasing plans allow any buyer to avoid high upfront costs of NGVs and allow individual consumers and some government agencies to benefit from government incentives. The Iranian government is providing loans up to $0.4 million with low to zero interest rate to private companies for constructing a refueling station. In South Korea, investors are facilitated with low interest loans for installing a CNG refueling station ($0.6 million/station) at conditions: 5 year deferment, 10 years amortization. Some US states (e.g. Wyoming) authorizes loans to support natural gas fueling stations for 75% of the project cost up to $1 million (Baldwin, 2014).

4.2.2. Performance contracting

These contracts can be used to finance the higher upfront costs of NGVs or new fueling infrastructure. In both cases, the investment can be repaid through future operational and fuel cost savings.

4.2.3. Insurance rebate

Motor vehicle insurance, to protect vehicle owners against the financial costs associated with vehicle damage and bodily resulting from road accidents, can be a significant annually recurring cost. Discounts and rebates on insurance premiums for vehicle owners can reduce the lifetime costs of NGVs. For example the Saskatchewan Government in Canada offers a 20% rebate on insurance premiums for hybrids and fuel efficient vehicles (Review of Alternative Fuel Vehicle Policy Targets and Settings for Australia, 2015). Similarly some US states provides a discount of up to 10% on all major insurance coverage for NGV owners.

In summary, the role of financing and related tools is crucial factors in driving growth in the transportation industry. However, ineffective financial plan lead to an equal status of financial disaster. For example, Introduction of CNG plan in China proved to be a failure because government was unable to determine the financial plan that failed in creating notable difference in the prices of the CNG and conventional fuels. Squeezed gap between the two increased the time required for recovering the additional cost of conversion; hence resulted in limited number of conversion. As a consequence the country does not have any CNG buses in operation; further, CNG is failing to deal with the competitive strength of diesel and there are chances that it will also lose taxi market to diesel. Moreover all type of financial incentive for the promotion of NGVs needs to be guaranteed for a certain period of time. For example, the German government introduced a national law in 2006 that fixed a reduced excise duty for CNG until 2018 (Nijboer, 2010). Due to this law, until the end of 2018, taxes for natural gas as a fuel in Germany are about 80% lower than those for diesel and about 65% lower than those for premium gasoline (Wang-Helmreich and Lochner, 2012). Incentives should be reduced gradually over time to avoid market shocks and 'dislocation'. Sudden end to incentives can kill the market, (even if the end date is known). However, it is interesting to note that this theory (sudden end to incentives) can damage the young NGV market only. For instance the Fig. 2b depicts the rapid growth of Italy's NGV market during 2008–2010. The main reason for this sharp growth was the government subsidies, which lasted from 2008 to 2010 and supported the conversion of existing cars ($900) as well as the purchase of new NGV ($1950). Due the mature Italian NGV market, although the end of subsidies slow the growth of NGVs penetration but there was no negative decline.

4.3. Non-monetary incentives

Many studies demonstrated that non-monetary governmental incentives can have substantial influence on the demand for AFVs (Adler et al., 2003) but their effectiveness depends strongly on local conditions. Some of the prevailing non-monetary incentives in the CNG market are listed below:

- Access to use high occupancy vehicle (HOV) lanes regardless of the number of passengers in a vehicle e.g many US states allows NGV driver to use HOV lanes (can save 1 h/day in traffic = 6.25 weeks of work equivalent per year).
- No-Wait' taxi zones at train stations and airports, for example Swedish cities (Goteborg). Similarly in August 2011, the Chicago city started a Green Taxi Program, which allowed dedicated CNG cabs to line up at the taxi stands at O'Hare and Midway airports. This increased the earnings of local cab drivers substantially, as the average airport fare is $35, which is quite a profitable fare, especially when the cabbies didn't have to wait for hours at airport holding lots.
- Grant free parking in short-term parking zones of urban centers, exist in Italy, Austria, Spain, Sweden, Switzerland, Croatia or Czech Republic.
- Exemptions from 'Bad-Air' day traffic bans or limitations e.g. 4 Italian cities, Paris, etc.
- Exemptions from time-of-day traffic restrictions i.e. London congestion charge;
- Restrictions on commercial traffic, such as noise limits on late night commercial traffic (bad for diesel; good for NGVs)
- Allow heavy-duty NGVs to exceed the national weight limits e.g. United States, where NGV can cross the federal weight limited of 82,000 pounds.
- Reduction/Exemption from Toll fee.
- Exemption from annual emissions control inspections e.g. Washington state

4.4. Command and control measures

Command-and-control policies typically require polluters to take specific actions to reduce emissions by installing a particular technology or meeting a specific performance (emissions) standard. It is particularly effective in breaking initial resistance in implantation of alternative policy measures. Governments can strongly influence how quickly CNG technology is adopted through the design of the regulatory framework. The most direct form of regulatory measure involves the use of legal mandates on public or private organizations to purchase a fixed number of NGVs. Legal mandates are best applied in conjunction with incentives, as this helps ensure compliance, and they must both be enforceable and enforced. Following are the few cases of the command and control instrument implementation in NGV market:

- Argentina has adopted a command and control approach by developing standards for a successful national private industry of compressors and dispenser, cylinders, and conversion kits to promote natural usage in transport sector.
- In order to reduce pollution in the city of Milan, Italian Government permits electric vehicles, bicycles and motorcycles fitted with catalytic converter in the streets only between 8.00 A.M. and 8.00 P.M.
- The popular "Delhi Decision" has set the command and control approach environment in a different league. As landmark decision, the Supreme Court of India ruling went into effect in New Delhi on March 31, 2001, that mandated the conversion of entire public transport system to CNG. In addition, the honorable court has ordered conversion of government owned petrol–driven cars to CNG. Though it has created considerable frication in the system in the short run, it has resulted in rich dividends in terms of improved air quality in the long run (Yedla, 2015).
- Since January 2011, in response to vehicle congestion and air pollution, the Chinese capital city Beijing has implemented a lottery plate licensing system which limiting new license to 240,000 per year, reduced to 150,000 per year since January 2014, while reserving 20,000 plates for alternative fuel vehicles. Any resident who

wishes to purchase a car in Beijing must first win a drawing for license plates. Monthly drawings are held, with success rates of under 1% per month over the year 2015 (Yang et al., 2016). This command & control measure has encouraged the consumer to opt for CNG due to very high chances of getting the license as compared to conventional vehicles.

- One of the major contributing factor towards the significant diffusion of NGVs in Iranian transport sector, is the government policy which enforce the local car manufacturers to allocate 25% of their production capacity for NGVs (Sharifi and Gougerdchian, 2012).

4.4.1. Regulatory actions

Different components of the regulation driven policy include setting industry benchmarks, protocols, and certification programs; liberal licensing for CNG refueling stations (e.g. sharp increase of refueling stations in Pakistan) accelerated agreements for CNG refueling stations installation forced early retirement of old fleet vehicles e.g. city buses and taxis(Delhi, India is a good example); regulations about penalties for dirty fuel based buses operation such as diesel; and traffic restrictions for which CNG vehicles are exempt. Hence, regulation pertaining to traffic, retailing, suppliers, and vehicles are critical to implement.

Regulation for the environment sustainability can set performance or technology related protocols and their implementation can be achieved through rewards and fines. There are no specifically defined covenant to be used a guideline for defining regulatory standards. These can be applicable to a product, its sub line or related service. Regulations can be set out depending upon parameters related to energy efficiency, technology, or emissions levels. It is important the set of standards should effectively deal with the present trade-offs between environmental factors like fuel regulations based on the emission level of different elements may have fruitful impact on air pollution (e.g. restriction on exhaust particulate matter–PM) but at the same time produces a negative impact on climatic changes (e.g. high emission of GHGs). Vehicles in EU are regulated emissions levels by setting "Euro" guides that are reducing the percentage of emission level allowed with every passing year. The current standards as of September 2015, passenger and light-duty vehicles are allowed Euro 6 standards.

Regulatory settings are one important way to deal with the NGVs market let-downs and challenges. The benefit comes from curtail need for additional information, alleviated cost of transaction, and building connection with the mass market for meeting training to households, car drivers, and SMEs. They are also widely used to require actors to account for environmental externalities and, if continually modified to account for technical progress, they can provide dynamic innovation incentives.

Deployment of the emission standards for the vehicle fleets in developing countries is one way to start supply of NGVs. In such case, the cars manufactured and sold during particular year would be mandated to have certain defined level of the average emissions intensity (in g CO_2-eq/km). The plan is also in place in the EU for cars as well as vans. Cars manufactured during certain year are required to ensure that the fleet for a that very specific year has emission level not more than an average of 130 g CO2/km and 95 g CO2/km by 2015 and 2020 respectively. For vans, allowed rate is 175 g CO2/km and 147 g by 2017 and 2020 respectively. Currently in Europe, the uptake of NGVs is being further encouraged by the adoption of stringent emissions standards for new vehicles in order to support the EU's emissions reduction targets. As NGVs produce lower levels of greenhouse gas (GHGs) emissions than petrol or diesel vehicles, they represent an immediate option for meeting the 95gCO2-e/km target in 2020. In countries like Pakistan where lack of the regulation is left vacuum, such regulation deployment has a potential to increase the share for NGVs in the transportation sector. Old and ill maintained diesel buses that contributes major share in emission are not required and mandated to abide with the emission standards; or more worsened situation where there are a complete vacuum of regulation to comply with, it becomes challenges for the CNG buses to compete with the dirty fuel vehicles in terms of operating expenses.

The development of an effective regulatory standard requires national leadership to balance the interests of various stakeholders (e.g. Car manufacturers, CNG kit and cylinder manufacturers, vehicle owners, refueling station operators etc.) while creating sufficient societal support and incentives for successful implementation. The ineffectiveness in the development and implementation of regulatory standards arises by the delegation of these responsibilities to public administration, which is not as transparent and accountable as the legislature that formulated these regulatory standards. Regulatory standards can be used for the correction of any problems caused by information failures and may prove beneficial for society if the regulation formulation and implementation costs are less than the losses caused by informational barriers. The International Energy Agency (IEA, 2003) urges the governments to adopt a rather aggressive approach for development of support infrastructure, codes and standards, which will in-turn help on speeding the early adoption of advanced vehicle technologies as they become available.

5. Conclusion and policy implication

Use of CNG as an alternative source of fuel for transportation has been at effect in many economies giving world a considerable experience to alternative sources of fuel. Hence, it is important to create future program while leveraging lesson from the successful and unsuccessful programs of such alternative sources of fuel. Keeping in view the international experience with CNG as an alternative transportation fuel, this study suggest a strategic framework for transition challenges to natural gas vehicles (NGVs) and examines the policy instruments, incentives, and economic drivers associated with the adoption of NGVs in selected case-study countries. Key lessons include:

- There is no universal policy for the implementation of CNG technology. Different policy models have been applied in different economies with varying levels of success. It is identified that a combination of the various policy measures is required to remove various barrier to NGVs.
- Introduction of CNG as transportation fuel and establishment of sustainable market is considerably and effectively done in developing countries when compared with the status of developed ones. Among main reasons contributing to this fact is the increased financial support available to lower income class who also owns a vehicle.
- Ultimately, the government has to take the driving seat in starting, progressing, and knitting stakeholders for introduction of NGV vehicles. At the initial stage it is important that the government crafts the necessary regulatory and other related frameworks by taking industry on board.
- It is important that government establishes a network of competent players specifically in the areas such as NGV producers, operators for fleet, natural gas suppliers and existing petroleum fuel retailers. All these and other related player carrying strong knowledge of the related business while it is also important for NGV program to duly address the concerns of stakeholders who have major role in the market pick.
- The engagement of a national automotive manufacturing industry in the introduction of NGVs greatly expedites market growth.
- The importance of providing substantial and sustained financial incentives to reduce the costs of NGVs to consumers is the most consistent finding in the case-study countries. Therefore the government should institute predictable and persuasive financing options to overcome incremental costs associated with the NGVs.
- Establishing predictable profit margins to influence the retail station investment decisions.
- Sending clear, reliable and enduring CNG price signal to consumers.

■ Government policies need to be consistent and stable to assure customers of long term market initiatives.

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Annexure-I

Khan, M.I., 2018. Evaluating the strategies of compressed natural gas industry using an integrated SWOT and MCDM approach. Journal of cleaner production, 172, pp.1035-1052.

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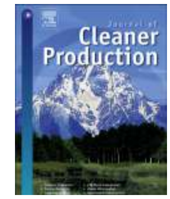

Evaluating the strategies of compressed natural gas industry using an integrated SWOT and MCDM approach

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ABSTRACT:

Out of available alternate fuels compressed natural gas (CNG) is the one which is meeting the maximum needs of countries worldwide, who want to switch over to alternate fuels. However, despite the fact that CNG are often seen as a panacea by policy-makers, there are a number of barriers to their widespread market penetration and diffusion. This paper aims to evaluate the internal and external environment of CNG industry in Iran applying SWOT (strengths, weaknesses, opportunities and threats) analysis and prioritizing the strategies for stimulating the growth of Iranian CNG market. Based on SWOT analysis nine strategies were suggested. Strategy prioritization to promote the development of CNG economy in Iran is a typical multiple criteria decision-making (MCDM) problem. To deal with the ambiguity associated with the judgments of decision-makers, a modified Fuzzy Goal Programing (GP) is used as an evaluation tool, where uncertainties of the decisions are translated into fuzzy numbers. The suggested technique is not limited to Iran, and it is a generic practice that can also be applied to evaluate the CNG market in other countries.

1. Introduction

Setting the energy policies aimed at addressing the increasing environmental concern and improving the country's energy security are the continuous challenges for many countries (Igos et al., 2015). The challenges arise mainly because energy policy includes a number of stakeholders and needs to incorporate the interests and requirements of all the major stakeholders to make energy policy viable (Greening and Bernow, 2004). The interests and requirements of the stakeholders are diverse and cannot be represented by one criterion. Therefore, when aiming at sustainable and low-emission energy, strategic decision making arises from the multi-dimensionality of stakeholders interests, socio-economic dynamics, sustainability goals and long-range nature of the problems (Kowalski et al., 2009).

Road transportation sector is the major energy consumer for many countries. If energy policy for road transportation is developed on the basis of political motivations rather than careful scientific evaluation of multiple criteria, it ultimately fails in terms of sustainability and acceptability. Therefore, in order to model the energy policy of road transport, it is necessary to explicitly consider multiple objectives that can appropriately meet the interests of stakeholders and the criteria for sustainability. For this reason, policymakers require detailed information and insights into multiple objectives to endorse appropriate policy measures (Strachan et al., 2009).

2. Motivation and objectives

The low oil prices in Iran make them attractive and the dominant family of fuels in road transportation. Although Iran has abundant fossil fuels resources, it lacks refining capacity to produce gasoline fuel that share major part of energy consumption of the Iranian transport sector. Given the number of light-duty vehicles in 2011, the average daily consumption of gasoline for each car was 10.5 L, which is about 5.2 and 2.6 times that of the same index in Europe and the United States respectively (IFCO, 2012). Owing to high petroleum fuel consumption of the Iranian transport sector, high emission associated with the Iran's low-grade petroleum fuels and high gasoline imports, country's energy security and environmental considerations are indispensable. Currently Iran's most significant energy policy is to reduce shares of oil and oil products' in the national energy basket and to substitute it for natural gas and

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renewable energies (Hafeznia et al., 2017).

The main objective of this study is to identify the key features of CNG economy in Iran and rank strategies for promoting its development toward a more environmental-friendly alternative at a reasonable financial cost. This is done through application of Multiple-criteria decision-making (MCDM) method to prioritize the strategies for appropriate budget planning and setting the roadmap for the development of CNG industry in Iran.

Assessments of energy planning for road transportation system scenarios with MCDM have been carried out before as shown in Table 1. The MCDM approached used in these studies are different in terms of the theoretical background, questions type and the achieved findings. Most of MCDM studies pertinent to automotive fuel and technology have been focusing on suitability of a specific fuel among various available options (Tzeng et al., 2005; Vahdani et al., 2011; Tsita and Pilavachi, 2012). There are very limited MCDM studies addressing the strategies prioritization for a particular type of fuel. To the best of our knowledge, there is no systematic empirical research exists addressing the question strategies prioritization for CNG industry. CNG sector often cope with many concerns related to economic, environmental, legal and technical issues, which should be addressed to get a successful market penetration of natural gas as transportation fuel. A common approach that integrates the stakeholder visions into the evaluation process of CNG options is currently lacking. In this paper, a methodology is proposed that addresses the above mentioned problem. Taking into account the current and midterm state of Iran's natural resources, as well as environmental and sustainability issues, the results of this study could provide useful insight on the diversification of natural gas as vehicular fuel and overcome the research and policy gaps in the context of Iran.

In this study, the method of strengths, weaknesses, opportunities and threats (SWOT) analysis is applied to explore the strengths, weaknesses, opportunities and threats of Iranian CNG industry. Consequently, the strategies were proposed for stimulating its growth by applying strengths, minimizing weaknesses, exploiting opportunities and avoiding threats. While the SWOT method does not provide an analytical way to quantify the effectiveness and to prioritize these strategies according to their importance, a multi-criteria decision-making (MCDM) method has been developed to rank the prior sequence of the strategies. By combining the MCDM and SWOT methods, the stakeholders/decision-makers can make correct decisions by giving top priority to these strategies that have significant effect on the development of CNG economy in Iran. In this study, a novel MCDM method by integrating Goal Programming (GP) and fuzzy theory has been developed for prioritizing the strategies for promoting CNG economy of Iran, in which, the fuzzy theory was used as a bridge to link the linguistic variables and crisp numbers by membership functions of the linguistic variables.

The remaining of the paper is structured as follows: Section 2 describe the CNG background in Iran. Section 3 presents the method of SWOT analysis and its implementation to analyze the CNG industry of Iran. Section 4 discusses strategy recommendations. In Section 5, describe the proposed MCDM technique and its application to strategies prioritization to promote the growth of Iranian CNG industry. Section 6 discusses the results of the evaluation. Finally results are concluded in Section 7.

3. CNG background in Iran

CNG projects in Iran were started in 1975 with the conversion of 1200 taxis and construction of two refueling stations as a pilot project in Shiraz (biggest city in south-west of Iran) and followed in 1983 with further conversion of 1200 cars facilitated by22 refueling stations in Mashhad (biggest city in north-east of Iran). The serious attention to NGVs was paid in 2001 after Iranian Parliament passed a law about the development of NGVs program and consequently in the same year the government started to plan and execute national scale projects via Iranian Fuel Conservation Organization (IFCO). For establishing CNG infrastructures and promoting NGVs, IFCO adopted the following strategies:

- Conversion of existing gasoline fueled cars to CNG
- Design and production of OEM bi-fuel CNG cars, vans and light duty commercial vehicles at local industry.
- Construction of public owned CNG refueling stations
- To promote and educate public about safety issues pertaining to usage of CNG as vehicular fuel, several educative films were broadcasted on TV and radio channels.
- Localization of CNG components e.g. CNG kit, cylinders and CNG stations equipment by technology transfer from abroad
- Dissemination of CNG technology awareness through arraignment of pertinent training courses for manpower associated with CNG conversation workshops, inspection centers, after sales services and CNG stations operators.
- Legislation of national directives and regulations.

After implanting the above strategies, the country's CNG industry has witnessed a rapid increase in both number of NGVs as well as refueling stations and 2012 it got first rank in the world NGVs market. Detail of Iran's natural gas strategies are given in Appendix A.

4. SWOT analysis

SWOT analysis is a proven technique for helping the strategy formulation, and often use as an instrument to analyze the internal and external environment of the organization (Nikolaou and Evangelinos, 2010; Terrados et al., 2007). This tool classifies the key strengths and weaknesses associated with the system and comparing with the current and future weaknesses and threats (Chen et al., 2014). It is widely used in strategic planning, where every individual factor affecting the system environment are analyzed in detail (Kotler, 1994). The strengths and weaknesses factors are recognized by evaluating the internal environment of the system while the factor associated with the opportunities and threats are recognized evaluating external environment of the system (Dyson, 2004). With SWOT analysis we can summarize the most significant and effective factor associated with the internal and external environment and which may affect the organization's future. These factors are usually labeled as strategic factors (Kangas et al., 2003). The internal and external environments involve variables which are inside and outside of the system, respectively.

Based on identification of aforementioned four parameters, the SWOT matrix is determined which is applied to recognize four types of strategies, i. e strengths–opportunities (SO) strategies, weaknesses–opportunities (WO) strategies, strengths–threats (ST) strategies and weaknesses–threats (WT) strategies, as shown in Fig. 1. When properly used, SWOT can be a good basis for devising a strategy (Chang and Huang, 2006). In particular, several examples of the successful application of SWOT method can be witnessed in the area of regional energy planning (Fertel et al., 2013), sustainable energy development (Markovska et al., 2009), electricity supply chain (Bas, 2013) bioenergy (Catron et al., 2013), wind energy (Igliński et al., 2016), solar energy (Sindhu et al., 2017), environmental policy and management (Grošelj and Stirn, 2015; Alvarez et al., 2016), development of shale gas (Xingang et al., 2013) and municipal solid waste management (Yuan, 2013). Several European

Table 1
Literature Review Alternative Fuel related MCDM studies.

Study	Study region	Application area	Study purpose	Gap and research problem	Technique & approach	Criteria						Results & outcome
						Technical	Economic	Environmental	Social	Safety	Other	
(Yedla and Shrestha, 2003)	India	Choice of alternative fuel technologies	Selection of best alternative in Delhi transportation system regarding to environmentally sustainable	Due to problem in Delhi urban transportation need to further study related to environmentally sustainable	Hybrid AHP	X	X	X			X	The results showed that CNG car is the better priority followed by CNG buses
(Macharis et al., 2004)	Europe	Choice of technologies	To develop a strategic evaluation methodology to assess the safety of advanced automotive technology for Europe	Need to develop a strategic assessment methodology based on a formal, analytical process that incorporates technical and stakeholder perspectives	AHP		X	X	X	X		The results suggest that the most promising technology include the integrated system, the driver monitoring systems, mandatory ISA and ACC.
(Tzeng et al., 2005)	Taiwan	Choice of "clean technologies" for vehicles	To evaluate a moderate fuel mode for buses in urban area of Taiwan.	Need to assess the potential of alternative fuels to displace oil as the main source of transport fuel	Fuzzy AHP & VIKOR	X	X	X			X	The result shows that the hybrid electric bus is the most suitable substitute bus for Taiwan urban areas in the short and median term
(Brey et al., 2007)	Spain	Strategies prioritization for alternative fuel transport system	To conduct a comparative analysis of FCVs to other alternative fuels vehicles	Need to evaluate the government support for private sector in the development of AFVs to compete with the traditional fuels vehicles	DEA		X	X				The results shows how alternative fuel vehicles can be cataloged as efficient depending on society's preferences for the criteria (environmental or economic) taken into consideration
(Mohamadabadi et al., 2009)	Canada	Choice of fuel technologies	To rank different road transportation fuel-based vehicles	Need to develop a multi-criteria assessment model in order for ranking different fuel option for road transportation by combining both qualitative and quantitative criteria	PROMETHEE		X	X				The results showed that on basis of economical parameters, gasoline-based vehicles are ranked first while on basis of environmental parameters, hybrid vehicles are ranked first.
(Vahdani et al., 2011)	Iran	Choice of fuel technologies	Selection of alternative-fuel buses for Iranian urban transport sector	As selection of alternative-fuel buses involve several and different types of criteria, combination of different decision models, group decision-making and various forms of uncertainty. Therefore it needs to develop a suitable method to select the right fuel buses.	Fuzzy TOPSIS	X	X	X	X	X		According to results conventional diesel engine is placed in the 1st rank and CNG and LPG are placed in the 2nd and 3rd ranks, respectively
(Tsita and Pilavachi, 2012)	Greek	Choice of alternative fuel technologies	To evaluate alternative fuels for the Greek road transport sector	Need to address economic and policy issues for a variety of alternative fuels for the Greek road transport sector	AHP	X	X	X	X			It is concluded that petroleum fuel blended with 1st and 2nd generation biofuels are the most suitable alternative fuels for the Greek road transport sector
(Zubaryeva et al., 2012)	Europe	Choice of "clean technologies" for vehicles	Identify and evaluation of potential market for electrified vehicles in Europe	There is need to integrate multiple criteria for ranking of various electric-drive vehicles market drivers	AHP		X	X	X		X	Results showed, infrastructure availability, car density, state incentives, average winter temperatures, GDP per capita, Well-to-Whell (WTW) CO2 emissions, diesel and gasoline fuel versus costs savings and share of Renewable Energy Sources (RES) are significant criteria of Electric Drive Vehicles (EDVs) lead markets
(Yang and Regan, 2013)	Korea	Strategies prioritization for alternative fuel transport system	to prioritize potential alternative truck operation strategies	Need to propose a general multi-criteria decision support methodology that enables the prioritization of potential alternative truck operation strategies in Korea.	AHP	X	X	X		X		The results provided a rational argument for prioritizing potential alternative truck strategies
(Tsita and Pilavachi, 2013)	Greek	Sustainable develpoemnt of a specific fuel	To evaluate next generation biomass fuels for the transport sector	Need to address economic and policy issues for the generation of biomass fuels for the road vehicles in Greek.	AHP	X	X	X	X			It is concluded that synthetic natural gas and electricity from biomass incineration are the most suitable next

(continued on next page)

Table 1 (*continued*)

Study	Study region	Application area	Study purpose	Gap and research problem	Technique & approach	Criteria						Results & outcome
						Technical	Economic	Environmental	Social	Safety	Other	
												generation biomass derived fuels for the transport sector
(Shiau, 2013)	Taiwan	Sustainable transport strategies	Assessment of sustainable transport strategies	Need to evauation of sustainable transport strategies in Taiwan	AHP							Finding of the study showed that measures of tailor are based on local circumstances
(Jones et al., 2013)	Ghana	Urban transport projects	Suggested a new framework for screening of projects regarding to urban transport based on sustainability criteria	Need to study for examine projects screening in urban transport systems based on sustainability criteria	AHP							Results of this study demonstrated that the suggested framework is adequately present for priorities, local sustainable transport needs and perceptions
(Streimikiene et al., 2013)	Europe	Choice of “clean technologies” for vehicles	Analysis of life cycle GHG emissions and private costs of the main road transport technologies	Need to develop the multi-criteria framework for comparative assessment of road transport technologies in terms of their environmental and economic impacts and facilitates decision making process in transport sector.	TOPSIS		X	X				The results indicated that road transport technologies based on biodiesel from waste vegetable oil have the lowest life cycle GHG emission while gasoline based transport technologies have the highest life cycle GHG emissions followed by diesel technologies.
(Lanjewar et al., 2015)	India	Choice of alternative fuel technologies	To select the most appropriate alternative fuel for a given transportation application	Need to develop a hybrid multiattribute evaluation model for assessment of alternative fuels for transportation sector using graph theory and AHP method	Hybrid AHP	X	X	X	X	X		The results model the fuel selection attributes and their interrelationships and represents decision maker preferences and value judgments.
(Zhang et al., 2016)	China	Strategies prioritization for alternative fuel transport system	To identify and remove barriers which hinder the customers' acceptance of alternative fuel vehicles.	Need to propose and prioritize a group of factors that may affect customers' preference on Fuel Cell Vehicles in China	Hybrid Fuzzy AHP	X	X	X	X	X		The results indicate that fuel availability, vehicle performance, and economic costs are the most important dimensions in affecting customers' attitude towards FCVs
(Maimoun et al., 2016)	USA	Choice of “clean technologies” for vehicles	To rank fuel alternatives for the U.S. waste collection industry with respect to a multi-level environmental and financial decision matrix	Need to determine if the US waste collection industry is moving in the right direction toward a more environmental-friendly alternative at a reasonable financial cost	Hybrid TOPSIS		X	X				The overall analysis showed that conventional diesel is still the best option, followed by hydraulic hybrid WCVs, landfill gas (LFG) sourced natural gas, fossil natural gas, and biodiesel.

	STRENGTHS-S	WEAKNESSES-W
	1. 2. . . List of Strengths . n	1. 2. . . List of Weaknesses . n
OPPORTUNITIES-O 1. 2. . . List of Opportunities . n	SO STRATEGIES-S 1. 2. . . Use strengths to take advantages of opportunities n	WO STRATEGIES-S 1. 2. . . Overcome weaknesses by taking advantages of opportunities n
THREATS-T 1. 2. . . List of Threats . n	ST STRATEGIES-S 1. 2. . . Use strengths to avoid threats . n	WT STRATEGIES-S 1. 2. . . Minimize weaknesses to avoid threats n

Fig. 1. SWOT matrix.

countries applied SWOT analysis for strategies prioritization and to ensure the consistency of horizontal policies in their national strategies for sustainable development (European Commission, 2004).

However one of the major limitations of traditional SWOT method is that the significance of each element in the process of decision making cannot be quantified, and it is hard to evaluate which element is more influential for the strategic decision (Pesonen et al., 2001). Put differently, SWOT method doesn't present an analytical tool to find the relative significance of the individual elements, or the capacity to evaluate the suitability of alternate option on basis of such elements (European Commission, 2004). Some key limitation of the SWOT methods are listed below:

i. Generally SWOT analysis consider the environmental elements through qualitative examination (Amin et al., 2011);
ii. It doesn't give any priority to different factors and strategies;
iii. There will be exponential increase in the number of adopted strategies, if there is increase in number of factors/agents. For instance if the number of elements involved in a set of S,W,O,T is equal to 5, the outcome of the collective strategies will be about which will make it very difficult to select a suitable strategy;
iv. It doesn't pay attention to the ambiguity of the elements.

For this reason, the comprehensive appraisal of the strategic decision-making process cannot be made through SWOT (Hill and Westbrook, 1997). However when it is integrated with the analytic hierarchy process (AHP), SWOT analysis can quantify the significance of individual factors involved in decision making process.

4.1. SWOT analysis of CNG industry in Iran

For SWOT analysis of Iranian CNG industry, this study used the author own personal data collected during several years of experience with CNG industry, secondary data from academic literature, published reports by a variety of Iranian agencies, expert presentations, and grey literature comprising of government publications, reports, statistical publications, news-letters, working papers, conference proceedings, technical reports, policy documents, fact sheets and questionnaire survey (Appendix B). Its framework consists of 4 steps (Fig. 2). The selected organizations for questionnaire survey are in given in Appendix C.

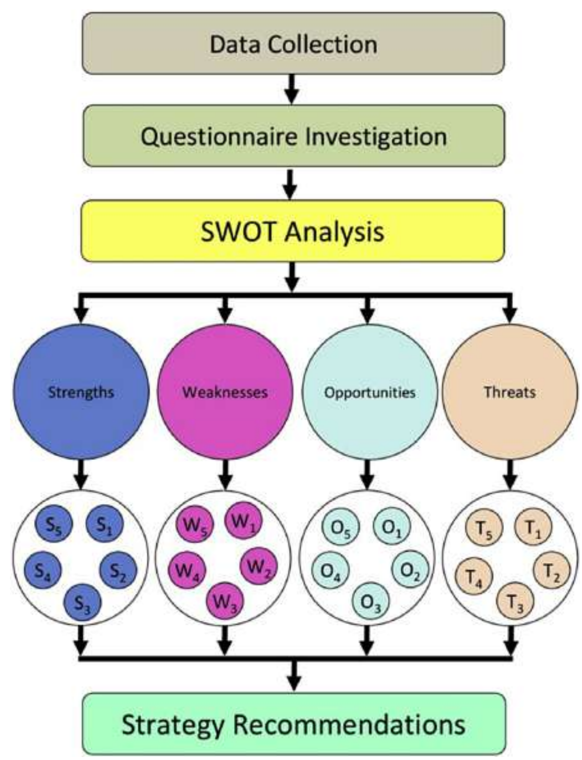

Fig. 2. The framework of SWOT method.

4.1.1. Strength

i. Owner of 18.2% (34 TCM) of world largest proven natural gas reserves.
ii. Well-developed natural gas infrastructure in the country. The infrastructure covered by 36000 km high pressure gas transmission pipelines and 264000 km gas distribution network spread in 1027 cities, 17400 villages and 25834 industrial units (Iranian Gas Industry Characteristics and Opportunities, 3 June 2015). More than 95% of cities and 47% villages population and totally 88% of country population covered by mentioned natural gas pipeline network (Iranian Gas Industry Characteristics and Opportunities, 3

June 2015). This wide network of gas pipelines gives rise to high ability and facility to feed of natural gas to the large network of CNG refueling station (Kakaee and Paykani, 2013).

iii. Government supporting and subsidizing CNG e.g. zero duties for equipment of CNG stations and NGVs. The import duty for CBU bi-fuel cars is 65% against 100% duty for gasoline cars
iv. Financial grants for companies in CNG fields; IFCO compensates all cost of CNG kit components for bi-fuel vehicles used by car companies, as well as procurement of CNG cylinders. It reimburses the main cost of vehicles prototyping and line production equipment for NGV products. Therefore the car manufacturers can sell their CNG vehicles even at the same price as gasoline vehicles. Up to US$ 400.000 loan with low to zero interest is provided for private companies constructing refueling stations. In the conversion workshop field, a subsidy of almost 90% of the retrofit costs is offered. Depending on the NGV market growth, the subsidies will be lowered gradually. The policy tools used by government to boost the CNG program in the country are listed below:
   - Compensating the entire incremental cost for factory built bi-fuel CNG vehicles and 90% cost for after-market conversion;
   - 35% concession in import duty for CNG Cars;
   - Exemption from import duty and sales tax on import of CNG machinery, equipment, kits and cylinders;
   - Providing loans up to $0.4 million with low to zero interest rate to private companies for constructing a refueling station;
   - Setting price differential gap of 80% (on the basis of energy content) between CNG and gasoline (but CNG cost is 20% above diesel);
   - Government placed a mandate on OEMs to reserve 25% of their annual production capacity for NGVs.
v. Making more necessary incentive for private investor to increase involvement of private sector in construction and operations CNG refueling stations.
vi. Favorable CNG price compared to petrol
vii. Included in the list of Top 3 NGVs countries. The CNG industry in Iran has witnessed a tremendous growth in the last decade, by virtue of friendly government policies and implementation of gasoline rationing plan. At present, it is stands 2nd and 3rd in the world with respect to number of natural gas vehicles and CNG refueling stations, respectively. Figs. 3 and 4 reflect the continuous increase in the number CNG stations and CNG vehicles respectively. Fig. 4 also depicts the trend of vehicle-to-refueling-station index (VRI) of Iranian CNG industry. VRI is an indicator to reflect the balance between supply (refueling stations) and demand (number of vehicles). For a CNG refueling station to remain profitable and for NGV drivel to fill their tank conveniently, Yeh, 2007 (Yeh, 2007) suggested that the optimal VRI is usually around 1000 vehicles to 1 refueling station. As shown, Fig. 4 shows that Iran commenced their CNG program with VRI value of less than 0.08 and maintained a level 1.7 within 5 years, which is well above the optimal VRI. In other words the number of refueling CNG stations in Iran has not grown along with the number of CNG vehicles owing to which it cross optimal VRI value. The underlying reason for this high VRI value is that government provides substantial financial incentives to NGV consumers but due to current low price of CNG, the business of CNG refueling station is not attractive for private investors. Therefore there is less participation from private sector in refueling stations and out of total 2268 refueling stations, 2233 stations are owned and operated by government. Owing to high VRI value, the drivers have to wait for hours in long queues to get their tanks filled. To avoid long lines for refueling in the country, we suggest an upper limit for VRI of 1.2–1.3.

4.1.2. Weaknesses

i. Depending technology: Although Iran now has local CNG cylinder productions plants (local and foreign brands), 65% of CNG equipment parts are still imported from overseas (valves, kits, compressors, etc). There is also a problem/lack

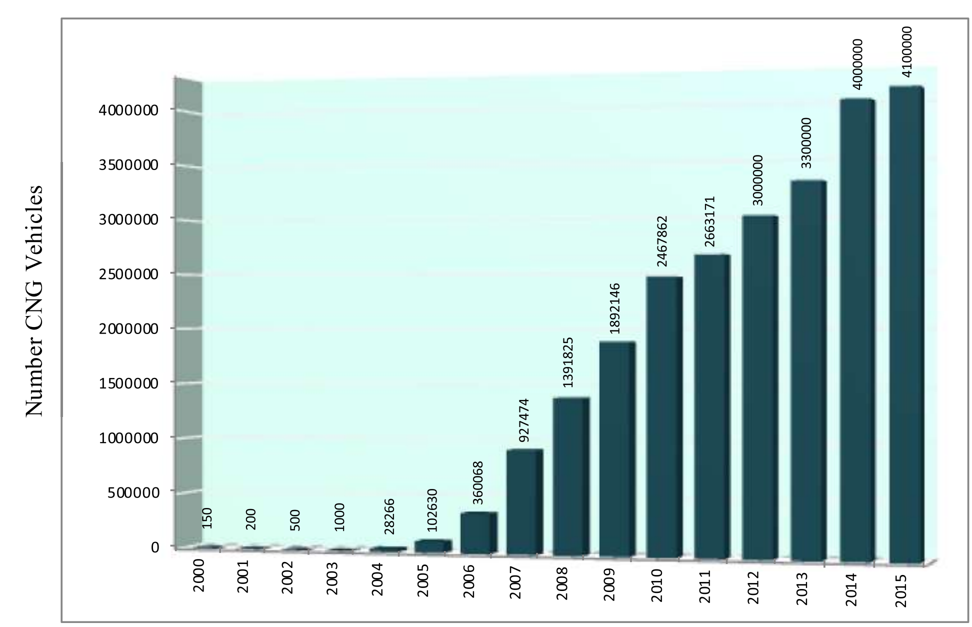

Fig. 3. CNG vehicle growth in Iran.

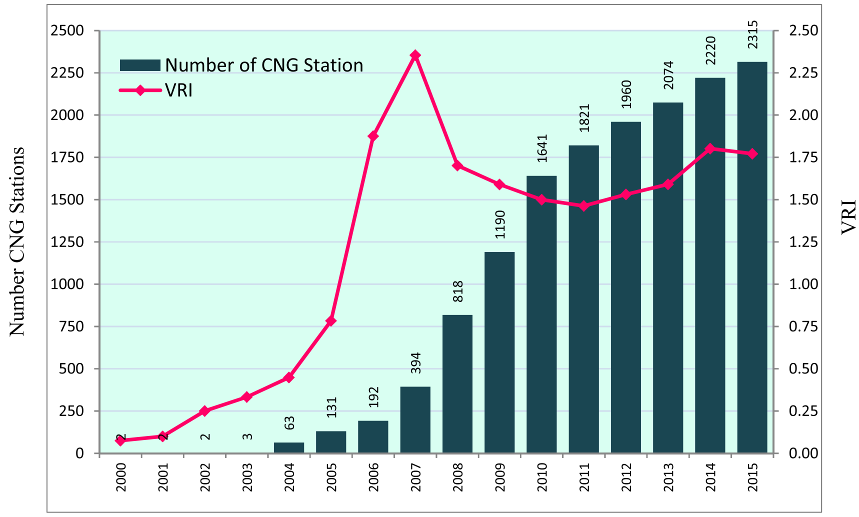

Fig. 4. Growth of CNG filling Station in Iran.

viii. Joint research collaboration of Iranian researchers with international researchers on the investigations on NGVs along resulted in the research objectives in line with the country's needs and priorities (Kakaee and Paykani, 2013).
ix. Availability of various models of NGVs from local car manufacturers.
x. Sound involvement from the private sector with its investment in bi-fuel vehicles and CNG kits.
xi. Utilization of local technology, with high motivation to improve environmental quality and to reduce import oil expenses.
xii. Making several joint venture partnership between foreign manufacturers (that are active and had long experience in CNG equipment production) and local companies which resulted in the annual production of approximately 0.5 million CNG kits and 0.4 million CNG type-I cylinders by more than 8 local producers. Also main CNG compressors equipment are now made inside the country by several local manufacturers. Currently, some local companies are manufacturing type-1 CNG cylinders with annual production capacity of these plants range upto 520,000 cylinders. Nearly 35% of the national CNG equipment requirement for vehicle conversion and refueling stations are fulfilled through local manufacturers. The country is working to get self-sufficiency, not only in meeting the CNG equipment demands of national CNG market but also to export the CNG related equipment to international market. Besides cylinders manufacturers there are currently four companies involved in the production kits and other allied parts required for converting gasoline vehicle into bi-fuel CNG vehicle. To fulfill the demand of stakeholders interested in the construction CNG refueling stations, some major parts of the CNG compressors are produced locally.

in spare parts supply. Moreover the NGVs produced by local automotive companies are based on gasoline engine technology which faces perception of inferior performance in contrast diesel or gasoline fuel technology. A number of research studies have revealed that gasoline vehicles converted to bi-fuel natural gas vehicles are endangered to a loss in total brake horse power ranging from 15% to 20% loss while operating with CNG (Khan et al., 2015a, 2016). In order to compete with modern gasoline and diesel Iran need to develop local decocted CNG engine technology.
ii. Lack of public access to credible and comprehensive government's long term policy towards development of CNG technology in the country limit the private investment in the CNG industry.
iii. Delays in standardization process as well as in CNG stations quality & safety improvement due to financial issues and lack of new directives. These bring obstacles in enlarging the quality and quantity of CNG filling network.
iv. The current low retail price of CNG makes it less attractive for some filling station owners to continue operating and for investors to continue building stations.
v. Lack of a comprehensive program regarding land allocation for new CNG filling site and other segments
vi. Lack of a single authoritative body for the CNG industry.
vii. The high price of CNG as compare to diesel fuel so discouraging the busses and fleet operator to adopt CNG as alternative fuel.

4.1.3. Opportunities

i High potential investment engaged
ii. Strategy of substitution of conventional fuels by CNG
iii. Enhancement of energy security and national self-reliance. Shifting to CNG has achieved some significant economic benefits for Iran by reducing the import of refined petroleum products. The IFCO reports that gasoline consumption in the Iranian transportation sector decreased from 146.8 MBOE in 2006 to 119.6 MBOE in 2011 (- 18.5%). Despite the decline for gasoline, total energy consumption of the LDV fleet continued to grow during the period. This means that CNG compensated for gasoline's share of total energy demand (Fig. 5). According to an estimate, CNG contribute to a saving of foreign exchange amounting to 3–4$ billion on gasoline imports and additional $3 billion in gasoline subsides the government is currently providing.

The use of CNG as a transportation fuel is associated with a number of potential benefits to the environment, particularly air emissions and noise. On a “well-to-wheels” basis, CNG is one of the cleanest burning alternative vehicular fuels available in the market today (Natural Gas Vehicles, 2014). Emissions from properly functioning CNG vehicles (NGVs) are generally considered to be lower than emissions from gasoline/diesel operating vehicles (Ristovski et al., 2004). A number of international studies demonstrate that CNG can reduce emissions in transport (Khan et al., 2015b). In CNG is identified as a leading candidate for the green transportation fuel among other alternative fuels. The main constituent of CNG is methane, the simplest alkane with only one carbon atom and consequently no carbon-to-carbon bonds. The simple chemical structure of methane makes it an inherently clean burning fuel. When used as motor fuels, this results in low particulate (PM) emissions and low toxicity of the exhaust gasses. Keeping in view the results of various studies, the rough potential reductions in the

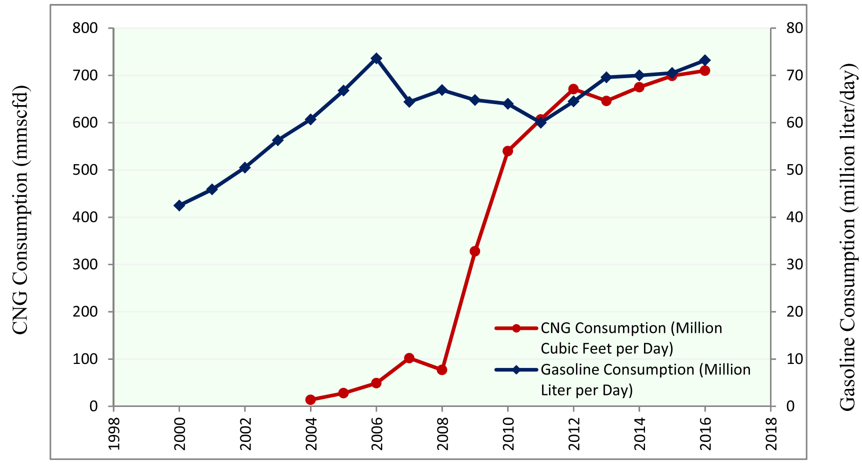

Fig. 5. Gasoline and CNG consumption by transport sector.

iv. Utilization of abundant natural gas reserves which enhancing energy security of the country. In other words, using CNG as transportation fuel will reduce the burden of imported gasoline on the economy or making the country needless to increase the high octane gasoline production capacities in local refineries via doing huge investment.
v. Strong government support with oil (petrol and diesel) rationing mandate and local OEM CNG cars and truck production.
vi. Reduction pollution in the urban areas caused by high consumption of petrol and diesel. Iran is one of most air-polluted countries in the world with two Iranian cities (Ahvaz and Khoramabad) among the top ten most polluted areas in the world, according to the latest World Health Organization report 2014 (Ambient (outdoor) air pollution in cities database, 2014). According to WHO report Iran is ranked 10th among the most polluted countries included among the top 10 GHG emitting countries in the world (Fig. 6) (IEA and CO2 Emissions from Fuel Combustion, 2016). The ambient conditioned conditions have worsened since 2010. The major reasons for the worsened situation are fueling of power plants with oil having high sulfur-content, significant number of heavy and light scrapped transportation fleet, lack of efficient public transportation systems and low quality domestically produced fuel i.e. gasoline and diesel. Transportation sector is the main consumer of gasoline and diesel in Iran. According to data of Iranian Ministry of Energy (MOE) transport sector was responsible for emission of 58% CO2, 48% NOx, 76% PM and 79% SO2 in 2012 (Eskafi, 2016). Similarly the Air Quality Control Company (AQCC) reports that the main pollutant source in Tehran and big cities of Iran is particulate matter (PM). According to the AQI (Air Quality Index, a yardstick to measure air quality) records, in the 12 months from 21 March 2014 the people of Tehran experienced 16 clean days, 233 healthy days, 113 unhealthy days for sensitive groups and 3 unhealthy days for everyone (Pouran, 2016). In 2012 an advisor to Iran's Health Minister announced that, in a period of one year from March 2011, 4460 people had died from air pollution in Tehran (Davidson, 2013). Gasoil (red diesel) consumption is the main cause of NOx, SOx and SPM emissions in Iran. For example in Tehran, the largest and capital city of Iran, cars account for 70%–80% of the normal air pollution due to the large number of automobiles using gasoline with sulfur content 2–3 times greater than legally permissible levels (Abrishamchi, 2013).

exhaust emission of CNG vs Diesel and gasoline fuel is illustrated in Fig. 7 (Khan et al., 2015b). As one simple calculation the 4.1 million NGVs caused at least 6.3 million tones reduction in greenhouse gas CO_2 annually in Iran. Although on the theoretical grounds combustion of CNG produce less amount of CO_2 emission as compared

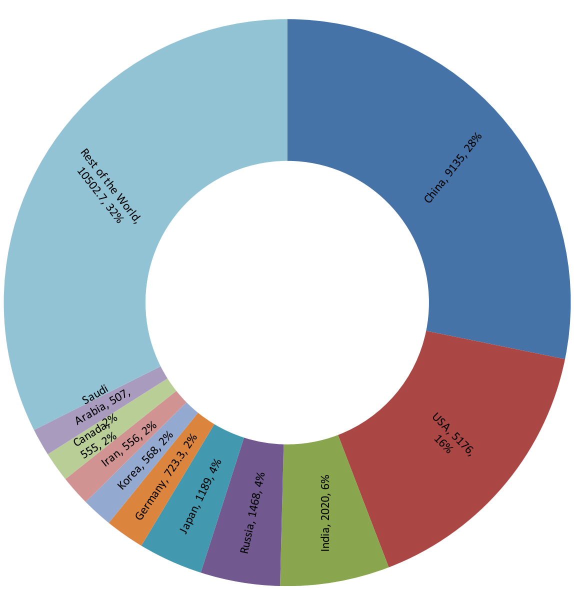

Fig. 6. Shares (in $MtCO_2$ equ) and percentages of top ten countries in global CO2 emission in 2014.

to conventional fuel (Khan et al., 2015a) but in contrast to petroleum fuel there is high chances of methane leakage during well-to-wheel cycle of natural gas. The global warming potential of these three gases were calculated based on the latest 5th assessment report released by Intergovernmental Panel on Climate Change (IPCC, 2013) (Stocker, 2014). According latest 5th assessment report released by Intergovernmental Panel on Climate Change (IPCC, 2013) (Stocker, 2014) the global warming potential (GWP) value of methane is 28 times higher than CO_2 over the 100 year time horizon. Hence while considering environmental protection potential of natural gas well-to-wheel methane emission should be taken in to account.

4.1.4. Threats

i. Public's safety awareness is still low. Most of the NGVs incidents happened in Iran during repairing or applying changes in vehicle CNG system by un-qualified people. So it is important to increase the public awareness via media programs or other effective ways to avoid similar incidents in future.
ii. Decrease in government's support and incentive in recent years.
iii. Despite the third party inspections certificates based on relevant international and local standards, some serious non-compliances were observed in the recent years. These non-compliance specially in case of CNG cylinders may cause severe accidents which will damage the public interest of CNG in transport.

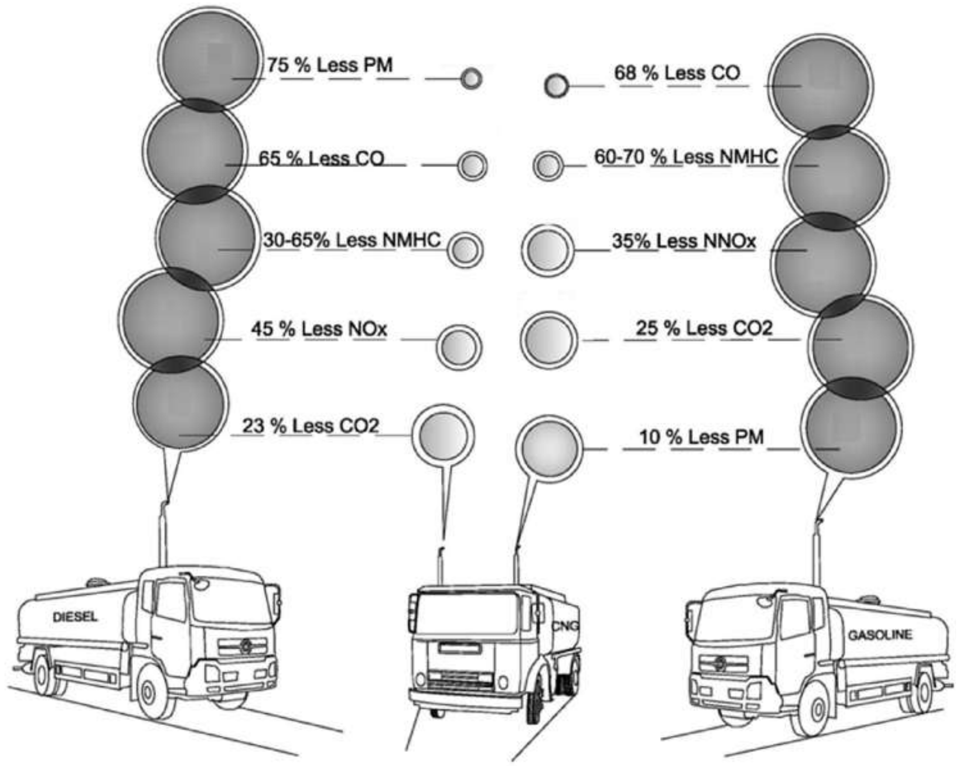

Fig. 7. Emission benefits of CNG vs diesel and gasoline (Khan et al., 2015b).

vii. More CNG stations are still needed (reported around 1500 more units required, especially in big cities) which provide employment opportunity.
viii. Due to the rapid growth of global CNG industry, the country can export the local made CNG kits and cylinders to foreign countries.
ix. It is expected that in near future subsidized gasoline policy will be ceased by government, so motivation for using CNG will be increased.
x. The government is planning for allocation of different fuel share in transport sector. According to this policy the share of CNG should be raised from current 23%–25% while gasoline and diesel share would be fixed at 70%. The remaining 5% would be allocated for other type alternative fuel vehicles e.g. electrical, bio-fuel etc.

iv. No serious enforcement of periodic inspection of CNG cylinder installed in vehicles as storage in refueling stations. It is strongly required that concerned government or public authorized organizations follow seriously the case and pay attention to periodic inspection of CNG cylinders.
v. High weight of cylinder (cylinder type −1 is used in Iran).
vi. The network of natural gas pipelines are far from enough. A lot of regions cannot share the network. Much more funding needs to be invested to set up both the network and gas refueling stations at local level, which forms a big challenge for further development of NGVs in Iran.
vii. High consumption of cars because of poor vehicles technology.
viii. International sanctions which restrict the Iran in area of international trade, banking and technology transfer.
ix. Low price of CNG has led to closures of 150–160 CNG stations.
x. Due to current low price of CNG and high operational and maintenance cost associated with the operation of CNG station, the business of CNG refueling station is not attractive for private investors.
xi. Out of total 2268 refueling stations, 2233 stations are owned and operated by government. Therefore the negligence or careless attitude has observed towards the regular preventive maintenance of equipment which causes the stations to operate under capacity and frequent brake-down during operation. Owing to this, motorists have to wait for hours in long queues to get their tanks filled, clogging traffic and car drivers waiting for CNG filling cannot serve passengers.
xii. More than 3 million NGVs still need to be officially tested and inspected within 2016. However, it is still unclear which inspection body and what testing device will be used.

Based on the above discussion, the key SWOT factor of Iranian CNG industry are summarized in Fig. 8.

5. Strategy recommendations

According to the SWOT analysis of CNG industry of Iran, a collection of strategies were obtained by matching the internal factors i.e. Strengths and Weaknesses with external factors i.e. opportunities and threats. Based on SWOT results nine strategies were proposed as shown in Fig. 9.

5.1. Strength-opportunities - SO strategies

SO1: Developing large scale CNG technologies including CNG cylinder and engines. Initially the growth in the CNG industry can be achieved by current bi-fuel technology and type-1 cylinder (fully metallic), but to fully exploiting large indigenous sources of natural gas through CNG program, government needs to develop dedicated CNG engine and type-4 cylinder (composite) technology in parallel to bi-fuel engine and type-1 cylinder technology. This move will stimulate the consumer choice for opting CNG vehicles. For acquiring the dedicated CNG technology the government should offer attractive concessions and incentives to attract foreign companies involved in manufacturing dedicated CNG engines (e.g. Volkswagen (Germany), Man (Germany), Opel (Germany), Volvo

Strengths (S)	Opportunities (O)
S_1: Owner of world largest proven natural gas reserves. S_2: Well-developed natural gas infrastructure and availability of various models of NGVs from local auto maker. S_3: Strong government support. S_4: Favorable CNG price compared to petrol. S_5: Great development potential.	O_1: Enhancement of energy security and national self-reliance. O_2: Economic opportunity value of the abundant indigenous reserves of natural gas O_3: Reduction of urban air pollution and health effects. O_4: Potential for job creation and export of CNG technology. O_5: Substitution of imported gasoline and saving of foreign exchange.
Weaknesses (W)	**Threats (T)**
W_1: Lack of CNG usage in heavy duty public road transport e.g. buses W_2: The high price of CNG as compare to diesel. W_3: Lack of public access to the reliable and comprehensive government's CNG policy. W_4: Heterogeneous geographical distribution of CNG refueling stations. W_5: Lack of dedicated CNG engine technology.	T_1: Lack of private investment in CNG refueling station. T_2: Decrease in government's support and incentive in recent years. T_3: U.N. sanctions on Iranian banks, trade and technology transfer. T_4: Lack of Public's safety awareness and enforcement of safety and emissions regulations. T_5: Strong lobby from diesel fueled fleet operators who prefer to maintain a liquid fuel "status quo"

Fig. 8. Key SWOT factors for CNG Industry of Iran.

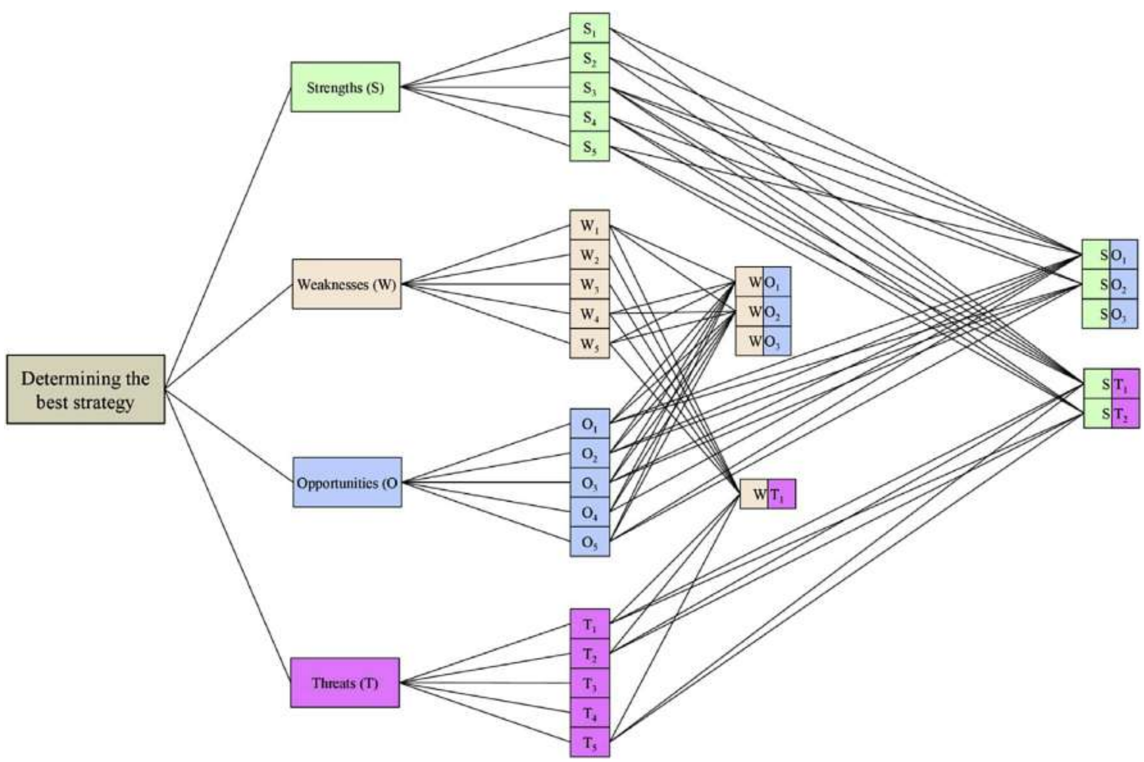

Fig. 9. SWOT matrix for CNG economy of Iran.

(Sweden), Iveco (Italy), Fiat (Italy), Scania (Sweden) etc. to set their plants at Iran.

SO2: Applying vehicle emission standards especially to diesel fueled vehicles. Although currently the country is practicing Euro III (Worldwide emissions standards, 2015–2016) vehicle emission standards but due to the lack of strict enforcement of these regulations, the results are not fruitful. For instances one thirds of vehicles operated in the metropolitan cities of Iran are over 20 years old (Air Quality Policies) with obsoleted fuel injection technology i.e. carburetor which are not meeting the Euro-III emission standards. Therefore there should be a measurement and penalty program for those who do not comply with rulings. For instance creating traffic restriction for "un-environmentally friendly" vehicles, such as: access limitations, banning polluting vehicles from entering certain areas in certain periods (days/hours). This can also couple with vehicle labeling system to distinguish "clean" vehicles from the "dirty" ones by offering different license plate or an exclusive feature/sticker for CNG vehicles. The implementation of this policy will further boost the growth of CNG program especially in heavy duty vehicles in the country.

SO3: Desulfurization of gasoline and diesel - Desulfurization from gasoline and diesel has been a critical issue in Iranian refineries. The domestic oil consumption of Iran is mainly consist of diesel and gasolne. The quality of locally produced diesel and gasoline is very low causing signifocant enviropmental problems (Cordesman et al., 2014). For example the average sulfur content of the gasoline and diesel produced in Iran is range from 180 to 1000 ppm and 7000–8000 ppm, respectively. The Iranian Ministry of Petroleum has a plan to enhance the quality of local fuel to the level of Euro-IV standard which was implemented in January 2005 by limiting the sulfur content of diesel and gasoline up to 50 ppm. This means that the sulfur content of diesel and gasoline produced in Iran is significantly high than Euro IV standard. To make it applicable as fuel for IC engine, CNG needs very less processing from the production well to wheel. While on the other side gasoline and diesel requires complex refinery processing to separate it from the crude oil. Therefore keeping in view the low processing cost of CNG, the desulfurization of locally produced diesel and gasoline will encourage the stakeholder to invest in CNG infrastructure (Khan et al., 2015a).

5.2. Weakness-opportunities - WO strategies

WO1: To promote the usage of CNG in heavy duty transport, it should be priced 50% cheaper than diesel as in the case of gasoline. Currently the price of CNG is 20% higher than diesel fuel which is one of the major hurdles for insignificant use of CNG in heavy transport. Being a developing most Iranian consumers can be described as being economically rational, in that they respond to price and given identical options will pick the cheaper of the two, and environmental pragmatists, who are willing to switch to an environmentally friendlier fuel so long as it does not force them to alter their behavior. However the price differential between CNG and diesel should be increased gradually over time to avoid market shocks and 'dislocation'. Sudden increase in diesel fuel prices can create confrontation among transporters.

WO2: Encouraging private investment in CNG refueling infrastructure. Some of the investment tool that can be used to support the stakeholder involved in the CNG infrastructure are soft loans, leasing arrangements and lessening of security requirement for the loans. There are several example of successful implementation of these tools in the development of renewable energy project and energy efficiency technologies. As mentioned due to current low price of CNG, the business of CNG refueling station is not attractive for private investors. Therefore to attract significant private investment in CNG refueling stations, the government should increase the profit margin of stations owners/operators. Furthermore to minimize the initial investment required for construction of dedicated CNG refueling stations, the government can also encourage local governments and communities to facilitate the stakeholders with designated land for construction of CNG refueling stations. This will ease the initial high investment required for the construction of CNG refueling station and would give a message to communities that CNG that government is interested in the development of CNG. Land along highways or at rest stops, or land co-located with other fueling sources, would be ideal.

WO3: Foreign capital importation—developing free market mechanism and attracting new CNG technologies. To enhance the local CNG technology, the government needs to encourage and facilitate foreign investment in the construction of various CNG related equipment.

5.3. Strength-threats - ST strategies

ST1: Establishing CNG development prior strategy in Iran—determining the strategic priority of CNG among all the transportation energy sources for substituting liquid fuels by gaseous fuels. Although the Iranian government has supported CNG for transportation as a national strategy but currently there is lack of comprehensive national plan with relevant detailed guidelines for the sustainable development of CNG industry. One of the major causes for the lack of sustainable CNG policy is the complex and very slow-moving nature of Iranian bureaucracy, with overlapping authorities. Even on issues with clear political support from the very highest levels of Iran's government, it could take years to secure action by relevant Iranian agencies. Therefore there is a need to expedite the prior strategies for CNG as alterative in the country.

ST2: Government subsidies and incentives allowance - One of the major barriers for growth of Iranian CNG program especially in commercial transport is the low prices of diesel fuel. The Iranian government pays huge subsidies to energy in the country. By 2009, Iran was the largest provider of fuel subsidies in the world (Chaharsooghi and Abbaszadeh, 2013). Diesel fuel retail prices in Iran have been much lower than the real price because of subsidies. Paying subsidies for energy is an old policy in Iran, since increasing oil revenues and removing subsidies has always been a real challenge for decision makers. Policymakers in Iran have preferred to solve economic problems with oil revenues rather than tax. Approaching this policy has led to high energy intensity and weak energy efficiency in all sectors such as transportation Removing subsidies is more complicated in Iran because of the close relation of the inflation rate and fuel prices. Increasing prices by removing subsidies in the short-term has caused serious social and political issues. Hence, the government has to use more conservative fuel policies in the long-term. Moreover there is no market mechanisms strategy such as carbon tax which can help the government to enhance fuel conservation and carbon emissions reduction. The problem is further aggravated poor quality of engines produced by local auto makers. Iran's vehicle industry benefits from a monopole and isolated local market. In a highly subsidized fuel price atmosphere, either consumers or producers do not prioritize fuel conservation. There are over 2.5 million old vehicles in Iran which are suitable for conversion to CNG. Another important factor is that most of the locally produced vehicles in Iran are of poor quality. For example, as per statement of Tehran Traffic & Transportation Organization, there are 1 million vehicles (25% of total registered vehicles) and 1.5 million motor-bike in produced with low quality/safety standards (Iran's Fragile Energy Security, 2014).

Absence of reliable strategic partners and limited access to new technologies for energy efficiency, along with the high potential the local LDV demand market, have resulted on Iranian local automakers focusing on production quantity rather than quality improvement. To meet the target of 30% of total registered vehicles as NGV, the government is required to develop mechanisms to reduce the subsidy on diesel fuel and force the local manufacturers for enhancing the emission standards of their auto engines. As CNG because of its inherent clean nature of combustion (Yamato et al., 2001) has now been recognized worldwide as environment-friendly fuel (Chandler et al., 2006). Therefore this move will encourage the local auto maker to produce CNG vehicles with regard to meet the increasingly stringent emission legislation. Moreover the reduction in the subsidy to diesel fuel and offering special incentives for fleet operators will break the strong lobby of diesel fueled fleet operators who prefer to maintain a liquid fuel "status quo".

5.4. Weakness-threats - WT strategies

WT1: Establishing a comprehensive fuel pricing mechanism: The government need to develop a long term fuel price mechanism with comprehensive price advantage of CNG over liquid fuel. People in Iran do not trust the government unless informed transparently about the benefits of costly policies (such as the Subsidy Reform Plan, carbon tax, etc.) (Eskafi, 2016). Therefore this move will send a signal to the communities that CNG deployment is a long term priority.

It is believed that all these strategies would be helpful Iran for expanding the Iranian CNG industry, but their effects for promoting the CNG market in Iran are unclear. Therefore, it is hard for decision makers/stakeholders to make comprehensive proper roadmap for

CNG industry, and thus to make appropriate budget planning and resources allocation without raking the priorities of these strategies. Thus, the prioritization of these strategies is meaningful. The method for prioritizing and ranking the importance of these strategies is illustrated in Section 3.

6. Strategy prioritization

The strategies prioritization is based on the effects of four elements of SOWT matrix i.e. utilizing strengths, alleviating the elements in weaknesses, exploiting the opportunities, and avoiding the possible threats imposing by the external environment. As a result, the strategies prioritization takes the case of multiple criteria and thus it is a typical multicriteria decision-making (MCDM) problem which is usually addressed with the pertinent MCDM methodology.

6.1. Multi-criteria decision making (MCDM)

Multi-criteria decision making (MCDM) is a tool used to make management decisions under multiple objectives conditions. Ideally, there are many options to choose from when solving a problem of multiple objectives. MCDM look for optimal solution from a range of options to meet most of the criteria, if not all. This tool helps to enhance the quality of decision by making it more comprehensive, rational and effective. The method can also facilitate the decision makers to negotiate, quantify and communicate the priorities. These methods have been successfully applied in the energy planning and policy processes and are recognized most appropriate technique to resolve the issues related to energy (Liu et al., 2017a; Yazdani et al., 2017; Ghorabaee et al., 2016; Garcia et al., 2016).

Various types of MCDM techniques can be found in literature, for instant Analytic Hierarchy process (AHP)) (Mathivathanan et al., 2017; Tramarico et al., 2017; Luthra et al., 2017; He et al., 2017), Data envelopment analysis (DEA) (Liu et al., 2017b; Chen and Jia, 2017; Gutiérrez et al., 2017; Wang and He, 2017), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Wang et al., 2017), goal programming (GP) (Li et al., 2017), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Arıkan et al., 2017), VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) (Xu et al., 2017; Zhao et al., 2017; Li and Zhao, 2016), Elimination and Choice Translating Reality (ELECTRE) (Heravi et al., 2017; Sánchez-Lozano et al., 2016; Wen et al., 2016), Decision making trial and evaluation laboratory technique (DEMATEL) (Liang et al., 2016; Quader et al., 2016; Xia et al., 2015), and their modified and hybrid methods, e.g. Fuzzy TOPSIS (Onu et al., 2017), and AHP/TOPSIS integrated approach (Chauhan and Singh, 2016; Gogate et al., 2017; Mohammadfam et al., 2016).

Among these methods, the goal programming is identified more appropriate to prioritize the strategies to promote CNG industry in Iran. . The Goal programming (GP) are being practiced at large scale in operations research. The classical GP model and its variants have been applied to address various types of large-scale MCDM problems. The GP is derived from Linear Programing (LP) and generally used to solve problems based on multi-objective (Rifai, 1996). The basic theory of LP and GP is the same. The philosophy of GP is to consider additional supporting variables known as deviations, which act as ‘facilitators’ in the decision making process to configure the model. They represent over-achievement of the goal value by positive deviation and under-achievement of the goal value by negative deviation (d^{-}) In other words the negative and positive deviations represent the distance between aspiration levels of goals values and the results achieved. The undesirable deviations between the goal values are then minimized with the help of objective function. The role of objective function is to optimize the multiple contradictory goals accurately defined by the stakeholders/decision makers by minimizing the undesirable deviations between the target values. Thus, the goals having primary importance are fulfilled first, and subsequently the goals with secondary importance are taken into account and so on.

The solution obtained through goal programming represents the best compromise that can be afforded by the decision-maker. The GP model includes two types of constraints i.e. system constraints and target constraints. System's constraints are based on theory of linear programing while goal or target constrains are supporting constraints that fix the best possible solution to a set of desired objectives.

6.1.1. Fuzzy sets and numbers

In reality, it is very difficult to draw accurate data related to measurement indicators. Therefore the decision makers favor the expression with natural language instead of using crisp numbers when evaluating and assessing decision-making problems. The theory of Fuzzy set can deal effectively with nebulous situations. It resemble of human thoughts and perceptions to produce the realistic alternate to decision making problems by using approximate information and vagueness. The concept fuzzy theory was first introduced by Zadeh in 1965 (Zadeh, 1965). This theory consist of fuzzy set, the membership function and fuzzy numbers to efficiently transform ambiguous data into useful data. It includes the data groups with boundaries which are not well defined. The advantage of expressing the relative importance of the alternatives and the criteria with fuzzy numbers rather than using crisp number, since in real world most of decision taken decision makers are in conditions where the relevant data and the sequences of possible actions are not accurately identified. Triangular type of fuzzy numbers (TFN) are commonly used to catch the uncertainty of the parameters relating to the selection of alternatives. Triangular fuzzy numbers are represented with boundaries instead of using crisp numbers for reflecting the fuzziness as decision makers choose the alternatives. This study uses TFN to prioritize CNG industry in Iran the sector of transportation energy technology roadmap with fuzziness. TFN is labeled as $\tilde{x}_{ij} = (x_{ij}^{L}, x_{ij}^{M}, x_{ij}^{U})$, x_{ij}^{M} is the median value of fuzzy number $\tilde{x}_{ij} \cdot x_{ij}^{L}$ and x_{ij}^{R} is the left and right side of fuzzy number $\tilde{x}_{ij}$ respectively.

6.1.2. Proposed GP model

The Suggested MCDM technique (Fig. 10) comprising of the

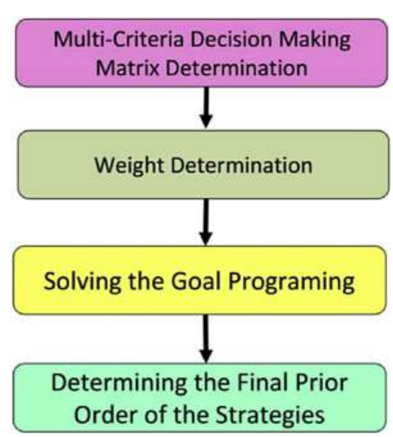

Fig. 10. The framework of MCDM methodology.

following four steps, determining MCDM matrix, assigning weightage, solving GP programing, and determining the final ranking of alternatives.

Step 1: MCDM matrix determination. The MCDM matrix comprises of the alternatives, the criteria, and the targets/goals set by the stakeholders/decision-makers with respect to the criteria, as shown in Eq. (1).

Usually all multi-criteria decision making methods follow the philosophy of on identifying a number of alternative solutions (A_1, A_2, A_3,…, A_n); selecting evaluation criteria (C_1, C_2, C_3,…, C_n) and determining the outcomes for the evaluation of each alternative, A_i, against the relative critera. Common to all MCDM analysis is the resulting matrix [aij], which is called a Decision Matrix (as shown in Eq. (1)).

X = (1)

		Criteria					
		C_1	C_2	⋯	C_j	⋯	C_n
Alternative	A_1	a_{11}	a_{12}	⋯	a_{1j}	⋯	a_{1n}
	A_2	a_{21}	a_{22}	⋯	a_{2j}	⋯	a_{2n}
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	A_i	a_{i1}	a_{i2}	⋯	a_{ij}	⋯	a_{in}
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	A_m	a_{m1}	a_{m2}	⋯	a_{mj}	⋯	a_{mn}
Target	T	g_1	g_2	⋯	g_j	⋯	g_n

where A_i represents the ith alternative, C_j represents the jth criterion, a_{ij} denotes the value of jth criterion associated with ith alternative, T is the goals' vector and g_j denotes the jth goal of stakeholders/decision-makers. At this stage, experts/stakeholders were asked to evaluate the performance of alternatives for each criterion by using the linguistic variables (Table 2). The linguistic variables were then converted into triangular fuzzy numbers (TFN) as per Table 3. Subsequently, the TFNs $(\tilde{x}_{ij} = (x_{ij}^L, x_{ij}^M, x_{ij}^U))$ for determining the performance of the ith alternative with respect to jth criterion, were converted into crisp numbers by center of gravity- CoG method (Eq. (2)) (Skalna et al., 2015). For example, if an alternative with respect to a criterion is considered as bad (BD) and the corresponding TFN was determined to be (1, 3, 5), the TFN could be converted into a crisp number of 3 (1+2x3+5/4 = 3). Similarly, the target/goal represents the expectation of the decision-makers/stakeholders of each criterion can also be determined.

$$x_{ij} = \frac{\tilde{x}_{ij}^L + 2\tilde{x}_{ij}^M + \tilde{x}_{ij}^U}{4} \tag{2}$$

where x_{ij} and $\tilde{x}_{ij}$ are the crisp numbers and the triangular fuzzy numbers describing the performance of the ith alternative regarding the jth criterion, respectively. $\tilde{x}_{ij}^L, 2\tilde{x}_{ij}^M$and $\tilde{x}_{ij}^U$ represent the three elements in the fuzzy number $\tilde{x}_{ij}$.

Table 2
The linguistic variables for assessing the performance of alternatives with respect to each criterion.

Linguistic variables	Abbreviation	Fuzzy number
Worst	WT	(0,1,1)
Worse	WE	(1,1,3)
Bad	BD	(1,3,5)
Medium	MM	(3,5,7)
Good	GD	(5,7,9)
Better	BR	(7,9,9)
Best	BT	(9,10,10)

Table 3
The linguistic variables for determining the importance of the criteria.

Linguistic variables	Abbreviation	Fuzzy number
Significantly low	SL	(0, 0.1, 0.2)
Very very low	VVL	(0.1, 0.2, 0.3)
Very low	VL	(0.2, 0.3, 0.4)
Low	L	(0.3, 0.4, 0.5)
Medium	M	(0.4, 0.5, 0.6)
High	H	(0.5, 0.6, 0.7)
Very high	VH	(0.6, 0.7, 0.8)
Very very high	VVH	(0.7, 0.8, 0.9)
Significantly high	SH	(0.8, 0.9, 1.0)

Step 2: Weights determination. In this paper, nine linguistic terms, i.e. significantly high, very very high, very high, high, medium, low, very low, very very low and significantly low are applied describing the significance of the criteria. These linguistic terms can be converted into TFNs according to the respective membership functions (Table 3). Similarly, the TFNs $\tilde{\omega}_J = (\tilde{\omega}_j^L, \tilde{\omega}_j^M, \tilde{\omega}_j^U)$ for representing the weight of the jth criterion, can be converted into crisp numbers by the mean area method (Skalna et al., 2015) (Eq. (3)). For example, if the importance of a criterion is regarded as very low (SL), so the triangular fuzzy number is (0.2, 0.3, 0.4), and the fuzzy number could be transformed in to a crisp number of 0.3 (0.2+2 × 0.3 + 0.4/4 = 0.3). Subsequently by using Eq. (4) weights could be normalized.

$$\omega_j' = \frac{\tilde{\omega}_j^L + 2\tilde{\omega}_j^M + \tilde{\omega}_j^U}{4} \tag{3}$$

where ω_j' represents the weight of the ith criterion described by using a crisp number.

$$\frac{\omega_j = \omega_j^{'}}{\sum_{j=1}^{n} \omega_j^{'}} \tag{4}$$

where ω_j represents the normalized weight of the ith criterion described by a crisp number.

Step 3: Solving the goal programming.

In this study, Weighted GP integrated with fuzzy theory has been developed for prioritizing the strategies for promoting CNG industry of Iran.

Objective

$$\text{Minimise} \sum_{i=1}^{n} \omega_j^+ d_i^+ + \omega_j^- d_i^- \tag{5}$$

Goals and constraints:

$$\sum_{i=1}^{n} a_{ij} x_i + d_i^- - d_i^+ = g_j \quad j = 1, 2, \ldots n \tag{6}$$

where $\omega_j^+ \& \omega_j^-$ are the weights associated with the positive and negative deviations of each goal, a_{ij} is a coefficient which states the contribution of the jth variable to the achievement of the ith criterion, x_i represent the decision variable, d_i^+ & d_i^- + represent the over and under-achievement of the jth goal, respectively.

0–1 Constraint

$$x_i = \begin{cases} 1, & \text{if jth alternative has been selected} \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

Selection constraint

$$\sum_{i=1}^{m} x_i = 1 \quad (8)$$

Step 4: Determining the final ranking of alternatives. At this stage, the 2nd best alternative is first determined by the best alternative of the previous step and repeating the Step 3, until the 3rd, the 4th, …. and the mth best alternative can be determined. Consequently the alternative can be ranked in their order of priority.

7. Results and discussion

As shown in Fig. 11, the suggested MCDM technique is applied for prioritizing the strategies for promoting the CNG as transportation fuel in Iran, which is obtained by using the SWOT method. The processes are listed below.

Step 1 - MCDM matrix determination. The MCDM matrix is determined in coordination with the industrial experts using the linguistic variables (Table 2) to measure the impact of proposed strategies by considering the sub-components in strengths, relieving the sub-components associated with weaknesses, exploiting the sub-components associated with opportunities and dodging the sub-components associated with threats on the basis of present condition of Iranian CNG industry. It is important to note, that the impact of a strategy on a sub-component can be indicated by zero if it is impractical to that sub-component. Table 4 represent the final outcomes. Consequently, using Eq. (2), the linguistic variables are converted into crisp numbers and the results are shown in Table 5.

Step 2—To determine the weights. As mentioned Fuzzy technique is applied to define the weights of sub-components with respect to four factors of SWOT i.e. strengths, weaknesses, opportunities and threats. The objective of this step is to assess the

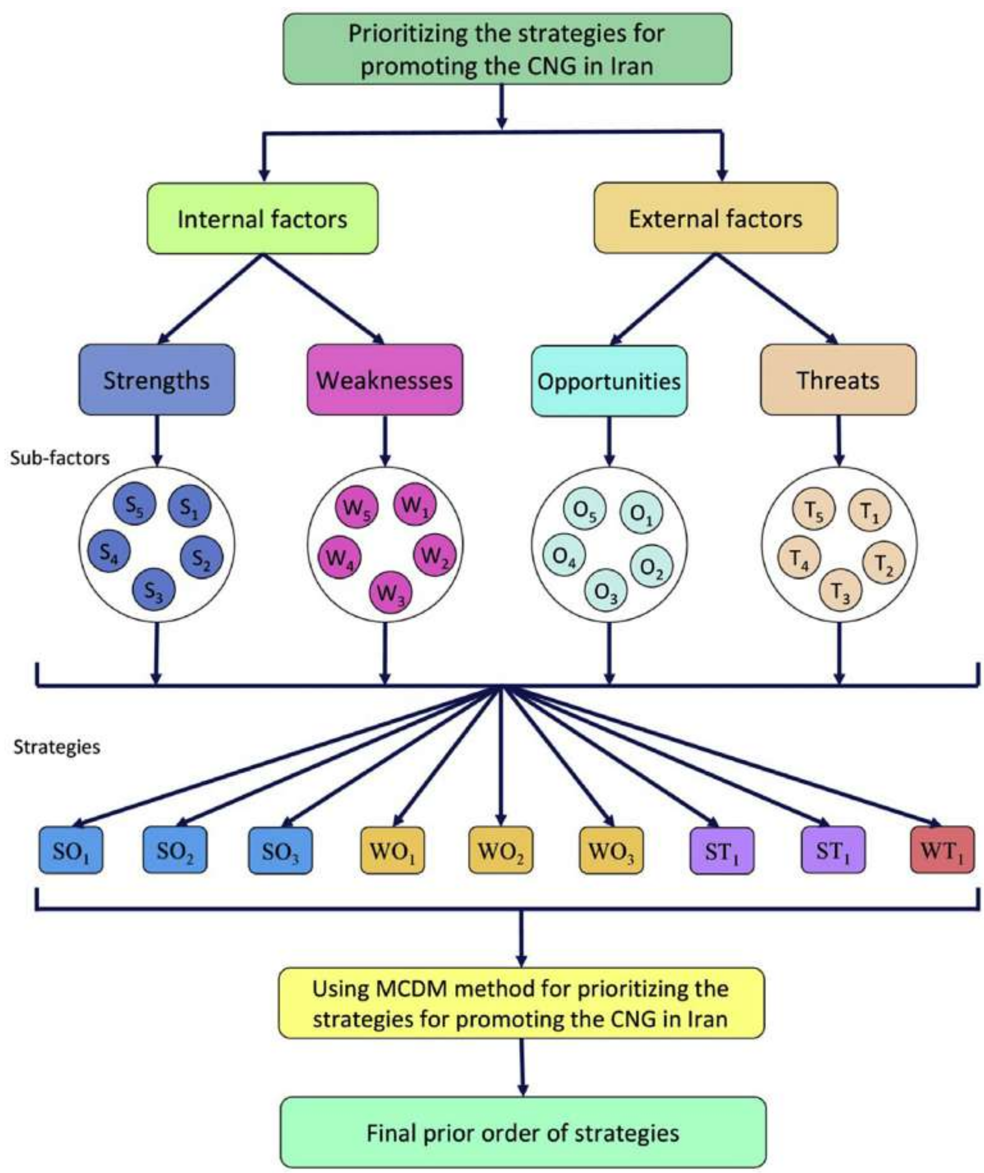

Fig. 11. Framework for prioritizing the strategies.

Table 4
Multi-criteria decision-making matrix using linguistic variables.

	S_1	S_2	S_3	S_4	S_5	W_1	W_2	W_3	W_4	W_5	O_1	O_2	O_3	O_4	O_5	T_1	T_2	T_3	T_4	T_5
SO_1	BR	GD	GD	0	BR	BD	WE	BD	WT	MM	BT	BR	BR	GD	BT	BD	MM	BD	MM	MM
SO_2	0	MM	MM	GD	MM	BT	GD	MM	MM	BD	0	0	BT	0	MM	BD	0	0	MM	BR
SO_3	BR	BR	GD	BR	BR	BR	BD	MM	BD	BD	MM	GD	BT	MM	WT	MM	BD	BD	MM	BR
WO_1	BR	BD	GD	BD	BR	BT	WE	0	BD	WE	BR	GD	BR	GD	0	BD	MM	BD	MM	BT
WO_2	BR	BT	BR	WE	BR	BD	WT	BD	BT	MM	GD	BR	GD	BR	BR	BT	GD	MM	0	BD
WO_3	GD	GD	BR	BD	BR	BD	WT	BD	BR	BR	GD	BD	BR	BR	BR	BT	BR	WE	0	BD
ST_1	BT	BT	BR	GD	BT	MM	BD	GD	GD	BD	BT	BR	BT	GD	BT	BD	BR	0	GD	BR
ST_2	BR	BR	GD	0	GD	BT	BT	0	WT	WE	BR	GD	BR	MM	BR	BD	BD	0	BD	BT
WT_1	GD	GD	BR	BR	BR	GD	BD	BT	0	GD	GD	GD	BR	0	GD	GD	MM	0	0	BD
T	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT	BT

significance of components affecting the growth of CNG industry in Iran. To assess the significance of the sub-factors, the linguistic variables mentioned at Table 3 are converted into crisp numbers by using Eq. (3). Next, the weightage of the sub-components are normalized and their outcomes are shown in Fig. 12.

Step 3—To solve the goal programming. At this stage, the suggested nine strategies (SO_1, SO_2, SO_3, WO_1, WO_2, WO_3, ST_1, ST_2, WT_1) are categorized as ith (i = 1, 2, … …., 9) strategy, respectively. A linear programming of mixed-integer type is then used for picking the most important and effective strategy. The program is formulated as follow:

Objective function

$$\text{Minimise} \sum_{i=1}^{n} \omega_j^+ d_i^+ + \omega_j^- d_i^- \quad (9)$$

Constraints:

$$AX - D^+ + D^- = T \quad (10)$$

$$\sum_{i=1}^{9} x_i = 1 \quad (11)$$

$$x_i \in \{0,1\}, \quad i = 1,2,....,9 \quad (12)$$

$$W = [\omega_1, \omega_2, ..., \omega_n] \quad (13)$$

$$= [0.056, 0.063, 0.056, 0.071, 0.056, 0.071, 0.071, 0.032, 0.048, 0.032, 0.071, 0.063, 0.048, 0.024, 0.071, 0.056, 0.008, 0.024, 0.024, 0.056] \quad (14)$$

$$A = \begin{vmatrix} 8.5 & 7 & 7 & 0 & 8.5 & 3 & 1.5 & 3 & 0.75 & 5 & 9.75 & 8.5 & 8.5 & 7 & 9.75 & 3 & 5 & 3 & 3 & 5 & 5 \\ 0 & 5 & 5 & 7 & 5 & 9.75 & 7 & 5 & 5 & 3 & 0 & 0 & 9.75 & 0 & 5 & 3 & 0 & 0 & 5 & 8.5 \\ 8.5 & 8.5 & 7 & 8.5 & 8.5 & 8.5 & 3 & 5 & 3 & 3 & 5 & 7 & 9.75 & 5 & 0.75 & 5 & 3 & 3 & 5 & 8.5 \\ 8.5 & 3 & 7 & 3 & 8.5 & 9.75 & 1.5 & 0 & 3 & 1.5 & 8.5 & 7 & 8.5 & 7 & 0 & 3 & 5 & 3 & 5 & 9.75 \\ 8.5 & 9.75 & 8.5 & 1.5 & 8.5 & 3 & 0.75 & 3 & 9.75 & 5 & 7 & 8.5 & 7 & 8.5 & 8.5 & 9.75 & 7 & 5 & 0 & 3 \\ 7 & 7 & 8.5 & 3 & 8.5 & 3 & 0.75 & 3 & 8.5 & 8.5 & 7 & 3 & 8.5 & 8.5 & 8.5 & 9.75 & 8.5 & 1.5 & 0 & 3 \\ 9.75 & 9.75 & 8.5 & 7 & 9.75 & 5 & 3 & 7 & 7 & 3 & 9.75 & 8.5 & 9.75 & 7 & 9.75 & 3 & 8.5 & 0 & 7 & 8.5 \\ 8.5 & 8.5 & 7 & 0 & 7 & 9.75 & 9.75 & 0 & 0.75 & 1.5 & 8.5 & 7 & 8.5 & 5 & 8.5 & 3 & 3 & 0 & 3 & 9.75 \\ 7 & 7 & 8.5 & 8.5 & 8.5 & 7 & 3 & 9.75 & 0 & 7 & 7 & 7 & 8.5 & 0 & 7 & 7 & 5 & 0 & 0 & 3 \end{vmatrix} \quad (15)$$

$$X = [x_1, x_2......, x_9] \quad (16)$$

$$\{D^+, D^-, T\} = \begin{vmatrix} d_1^+ & d_1^- & 9.75 \\ d_2^+ & d_2^- & 9.75 \\ d_3^+ & d_3^- & 9.75 \\ d_4^+ & d_4^- & 9.75 \\ d_5^+ & d_5^- & 9.75 \\ d_6^+ & d_6^- & 9.75 \\ d_7^+ & d_7^- & 9.75 \\ d_8^+ & d_8^- & 9.75 \\ d_9^+ & d_9^- & 9.75 \end{vmatrix}$$

where A is the processed MCDM matrix, X is a decision variables' vector, D^- and D^+ are the under-achievement and over-achievement goal vectors, respectively, T is the goal vector, $x_i = 1$ implies that the strategy chosen as ith strategy is the most important and effective strategy, otherwise, it will not be selected to be the most important and effective strategy. The programming was performed with Lingo 13.0, and the outcomes are displayed in Table 6. The results indicates that the 7th strategy, namely ST1 (establishing CNG development as prior strategy in Iran), is considered the most important and effective strategy for promoting the growth of CNG industry in Iran.

Step 4 - To determine the final ranking of the strategies. By excluding the strategy for which order of priority has already been allotted, the 2nd best, the 3rd best, and until the last best strategy were determined by repeating step 3. The final ranking of the strategies was determined to be $ST_1 > ST_2 > WO_2 > SO_3 > WT_1 > WO_3 > SO_1 > WO_1 > SO_2$. As a result, the strategy of considering CNG development as prior strategy in Iran has been identified as the most important and effective strategy for promoting the growth of CNG industry in Iran, followed by government subsidies and incentives allowance, encouraging private investment in CNG refueling infrastructure, desulfurization of gasoline and diesel, establishing a comprehensive fuel pricing

Table 5
Multi-criteria decision-making matrix described by using crisp numbers.

	S_1	S_2	S_3	S_4	S_5	W_1	W_2	W_3	W_4	W_5	O_1	O_2	O_3	O_4	O_5	T_1	T_2	T_3	T_4	T_5
SO_1	8.5	7	7	0	8.5	3	1.5	3	0.75	5	9.75	8.5	8.5	7	9.75	3	5	3	5	5
SO_2	0	5	5	7	5	9.75	7	5	5	3	0	0	9.75	0	5	3	0	0	5	8.5
SO_3	8.5	8.5	7	8.5	8.5	8.5	3	5	3	3	5	7	9.75	5	0.75	5	3	3	5	8.5
WO_1	8.5	3	7	3	8.5	9.75	1.5	0	3	1.5	8.5	7	8.5	7	0	3	5	3	5	9.75
WO_2	8.5	9.75	8.5	1.5	8.5	3	0.75	3	9.75	5	7	8.5	7	8.5	8.5	9.75	7	5	0	3
WO_3	7	7	8.5	3	8.5	3	0.75	3	8.5	8.5	7	3	8.5	8.5	8.5	9.75	8.5	1.5	0	3
ST_1	9.75	9.75	8.5	7	9.75	5	3	7	7	3	9.75	8.5	9.75	7	9.75	3	8.5	0	7	8.5
ST_2	8.5	8.5	7	0	7	9.75	9.75	0	0.75	1.5	8.5	7	8.5	5	8.5	3	3	0	3	9.75
WT_1	7	7	8.5	8.5	8.5	7	3	9.75	0	7	7	7	8.5	0	7	7	5	0	0	3
T	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75	9.75

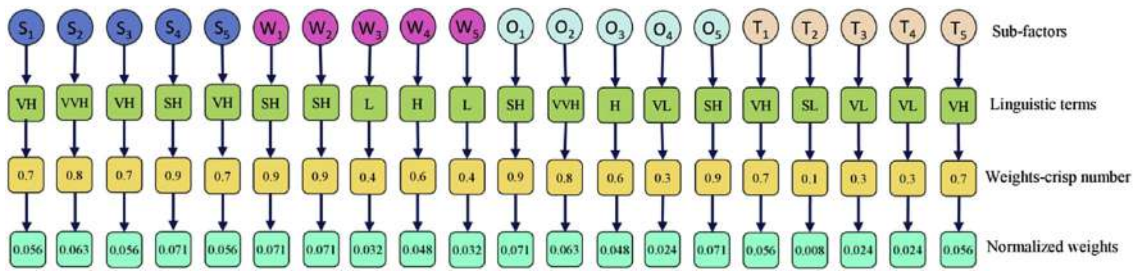

Fig. 12. The weights of the sub-factors.

Table 6
The results of the mixed-integer linear programming.

Item	x_7	x_i ($i = 1,2, \ldots \ldots,9 \cap i \neq 7$)	Objective function
Value	1	0	2.4205

mechanism, foreign capital importation, developing large scale CNG technologies, enhancing CNG Price differential w.r.t. diesel and adopting vehicle emission standards.

It makes sense that the strategy "establishing CNG industry prior strategy in Iran", which belongs to the ST strategies and can place the CNG as priority fuel for replacing diesel and gasoline, was identified as the most important and effective strategy for stimulating the CNG market of Iran because it is favorable for considering the benefits of the strengths, alleviating the weaknesses, taking the advantages of opportunities and dodging the threats. For example, it is useful to avail the economic opportunity value of utilizing abundant ingenious natural gas reserves, enhancement of energy security and national self-reliance, reduction of urban air pollution and health effects, substitution of imported gasoline and saving of foreign exchange. Moreover, this strategy reflects that to achieve the plan target of 50% CNG share in the fuel basket by 2026s, the CNG industry in Iran needs clear and positive support from the Government. It has been pointed out that currently there is lack of comprehensive national plan with relevant detailed guidelines for the sustainable development of CNG industry.

Concluding observation

Natural gas is clearly a powerful weapon for Iran in the battle to replace oil in the transportation sector, enhancing the energy security and to address the challenge posed by climate change. To help the decision-makers/stakeholders to comprehend present status CNG market in Iran, then design the productive future strategies to stimulate the growth of CNG industry in Iran, SWOT analysis has been used to examine the CNG market in Iran and nine productive strategies were suggested. Moreover, a MCDM method by integrating it with the goal programming and fuzzy theory was developed for ranking the strategies.

In the SWOT analysis, twenty sub-factors, i.e. owner of world largest proven natural gas reserves, well-developed natural gas infrastructure/availability of various models of NGVs from local auto maker, strong government support, favorable CNG price compared to petrol and great development potential (belonging to 'Strengths'), lack of CNG usage in heavy duty public road transport, high price of CNG as compare to diesel, lack of public access to the reliable/comprehensive government's CNG policy, heterogeneous geographical distribution of CNG refueling stations and lack of dedicated CNG engine technology (belonging to 'Weaknesses'), enhancement of energy security and national self-reliance, economic opportunity value of the abundant indigenous reserves of natural gas, reduction of urban air pollution/health effects, potential for job creation and export of CNG technology and substitution of imported gasoline/saving of foreign exchange (belonging to 'Opportunities'), lack of private investment in CNG refueling station, decrease in government's support/incentive in recent years, U.N. sanctions on Iranian banks, trade and technology transfer, lack of public's safety awareness/enforcement of safety/emissions regulations and strong lobby from diesel fueled fleet operators who prefer to maintain a liquid fuel "status quo" (belonging to 'Threats'), were identified to depict the current status of CNG market in Iran. Four types of strategies (SO strategies, WO strategies, ST strategies and WT strategies) have been obtained, with SO strategies consisting of **d**eveloping large scale CNG technologies, adopting vehicle emission standards and desulfurization of gasoline/diesel, WO strategies comprising enhancing CNG Price differential w.r.t. diesel, encouraging private investment in CNG refueling infrastructure and foreign capital importation, ST strategies including **e**stablishing CNG development prior strategy in Iran and government subsidies/incentives allowance, and WT strategies consisting of **e**stablishing a comprehensive fuel pricing mechanism.

The developed MCDM method by integrating it with GP and fuzzy theory was applied to prioritize the strategies for appropriate budget planning and setting the roadmap for the development of CNG industry in Iran. In the proposed method, linguistic terms were applied to measure the effectiveness of each strategy and selecting the strategy that can fulfill of the goals set by decision makers/stakeholder in best possible manner. The ranking of the strategies from the productive and important to the least was measured to be: establishing CNG development as prior strategy, government subsidies and incentives allowance, encouraging private investment in CNG refueling infrastructure, desulfurization of gasoline and diesel, establishing a comprehensive fuel pricing mechanism, foreign capital importation, developing large scale CNG technologies, enhancing CNG Price differential w.r.t. diesel and adopting vehicle emission standards. According to the prior sequence, stakeholders/decision-makers can draft the future actions towards a better future of CNG economy in Iran.

Nomenclature:

AFV	Alternative Fuel Vehicles
CNG	Compressed Natural Gas
EIA	Energy Information Administration
GP	Goal Programming
MCDM	Multi-criteria decision-making
LDV	Light Duty Vehicle
NGVs	Natural Gas Vehicles
OEM	Original Equipment Manufacturer
SWOT	Strengths, weaknesses, opportunities and threats
VRI	Vehicle-to-Refueling-Station Index

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.10.231.

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Annexure-J

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A failure analysis of the exhaust valve from a heavy duty natural gas engine

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ABSTRACT

Increasingly stringent emission standards are changing the conditions that valve systems in heavy duty engines are exposed to. Increased pressures and temperatures are challenging system endurance. A consequence of these changing conditions is a reduction in the levels of soot production that had formerly generated protective films. In order to help combat this, nickel-based super alloys have been widely used in applications requiring strength at high temperature. This study presents a premature failure case of a set of exhaust valves belonging to a heavy duty natural gas engine; where the valves were manufactured from one of these alloys, the precipitation hardened Inconel-751. The failure occurred at approximately 5000 operating hours after its first commissioning, whilst the standard expected service life of the valves is 20,000 h. Several examinations employing multiple techniques were carried out in order to identify the root cause of failure, whilst comparing results against those of a new valve. It was found that there was some mechanical lapse in proper sitting of the valve, which had been responsible for unwarranted overheating especially at thinner sections. Microstructure examination revealed that overheating had been responsible for a creep-rupture failure accentuated by precipitation of undesirable constituents at grain boundaries.

1. Introduction

The Global demands for inexpensive and clean power is increasing day by day and in this regard, the market of stationary generators have proven to be one of the major sources of power providers globally. In Asia, generators powered by stationary gas engines are becoming increasingly popular in areas where natural gas is readily available. Currently Caterpillar Inc., GE Waukesha and Cummins Power Generation are the key players in Global and Asian gas engine market [1].

The inlet and exhaust valves are one of the vital components of an IC engine. The major function of an Inlet valve is to control the flow of air to the combustion chamber while the exhaust valves are used to monitor the outward passage of flue gases from the combustion chamber [2–4]. Their operation has a direct effect on performance parameters (power, torque, fuel consumption and etc.) and also the engine emissions. Wear and failure of the exhaust valves, is an unavoidable problem in Internal combustion engines which ultimately leads to under performance, large down time, and high maintenance costs. Numerous numbers of alterations in the design, material and production techniques have greatly enhanced the running life and performance of the exhaust valves, but these up gradations cannot keep their pace with the continuous rise in the requirements of enhanced engine performance in our global competitive environment [4,5].

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Nomenclature

C–C	Carbon-Carbon
C–H	Carbon-Hydrogen
CH_4	Methane
DTA	Differential Thermal Analysis
EDS	Energy Dispersive Spectroscopy
IC	Internal Combustion
OEM	Original equipment Manufacturer
SEM	Scanning Electron Microscope
TGA	Thermo Gravimetric Analysis
XRD	X-ray Diffraction

There is very limited number of peer reviewed studies available about the failure analysis of exhaust valves especially that of Inconel-751. A failure analysis of the exhaust valve stem in a Waukesha P9390 gas engine was performed by Kwon OG et al. [6]. They observed a significant loss of hardness in valve material and concluded overheating as failure cause. The significant hardness loss, the extensive surface oxidation and fretting/galling on the valve stem were indicative of the overheating. Yu ZW et al. [7] performed a failure analysis and metallurgical investigations of diesel engine exhaust valves. Their fractographic studies indicated that formation of the lamellar structure in the material of the valve head was the dominant mechanism for the fatigue failures in the exhaust valve. Vardar N. et al., [8] investigated the failure of exhaust valve failure in heavy duty diesel Engine. This was carried out by using several experimental tests methods like optical emission spectroscopy, optical microscopy, scanning electron microscopy SEM and EDX. They concluded that the valve was failed and broken down prior to its desired service life. Very recently Witek L et al., [9] investigated the fracture problem of the exhaust valve of a passenger car diesel engine in order to explain the reason of premature fracture of the valve, author used finite element model consisting of the valve, the seat and the guide. The results shows that irregular depositions of the carbon on the seat face of the valve caused large amplitude of bending stress in the valve stem which subsequently caused the premature fatigue failure. Scott CG et al., [10] studied the effect of valve deposit morphology and composition on the erosion-corrosion of valve seat surfaces. The study provides some initial evidence that although valve seat deposits may have played a role in valve failure but the erosion-corrosion of exhaust valves was not exclusively related to the thickness of valve seat deposits. Forsberg P et al. [4] investigated the wear mechanism of three pairs of exhaust valves and valve seat inserts with the same material and design properties but with different service condition. The study revealed that oxidation and formation of a tribofilm was the dominant wear mechanism.

Although the alloy Incolnel-751 is being used extensively in modern heavy duty natural engines by various manufactures around the world but to the best of our knowledge, there is no systematic empirical research exists addressing the thermal performance of Inconel-751 in IC engines. The aim of this study is to analyze the failure mechanism of exhaust valves made of Inconel-751 failed due

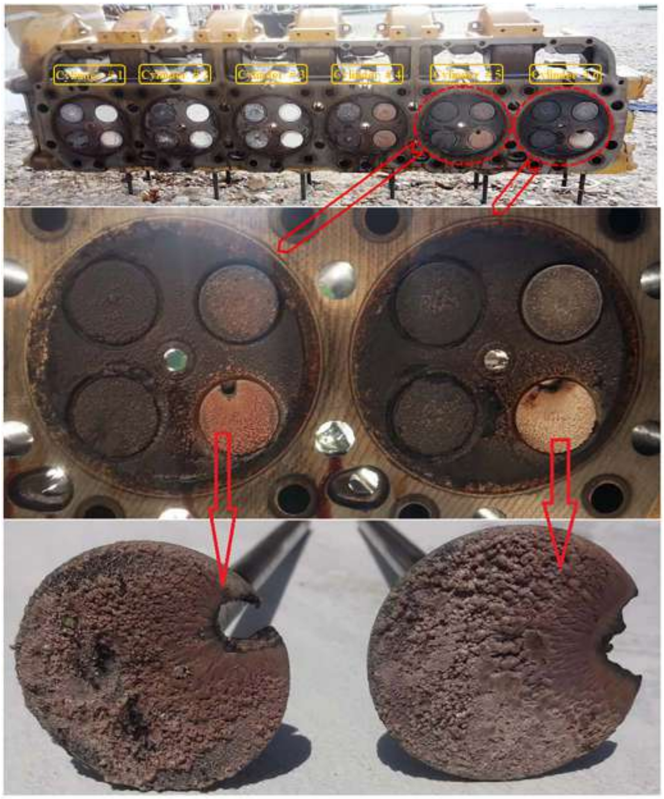


Fig. 1. Showing Cylinder head from a Caterpillar G3406 natural gas engine with guttered exhaust valves and showing high deposits after 10,000 h.

to guttering in heavy duty natural gas engine.

2. Problem statement

In the present work, failure analysis of exhaust valves form Caterpillar G3406 gas engine coupled with electric generator, were carried out. This engine was a 4 stroke, 6 cylinder 14.59 l natural gas fueled engine. The Genset was installed at an oil field located in Pakistan for continues power generation. It was commissioned on August 2013 and had been taken into operation since that date. The average total power consumption of the oil field was 40% of the generator capacity i.e. 200 Kva. It was reported that the Genset has trouble of tripping under low frequency just after 5000 h. in service. The problem was investigated by the OEM service team and it was wrongly concluded that the problem was due to stucking of exhaust bypass valve of turbocharger.

The exhaust was repaired and problem was fixed. It was also found that the pressure of cylinder # 5 and 6 were 180 psi and 160 psi respectively against OEM standard value of 220 psi. As the required power load was very low against the Genset rated capacity, hence it was decided to run the engine up to 10,000 h. Service life, the OEM recommended schedule for top-end overhauling. After completing 10,000 h. of service operation the top-end overhauling of the engine was performed. All parameters recorded before going for overhaul execution phase. The problems observed with the Genset were: Genset shut down under frequency, white smoke from exhaust and abnormal jacket water temperature. The recorded pressure values for cylinder # 1, 2, 3, & 4 were complied with OEM normal pressure range of 220 psi, while pressure value for cylinder 5 & 6 were 80 psi and 50 psi respectively which is considered very poor. After disintegrated the engine head guttering was found in the exhaust valve of the cylinder # 5 & 6 which was the main cause for poor cylinder pressure of these cylinders as shown in Fig. 1. The initial cause of guttering could not be determined, however, records of engine temperatures support the existence of guttering as they showed elevated exhaust temperatures at the affected cylinder beginning roughly 5000 h into operation of the generator. After 5000 h of operation, the temperature of jacket water cooling systems was increased from normal average temperature of 185 °F to 205 °F.

3. Factors affecting the life of exhaust valve

3.1. Effects of temperature

Exhaust valves mostly fail due to overheating which manifests itself in the form of decreased hardness, erosion-corrosion and extensive oxidation of the valve surface. Because of their installation in the path of flue gases, exhaust valves are constantly exposed to hot corrosive gases and the temperature these valves are subjected to, ranges from 750 °C to 950 °C [3,11,12]. In addition, Exhaust valves are exposed to a much higher temperature than the intake valves because the incoming fresh charge/air at atmospheric temperature cools the intake valves [8]. Due to abnormally high temperature in the region of exhaust valve and its seats, the material prematurely loses its mechanical properties like hardness, elasticity, strength, etc. And in addition the continuous valve closing and opening leads to the valve and valve seat wear.

This should also be noted that in case of inlet valve, the valve head is kept cool owing to the flow of cool inlet charge over it, and very little heat is rejected to anywhere other than the valve seat. But in the case of an exhaust valve, a high heat flux is not only absorbed by the valve head, but also by the area behind the head. For instance about 76% of thermal input to an exhaust valve exits when it sits in its seat and the remaining 24% leaves by means of the stem [13,14]. Effective heat transfer to the seat insert and into the cylinder head is, therefore, essential. Heat transfer can be significantly affected by seating deposits. If deposits are allowed to build up, they may not only lead to an increase in valve temperature, but may also break away locally and create a leakage path, leading to valve guttering.

3.2. Effects of loading and seating

Studies have shown that the exhaust valve sear wear mainly involves two distinct mechanisms. The first one is the impact of valve on the seat as it closes and second mechanism is Micro-sliding, caused by the elastic deformation at the valve seat interface as the

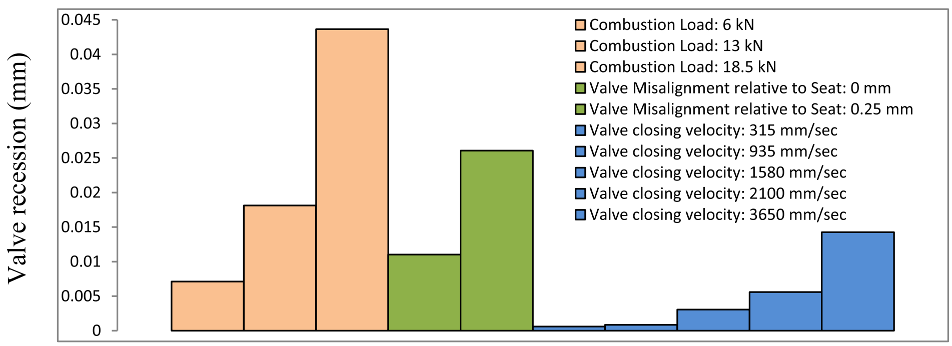


Fig. 2. Relation of valve recession with (i) valve closing velocity (ii) combustion load and (iii) valve misalignment Source: Prepared by the authors based on [16].

valve head is pressed into its seat by the high combustion pressure [15]. Experimental work performed also show that combustion load, valve misalignment and most importantly, the valve closing velocity have a significant effect on valve face recession [16], which is shown in the Fig. 2.

3.3. Effects of combustion deposits

Depositions building up on valve face and valve seats leads to poor sealing and seat can have an insulating effect which causes poor cooling and makes the valve run hot. If deposition is built up on valve face in the form of one spot, then poor sealing appears. This poor sealing leads to leaking of the combustion and creates hot spot on valve sealing face which in turn results in channeling effect. The deposition on valve seat, valve face, valve stem, is from combined reaction of impure contaminated fuel and lubricating oil. They are composed almost entirely of inorganic compounds. The oxides e.g. sulfur dioxide act with calcium contents in lubricating oil to form low melting point salts. These salt particles get deposited on valve surfaces in their molten state. These salt particles get cooled sufficiently to adhere to valve stem and valve spindle and do not get carried away by the exhaust gases. As operating temperature is more than 700 °C the deposited salts change into molten state. This molten state salts flow along the grain boundaries depending on valve material and dissolves the protective oxide on the grain boundaries. This phenomena is called intergranular corrosion, which leads to burning of the valve sealing face.

In a modern engine with low oil consumption running on a typical full boiling range fuel, combustion chamber deposits are formed primarily by the fuel though the lubricant also contributes to their formation. Deposit growth is a dynamic and reversible process, which at a given time, reflects the balance between the formation and removal processes. The single most important parameter that controls deposit formation is the surface temperature, which itself changes as deposits grow because of their insulating properties. Changes in engine operating parameters that tend to increase surface temperatures reduce deposit formation [12]. Thus increasing the speed, load and coolant temperature or making the fuel/air mixture slightly richer than stoichiometric all reduce deposit growth. Boiling point is the most important fuel or lubricant property in combustion chamber deposit formation - the higher the boiling point, the greater the deposit forming tendency.

Studies into the characteristics of combustion or ash deposits on the sealing faces of valves and seats have shown that these play an important role in the guttering process [17]. Such scales are ubiquitous, consisting of, for example, sulphates, phosphates and oxides of inorganic fuel and oil constituents. Not only do these scales interfere with the tight geometric fit of valves and seats, but they also restrict heat flow out of the valves. Around 75–80% of the heat absorbed by exhaust valves exits through the contact between valve and valve seat [15]. Valves can therefore be insulated by excessive scale, raising their temperature and making them more susceptible to distortion or damage. Finally, uneven flaking or spalling of the scale itself under the closing action of valves can create sufficient localized leakage paths to initiate valve guttering.

3.4. Effects of the fuel and lubricant

Natural gas which is primary fuel used in gas engine mainly consist of methane (CH_4). The four C–H bonds of methane give it a higher specific heat content than liquid fuels like gasoline or diesel that contain some lower energy C–C bonds. Consequently, it burns hotter than other fuels and can cause severe oxidation and nitration of the engine oil [21]. In addition, since it is already a gas, methane does not cool the intake air by evaporation as liquid fuel droplets do. This has a significant effect on the intake and exhaust valves because there is no fuel-derived lubricant for the valves like liquid droplets or soot. Consequently, gas engines are solely dependent on the lubricant ash to provide a lubricant between the hot valve face and its mating seat. The ash is the portion of the lubricant that is left behind as a deposit after complete burning of the oil. It is whitish-gray and comes from the metallic detergents (calcium and barium) and antiwear (zinc) additives. In addition, ash concentration and composition, thermal expansion, melting and boiling points of the ash deposits, which are majorly influenced by the additives and detergents employed in the engine oil, play a vital role in exhaust valve failure mechanism [8]. Too little ash or the wrong type can accelerate valve and seat wear, while too much ash may lead to interference in the geometrical fit of the valve and its seat, leading to distortion, leakage, guttering and hot spots subsequently resulting in valve torching [10,22]. A Well formulated gas engine oil can not only provide excellent wear resistance, cooling and deposit control, but misapplication of such an oil not designed for gas engines can degrade life expectancy, and performance of the engine and also negatively impact operating costs [15,16,21]. Too much ash deposit may be caused by using an oil with too high of an ash content, over lubrication or many other mechanical factors. It is noteworthy to mention that exhaust valve failure can result from both lubricant (too much ash) and non-lubricant factors, as well as from valve recession itself. This is a complicated process as these factors are intertwined with each other, which makes the process of finding the root cause of a valve failure difficult. The ash content of engine oil used in this case study was 0.14% which comes under category of low ash oil.

3.5. Valve materials

As the inlet and exhaust valves are exposed to varying operating conditions in heavy duty engines, so the materials used in their manufacturing are also generally different. Specifically, the material used for exhaust valve must have high resistance to corrosion at the elevated operating temperatures, sufficient strength and hardness to resist tensile forces and wear, adequate fatigue and creep strength. In addition, coefficient of thermal expansion should be low to avoid excessive thermal stresses and most importantly they should have a high thermal conductivity for good heat dissipation [11,18,19]. Exhaust valves of heavy duty engines are generally made of austenitic steel. Typical austenitic alloys for exhaust valve are 21-2 N, 21-4 N and 23-8 N, Inconel-751, Pyromet 31 and

Nimonic 80A. In gas engines the exhaust valves have high levels of cobalt, nickel, iron, chromium, titanium and other elements to increase hardness [20].

3.6. Failure's mode of exhaust valves

The exhaust valves are exposed to thermal and mechanical overstress which can be sources of valve failures. During each combustion event, high stresses are imposed on the combustion chamber side of the valve head. These generate cyclic stresses peaking above 200 MN/m2 on the port side of the valve head. The most common type of failure that can be caused by these thermal stresses is the valve and seat wear. The understanding of wear mechanisms is complicated by inconsistent patterns of valve failure. For example, failure may occur in only a single valve operating in a multi-valve cylinder. Furthermore, the apparent mode of failure may vary from one valve to another in the same cylinder or between cylinders in the same engine. It has been noted that in practice, every engine manufacturer has had share of their exhaust valve failure problems but no hard and fast rules can be used to predict or achieve a satisfactory exhaust valve life. The literature study shows that valve wear generally occurs by the three main modes namely the abrasive wear, adhesive wear, and corrosive wear [4,20,23–25].

Abrasive wear can be observed in exhaust valve and its seat, by the presence of gouging and scaring on the mating surfaces. Relative sliding, wear particles of the mating surfaces and solid combustion products from the fuel, lubricating oil and air containments are influencing factors in this mode of wear [4,15]. Micro welding or bonding of the mating surfaces has been characterized as Adhesive wear mechanism. At high temperatures, the plastically deformed asperities or projections present on the mating surfaces are eventually welded together when the valve is pressed into its seat [25]. Incompatible valve and seat materials, critical temperature, minimal solid film lubrication, and High contact pressure result in adhesive wear [15].

Presence of High operating temperatures, high ash level and Corrosive constituents from combustion products, might lead to Corrosive wear in Exhaust valves [10,26]. On micro level, presence of high ash level, might lead to insulation of the exhaust valve, which will not only increase the temperature of the valve, but will also make it prone to the chemical attack by the fuel and deposits compounds, present in the form of salts and oxides of Sulfur, Magnesium, Calcium, Phosphate, Zinc, Silicon [18,27]. Corrosion manifests itself in the form of Intergranular attack on the grain boundaries leading to guttering of the exhaust valves [28,29]. The above mentioned wear mechanisms lead to three main types of valve failure that have been known to occur on the valve face, seating and sealing face of the valves, which are: Valve recession, Guttering and Torching [4,23,25,26,30].

3.6.1. Valve recession

Valve recession is said to have occurred if wear of the valve and seat insert contact faces has caused the valve to ‘sink’ or recede into the seat insert, thereby altering the closed position of the valve relative to the cylinder head (as shown in Fig. 3). Valve recession is the most common form of valve wear in gas-fired engines; valve recession occurs gradually over thousands or tens of thousands of hours. The recession occurs by metal abrasion, high temperature corrosion, frictional sliding, and adhesion mechanisms [31]. Excessive amount of valve recession leads to incorrect or incomplete seating which leads to losses in the cylinder pressure [32] Valve and Seat recession mostly occur due to impact of valves on the seat, and by the systematic gouging, dulling, deformation and eventual wear out, of the exhaust valve or seat insert material [30,33,34].

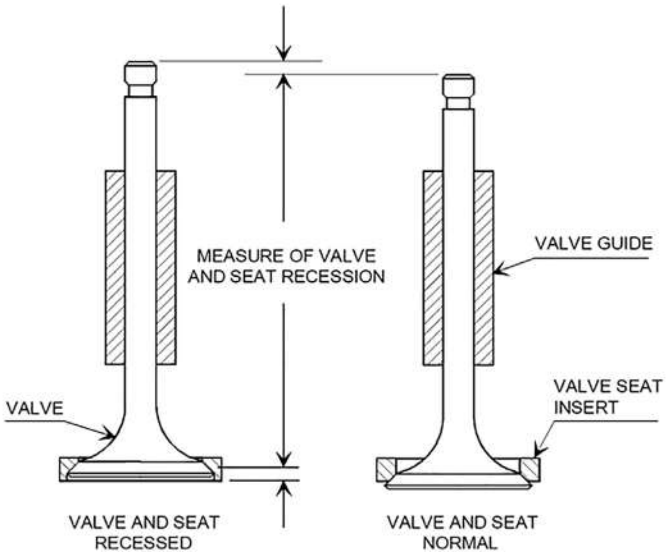


Fig. 3. Showing valve recession phenomenon [32].

3.6.2. Guttering

In case of the valve not seating properly, which might be due to valve deformation or due to the interference of the solid deposits, the pressure inside cylinder will be lost in the form of a leakage path for the exhaust gases [32]. This leakage path will lead to material losses in the valve and its seat by means of an erosive-corrosive mechanism [10]. Over repeated engine cycles, this leakage path will widen and will eventually lead to valve guttering [35] which can be easily identified in leaked engine cylinders by a distinct hissing sound [32]. Literature Study about the ash deposits or scales on the valve sealing face have clearly confirmed their influence in the valve guttering process [15,20]. Guttering of exhaust valves will eventually result in an alarming leakage of the cylinder compression, and will also manifest in the form of power loss due to misfiring [36,37,10].

3.6.3. Torching

Valve torching is the phenomena which may happen where temperature of the valve-face or valve-seat surface is elevated to the melting point of valve material by pre-ignition. This is caused by the hot surface of valve or deposit particles which act as a "glow plug" and ignite the fumigated fuel-air mixture during the compression cycle, earlier than the spark plug. The burning gases are driven through valve and seat interface leakage passages by the high differential pressure of abnormal combustion, heating the surface to the melting point. Like a cutting torch, the molten metal is carried away from the valve surface into the exhaust passage by the jet of burning fuel gas and air. Torching can occur in natural gas engines that operate with excessively advanced spark plug ignition timing for a given fuel, which produces abnormal combustion. With abnormal combustion there is a high pressure rise before or near piston top-dead-center. The high pressure rise causes compression heating of the burning gases and a more rapid heat release rate, raising the valve temperature. Deformation of the valve head and cylinder head is increased. The higher heat release rate increases radiation and convection heat transfer to the combustion chamber and valve surfaces, causing a large surface temperature rise.

4. Experimental procedures

The failed exhaust valves under investigation were subjected to the following procedures to assess failure causes:

(i) Visual examination of inner and outer surfaces
(ii) Energy dispersive spectroscopy (EDS) analysis for elemental composition
(iii) Hardness measurement
(iv) Scanning electron microscope (SEM) examination of the valve head
(v) Optical microscopy of the valve head
(vi) X-ray diffraction (XRD) analysis of valve-face deposits
(vii) Thermo gravimetric analysis (TGA) for thermal analysis of valve material

First, the inner and outer surfaces of the failed exhaust vales were visually examined, the amount of the obvious guttering was listed and the typical macro-morphology was taken using the digital camera (NIKON L100). Then the sample pieces of failed valves were cut from the corresponding parts based on the requirements of different tests. Some of the samples were cross-sectioned and mounted in epoxy. They were then grounded by different grit size silicon carbide (Sic) emery papers in a sequence of 320, 600, 800, 1000, and 1200 and subsequently mechanically polished with diamond paste (6, 3, and 1 μm) and 0.05 μm alumina suspension. Pressurized water coolant was applied during grinding process to prevent sample heating. Ultrasonic cleaning for 2 min was carried out after each step of diamond paste polishing to remove any diamond abrasive on the sample surface. The samples were then etched for 60 s using etching solution of Modified Glyceregia (30 ml HCl, 25 ml Glycerol, 10 ml HNO_3). After etching microstructure analysis of the polished samples were performed using SEM (JSM-5910, JEOL Japan). After thermal aging, microstructure of the polished

Fig. 4. Failed valves.

samples was performed using optical microscope (Olympus GX51, *Olympus Co. Japan) and Scanning Electron Microscope - SEM (JSM-5910, JEOL Japan). The chemical composition of the exhaust valves was analysed using EDS (Oxford Ins Inca-200) coupled with SEM on the basis of ASTM A751-2008. Hardness of the valve materials was found with micro-hardness tester (Model HMV-2T, Made by Shimadzu). X-ray diffraction (XRD) measurements were carried out in order to determine the constitution of the phases present combustion product of valve surface deposits.

5. Results and discussion

5.1. Visual inspection

As shown in Fig. 4 the two out total twelve exhaust valves have suffered from severe erosion–corrosion with the axial distributing wide channel. It can be observed from the morphology of the guttering channel on the surface of failed valves have macro-features consistent with erosion induced by turbulence of high velocity of hot gas stream.

5.2. Chemical analysis

Chemical Composition of the failed valves and new un-used valve (from warehouse) specimen was studied using EDS and the result is shown in Table 1. The composition is in closed matching with Nickel Alloy Inconel-751which is a precipitation hardened Ni-Cr-Fe alloy, having traces of Al and Ti and is widely used in the diesel engine exhaust valves.

5.3. Hardness test

Polished samples were taken from the new and failed exhaust valves, in accordance with ASTM E92 standards. A Vickers hardness test with 30 g force was performed for 15 s and it was repeated for 4 times for each sample according to ASTM-E92 standard. The average hardness of the unused new valve was determined to be 348 HV which comply with the standard hardness value of Inconel-751 super alloy. The hardness value of the failed valve was 255 HV, which is at lower side of unused valve. Normal heat treatment of the Inconel-751 would produce a hardness of about 350 HV. The measured hardness of about 255 HV indicates that the valve had been heavily overaged. This hardness is effectively the same as in the solution annealed condition of the said alloy which is normally the softest condition available. Although the specific aging characteristics for the alloy and the normal valve operating temperatures are not known it strongly suggests that the valve has been running hot.

The measured hardness value of about 240 HV for the Failed valve shows an alarming percentage decrease of 27%, this clearly points to the fact that the hardness of the failed valve had alarmingly fallen, which may be the effects of intergranular corrosion IGC. The possible reasons for decrease in the hardness of failed valve is the increased in the amount of γ' precipitates during the service (see Section 5.4 for detail).

5.4. Microstructure analysis

SEM Analysis of the polished samples revealed the microstructure of failed and new-unused exhaust valves. It was found that the failure had taken place primarily due to microstructural reasons. The γ matrix of the new un-used valve (Fig. 5) contained precipitates γ' presumably of nickel based intermetallics like Ni3 (Al, Ti, and Fe) at the grain boundaries, these precipitates have assumed a cylindrical morphology and their presence along the grain boundaries in a heterogeneous manner, greatly diminished the grain boundary separation strength and presence of such precipitates at the triple points might have led to initiation of stress rupture. Essentially this is a case of combined failure characterized by creep fatigue interaction.

It seems that the solutionizing heat treatment was not properly performed. Most likely the solutionizing temperature and time for homogenization were not adequate. The quenching practice might have had slower cooling rate too.

During service, the precipitates have increased in amount; this means that areas adjacent to grain boundaries have been depleted in strengthening precipitates and initiated void formation at grain boundary triple points. Classically we may say that the failure has been creep rupture accentuated by the precipitation of undesirable constituents at the grain boundary with unusual morphology.

The microstructure of failed valve (Fig. 6) contains some unusual phases at the grain boundary; the material is subjected to harsh condition of high temperature fatigue where flow stress of the material becomes lower. Therefore continued use has opened voids at the triple points; because the environment is corrosive, it is quite possible that at high temperature hydrogen aided failure is possible. It is for certain that corrosion aided thermal fatigue have played big role in accelerating creep damage. In Nickel super alloys, where chromium is added to the matrix for its role in optimum corrosion resistance, continuous over heating led to over-aging of the

Table 1
Chemical composition of failed valve material (mass %).

Super alloy	Elements				
Inconel-751	Ni 72.30	Cr 16.52	Fe 7.85	Ti 2.25	Al 1.10

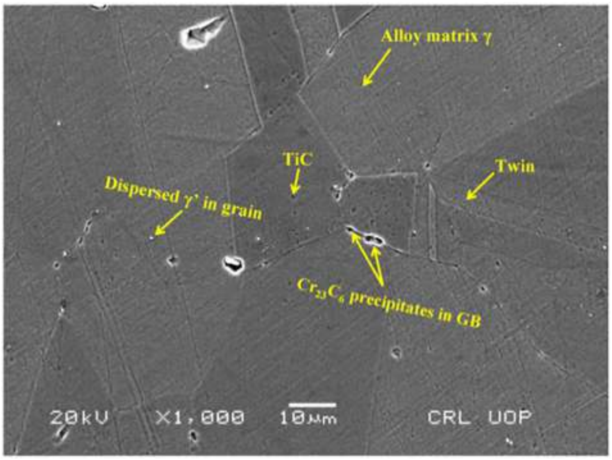


Fig. 5. SEM image of the new exhaust valve specimen.

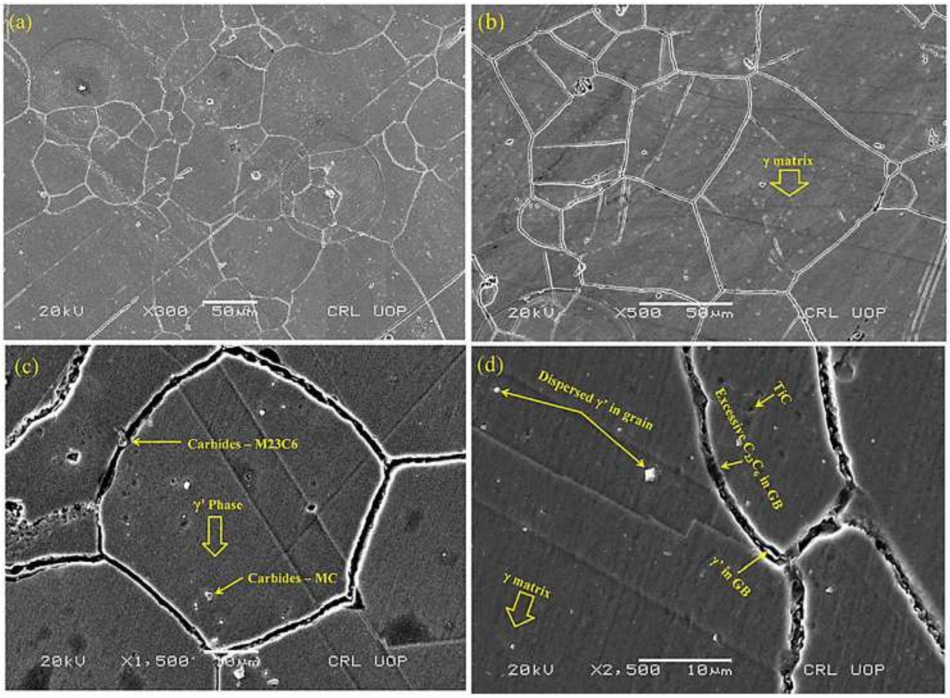


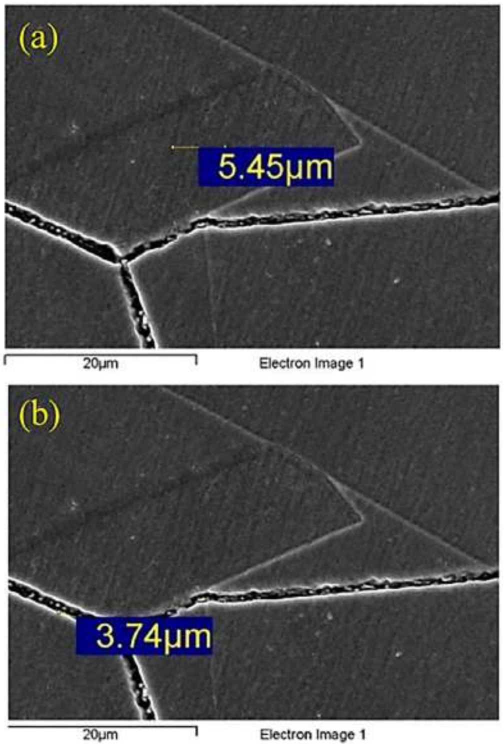
Fig. 6. SEM images of the failed valve specimens.

material, which ultimately resulted in formation of chromium-depleted zones adjacent to the grain boundaries which is a well-known failure mechanism in super alloys and steels called "sensitization".

This precipitation depletes the Cr content near the grain boundaries, thereby decreasing its corrosion resistance, as shown in the EDS analysis (Fig. 7) of the failed valve, where chromium content in the near boundary region has depleted.

The mechanism involved is known as the Intergranular corrosion (IGC), and is such a form of corrosion whence the boundaries of crystal lattice are more prone to corrosion than their insides. Micro hardness tests in accordance with ASTM E92 standards indicated a percent decrease of 27% confirming our speculation.

In summary it seems there was some mechanical lapse in proper sitting of the valve which has been responsible for unwarranted overheating especially at thinner sections. This has led to particle coarsening which is found in the microstructure of failed valve. The grain boundary corrosion is also there and at the same time intergranular precipitates of γ' have become coarse and non-uniformly distributed especially near the grain boundaries. The significant loss in hardness of failed valve is also due by this particle coarsening phenomena. One of the possible reasons for the particle coarsening is rise in temperature which has softened the matrix which made it vulnerable to failure at the working pressure, especially in a situation where grain boundary has weakened and section thickness has locally diminished due to erosion-corrosion. These have led to premature failure.



(a)

Element	Weight%
Al	1.59
Ti	2.58
Cr	19.79
Fe	6.66
Ni	70.37
Totals	100.00

(b)

Element	Weight%
Al	1.31
Ti	2.40
Cr	16.08
Fe	7.28
Ni	72.93
Totals	100.00

Fig. 7. EDS results for a) EDS at the Grain Boundary b) EDS at a random location in Grain.

One of the possible reasons of the overheating is the lack of tappet clearance, resulting in light seating and carbon build up on the seating face. Both factors lead to destruction of the thermal heat path outlet from the valve face through the valve seat to the coolant. This causes a considerable rise in valve head temperature, particularly in the valve face area. Eventually, the conditions exceed the

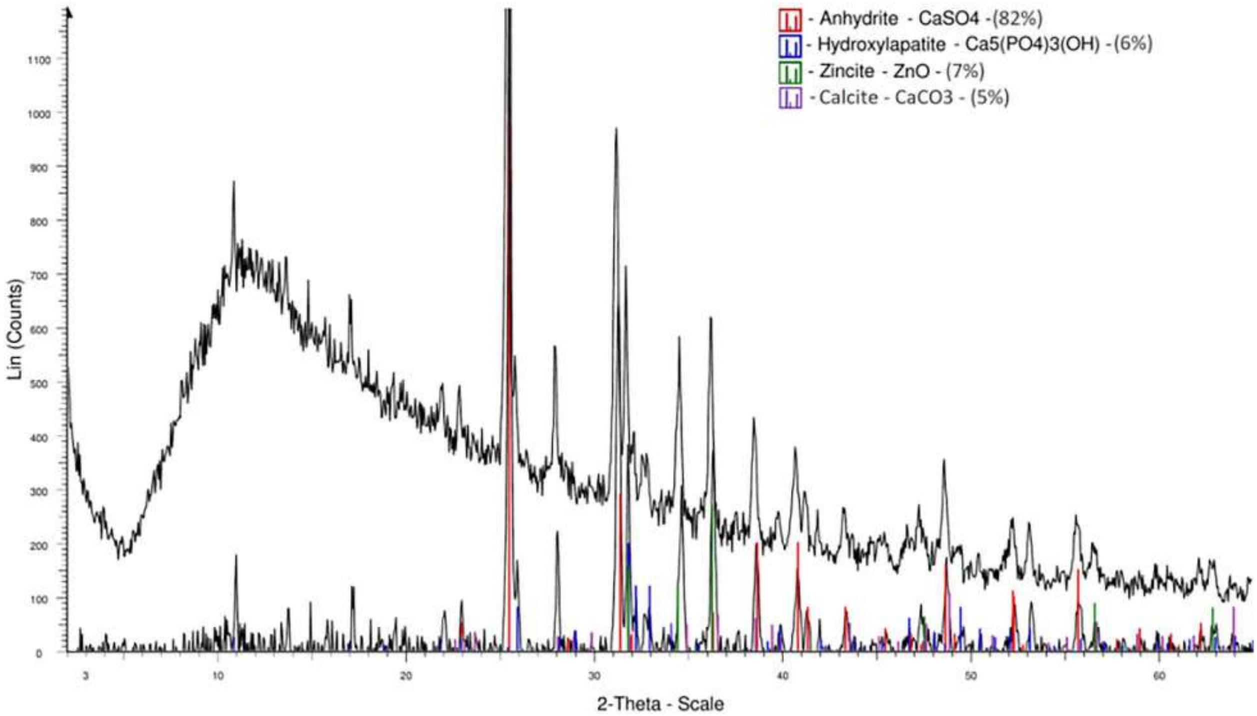


Fig. 8. XRD spectrums for the exhaust valve deposits.

material's resistance to hot corrosion or burning. As the localized gas leak increases, so does the torching effect through the gap, eventually producing the characteristic gutter.

5.5. Combustion deposits analysis

The compounds formed by combustion deposits on the valve surface were obtained by XRD spectrum as shown in Fig. 8.

Using XRD software, the deposits were identified as Anhydrite, Hydroxyl apatite, Zincate and Calcite (Table 2). Ca5(PO4)3OH is calcium phosphate hydroxide (hydroxyl apatite), a form of enamel that is difficult to remove. It is possible that this deposit protects or seals the valve from attack of high temperature exhaust gases and prevents high temperature corrosion.

No traces of free carbon were detected in the solid deposits, this fact was also verified by TG/DTA of the deposits, as it would have reacted with anhydrite at 800–900 °C to form calcium Sulphates. When analyzing the behavior of solid combustion deposits, the most direct method is to refer to Thermogravitmetric TG and differential thermal analysis DTA. In the Fig. 9, weight loss can be clearly seen (Blue Line), with the corresponding heat flow (Red Line), demonstrating the effectiveness of TGD/TA in studying the characteristics of our sample deposits.

For the TG/DTA analysis of Exhaust valve deposits, the weight was kept as 9.510 mg, which was held for 1.0 min at 40.00 °C after which it was heated from 40 °C to 1000 °C at 10.00 °C/min, while Nitrogen gas was supplied at 20.0 ml/min during the whole process. The positive and negative heat flows in the DT curve represent exothermic and endothermic processes, respectively. From ambient temperature to 200 °C, the evaporation of moisture present in the form of free water or absorbed water occurred which lead to the initial weight decrement and the first endothermic peak, and this subsequently means that the fuel natural gas was not well dry and there was free water in the gas, This behavior is similar to the peak as a result of H2O, in the TGA of injector deposits [38].

In the TG curve there is significant weight loss between 200 and 400 °C, which is due to loss of lattice water in Hydroxyl apatite Ca5(PO4)3(OH). This results in an exothermic reaction which is represented by the 2nd peak at 280 °C in DT curve. Beyond the temperature of 490 °C till 1000 °C, the mass of the deposits remained negligibly unchanged at 8.5 mg with a total of about 10% loss in its weight.

If free carbon was present in the exhaust valve deposits, then further decrease in the sample weight would have occurred. These solid deposits cling to the surface of the valve face, and act as a thermally insulating film, and as we know that about 76% of the heat absorbed by the exhaust valve during combustion and exhaust gases flow, is given off when the exhaust valve sits in its seat, this will restrict the cooling process [15] therefore Exhaust Valve will be insulated by the excessive scale, and will become susceptible to intergranular attack IGA, ultimately leading to guttering of the said valve.

6. Conclusions

The exhaust valves were analysed to be typical of Nickel based supperlloy Inconel-751. This alloy is commonly used for high performance valves. The valves probably failed as a result of overheating. The possible cause for overheating is lack of tappet clearance, which results in light seating and carbon build up on the seating face. Both factors lead to destruction of the thermal heat path outlet from the valve face through the valve seat to the coolant. This causes a considerable rise in valve head temperature, particularly in the valve face area. Eventually, the conditions exceed the material's resistance to hot corrosion or burning. As the localized gas leak increases, so does the torching effect through the gap, eventually producing the characteristic gutter.

The significant overaging of the alloy caused the particle coarsening which subsequently resulted in the decrease of hardness. There are some traces of low melting point compounds in the valve surface deposits which can cause hot salt corrosion that attacks the grain boundaries. The grain boundary corrosion is there and at the same time intraganular precipitates of γ' have become coarse and non-uniformly distributed especially near the grain boundaries. The grain size in the failed valve indicates that performed heat treatment had not achieve the aim of optimal creep resistance. Probably the microstructure is set to achieve optimal fatigue resistance. The microstructure of the failed valve indicates without doubt on the creep type of fracture (coalescence of cavities along grain boundaries).

7. Recommendations

Based on the results of this investigation, the major causes of valve failure are distortion of the valve seat, deposits on the valve and small tappet clearance. Therefore the following items may be considered for future operational and design concerns regarding prevention of exhaust valve's failure of a natural gas engine. These recommendations are not identified as a comprehensive list, but

Table 2
Phases present in the combustion deposits.

Name of compound	Chemical formula	Crystal shape	Weight %
Anhydrite	CaSO4	Orthorhombic	82
Hydroxyl apatite	Ca5 (PO4)3(OH)	Hexagonal	6
Zincate	ZnO	Hexagonal	7
Calcite	CaCO3	Hexagonal	5

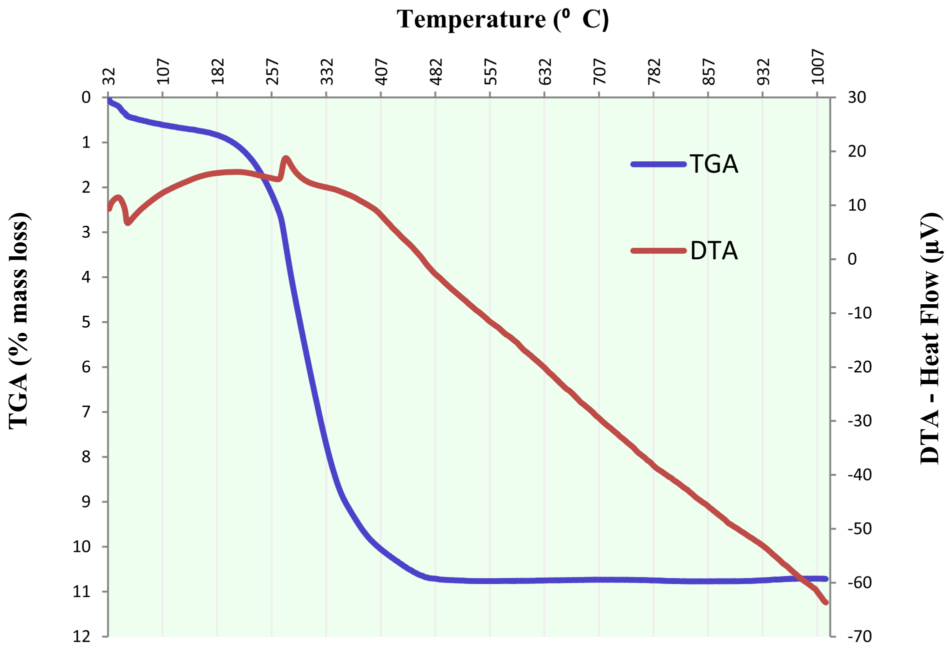


Fig. 9. TG/DTA for the exhaust valve deposits. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

may provide partial guidance for safe operation of natural gas engines:

- Check the clearances at regular intervals as specified in the OEM service manual or when there is abnormal increase in the temperature of jacket water.
- To prevent the intergranular corrosion in exhaust valve system made of a Nickel based super alloy, engine oil with Mg-based additives is recommended.

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Annexure-K

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Comparative Well-to-Tank energy use and greenhouse gas assessment of natural gas as a transportation fuel in Pakistan

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ABSTRACT

This study aims at performing the first comprehensive Well-to-Tank (WtT) energy consumption and greenhouse gas (GHG) emission analysis of 10 different petroleum and natural gas fuels pathways, i.e., gasoline, diesel, CNG and LNG, in Pakistan. The GREET model, developed by the U.S. Argonne National Laboratory, was adopted as a tool for WtT calculation, and most of the data were replaced by Pakistani operating environment. Additional analysis was also performed for the refining process which was the most energy-intensive in the fuel life cycle. A process-level allocation method was used in calculating the refining energy use of individual petroleum products, which could reflect the detailed refining processes. The results indicate that petroleum fuel have WtT efficiencies in the range of 82–86% while WtT efficiencies of natural gas based fuels are in the range of 75–88%. The results reveals that WtT GHG emission associated with CNG produced from indigenous natural gas sources are 16% and 21% higher than the gasoline and diesel fuel produced from ingenious crude oil, respectively. As compared to other countries, the WtT GHG emissions results of Pakistani petroleum and natural gas based fuels are 10% and 29 higher than those of the Europe mainly due to higher methane emission.

Introduction

The transportation sector is responsible for almost a third of the global energy consumption and a significant portion of greenhouse gases and pollutants emissions (Sources of Greenhouse Gas Emissions, 2015). The sector has been dominated by oil for over a century, creating what de facto is an oil monopoly in transportation fuel markets. Recently, environmental concerns and geo-political issues related to oil procurement have spurred an interest in developing solutions to reduce vehicle fuel consumption and tailpipe emissions, and exploring the use of alternative fuels (Orsi et al., 2016). Among the available options natural gas is receiving considerable attention as a plausible alternative to conventional transport fuels. The recent shale gas supply boom, resulting from the development of new extraction techniques in the United States and elsewhere, has decoupled its price from that of crude oil and spurred major investments in the infrastructure for its production, storage, and distribution. As natural gas becomes more desirable for transportation, technology providers have eased its adoption by devising new engines and retrofits for cars, trucks, and ships.

Road transport is a backbone of Pakistan's transport system, accounting for 90% of national passenger traffic and 96% of freight movement. The consumption of transport fuel has increased at cumulative growth rate of 16.5% during the last six years (2010–2015) while the rest of country's energy consumption increased at cumulative growth rate of 4.7% during the same period (Pakistan Energy Yearbook, 2015). This increase in share of transport fuel demand was due to social and economic progress and rapid urbanization. It is expected that the demand of transport fuel in Pakistan would increase in future due to strong economic growth, dramatic shift in the population to urban centers and the rapidly increasing demand for transportation. Like many other countries (e.g. Canada, India, Switzerland) the transportation sector is one of the largest source of greenhouse gas (GHG) emissions in Pakistan, accounting for more than one third of Pakistan's total GHG emissions. In 2015, the transport sector accounted for 32.4% (13.6 million TOE) of total primary energy consumption in Pakistan (Pakistan Energy Yearbook, 2015).

With the aim to reduce the transportation sector's oil consumption and emissions of greenhouse gases (GHGs) and criteria air pollutants, in 1998 the government of Pakistan announced a two year goal of establishing 150 CNG stations and conversion of 100,000 vehicles to natural gas fueled vehicles. Due to Government's consumer friendly policy, ample regulatory framework and available price difference between CNG and gasoline/diesel, NGVs (natural gas vehicles) have increased significantly at an unprecedented rate of around 52.5% per annum during the last few years (Khan & Yasmin, 2014). Currently the country NGV fleet share about 80% of total registered passenger vehicle fleet in Pakistan and 16% NGVs strength worldwide.

Emissions and energy consumption are often measured at the point of use. This does not, however, account for the overall emissions and

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energy consumption. To evaluate the impact of fuels and energy carriers the whole supply chain has to be considered (Bossel, 2003). To validly evaluate and assess the energy, emissions, and economic effects of automotive fuels and vehicle technologies, a holistic or comprehensive approach has to be considered. The approach, often referred to as Well-to-Wheel analysis must include all the steps required to produce a fuel and to burn the same fuel through vehicle operations. The whole WtW cycle is comprised of two independent stages, as shown in Fig. 1. These include (a) a Well-to-Tank (WtT) stage, which includes the recovery or production of the feedstock for the fuel, transportation and storage of the energy source through conversion of the feedstock to the fuel and the subsequent transportation, storage, and distribution of the fuel to the vehicle tank, and (b) a Tank-to-Wheel (TtW) stage, which refers to the vehicle in utilizing the fuel for traveling purposes throughout its lifetime.

Although there are many WtW studies available comprehensive in relation to developed countries conditions, however it is problematic to apply the results of those studies to developing countries fuel markets like Pakistan, since the local conditions and respective vehicle powertrain technologies are considerably different. To the best of our knowledge, no comprehensive assessment, especially for fuels with commercial availability, has been fully investigated in the developing countries except China and Lebanon (Mansour & Haddad, 2017). Till date no attention has been paid to WtW analysis on automotive fuels in Pakistan. Therefore main goal of this study is to construct the first comprehensive WtT GHG emissions database of petroleum-based automotive fuels commercially available in Pakistan i.e., CNG, gasoline, diesel, and LNG in Pakistan.

The study presents a detailed exergy-based WtT analysis to compare vehicles fueled with one of the following fuels: CNG, LNG, gasoline and diesel. The comparison is based on two indicators: (i) primary energy consumption; (ii) GHGs emissions. Instead of simply listing the comparisons, this paper discusses the reasons that cause the changes in the efficiencies and emissions that are brought about by automotive fuels. The analysis in this paper focuses on transportation fuels available at commercial level rather than on advanced vehicle powertrain (e.g., hybrid vehicles, plug-in hybrids or fuel cell vehicles). The results of this study serve as valuable inputs not only for policy decision-makers in Pakistan, but analysis would also be applicable to other countries having similar characteristics, i.e., oil importing developing countries with their own or easy access to natural gas resources (e.g., via relatively short distance pipelines); some countries in Latin America, Africa and Southeast Asia would seem to fit this description.

Review of the state-of-the-art

Many variations of WtW studies have been proposed in the literature (Ally & Pryor, 2007; Curran, Wagner, Graves, Keller, & Green, 2014; Karman, 2006; Ou, Zhang, & Chang, 2010; Rose, Hussain, & Ahmed, 2013; Tan & Culaba, 2002; Torchio & Santarelli, 2010; Yazdanie, Noembrini, Dossetto, & Boulouchos, 2014) to capture different aspects of the fuel life-cycle of transportation fuels in different regions of the world. However WtW studies on CNG vehicles haven't got much academic interest and only few analyses have been conducted targeting the CNG fuel, with often varied and even contrasting results. In this section we have presented a brief review of those WtW studies pertaining to CNG.

A study by Torchio and Santarelli (2010) described a WtW analysis in the European context introducing a new global index by assigning costs to energy, emissions and other factors. This study concludes that usage of natural gas-based fuels and hybridization as promising options compared to conventional gasoline and diesel fuel vehicles.

Similarly a WtW analysis by Yazdanie et al. (2014) concerned the operation of conventional and alternative passenger vehicles in Switzerland. This analysis showed that HEVs using alternate fuels particularly biogas and CNG resulted in remarkable reductions in WtW energy and GHG emissions over a conventional gasoline-powered IC engine vehicle.

For Philippines, Tan and Culaba (2002) conducted a WtW study on several fuels (gasoline, diesel, CNG, LNG and biodiesel) considering the global environmental impact of each fuel with the aid of EDIP–GREET composite-program. The end result was that, based on the authors' assumptions, the fuels derived from natural gas could offer no substantial environmental benefit by comparison with the conventional fuels.

In Australia, as part of the Sustainable Transport Energy Program (STEP), Ally and Pryor (2007) did an LCA (life cycle analysis) comparison of bus fleets powered by diesel, CNG and hydrogen fuel cell respectively. They showed that CNG required more energy per distance traveled and resulted in slightly higher GHG emissions compared to diesel driven vehicles. However, vehicles driven by CNG showed lower emissions related to smog, acidification, and soil/water contamination (NOx, CO, SO2, and non-methane volatile organic compounds) for Western Australia.

In Canadian setting, Rose et al. (2013) carried out a comparative LCA with GHGenius (LCA model developed for Canadian Transport system) on refuse collection vehicles powered by diesel and CNG and found that a 24% reduction of GHG emissions was achieved by switching from diesel to CNG.

In China, Karman et al. presented the results from an assessment of WtW GHG emissions from buses fuelled with diesel and CNG in the city of Beijing. The model employed was the ‘China version’ of ‘GHGenius’, created by using specific data and estimates wherever China specific information was available to replace its default data for North America. It was found that GHG emissions ‘per vehicle-kilometre driven’ for CNG were slightly lower than those for diesel.

Ou et al. (2010) employed Tsinghua-CA3EM model to compare the WtW performance of alternative fuel buses with conventional buses specific to China. They showed that CNG buses consumes 14% less energy and produce 28% less GHGs than a counterpart diesel vehicle.

Similarly, Curran et al. (2014) used the GREET model to analyze the WtW energy use and GHG emissions from natural gas pathways. They

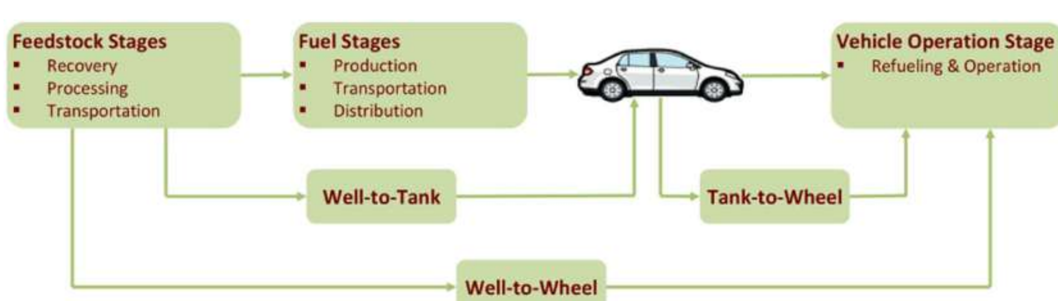

Fig. 1. System boundary of well-to-wheel analysis of the case study fuels.

specifically compared CNG vehicles and electric vehicles charged with natural gas-based electricity and found that the latter is better.

It is clear from the above studies that the different tools used to analyze the WtW analysis of fuels give rise to results that depend largely on the baseline hypotheses and the scenario considered. Different methodologies and assumptions in different studies make scenario comparison difficult or impossible. Therefore comparison of absolute results from these studies and our study are less meaningful, mainly because of different locale specific data. However, comparison of the relative change results among these studies should improve our understanding of the range of energy and emission benefits of advanced vehicle technologies and alternative transportation fuels, although such comparisons are beyond the scope of this study.

Methodology

This study takes advantage of the WTW analysis tool known as the GREET (Greenhouse Emissions and Energy Use in Transportation) model (version 2016) developed by ANL (Argonne National Laboratories) developed for the US Department of Energy by Argonne National Laboratory. For energy use, GREET includes total energy use (all energy sources), fossil energy use (petroleum, natural gas (NG), and coal), and petroleum use (each energy item is a part of the preceding energy item). For emissions, the model includes three major GHGs (carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) and five criteria pollutants (VOCs, CO, NOx, PM10, and SOx).

Because the original GREET model and default parameters were designed based on the energy production chain in the United States, we changed all the detailed data in GREET for Pakistani application. Thus, the results generally reflect the actual operation conditions in Pakistan. The Pakistani data were mainly provided by following government and private organization operating in Pakistan:

i. Hydrocarbon Development Institute of Pakistan (HDIP)
ii. Sui Northern Gas Pipelines Limited (SNGPL)
iii. Sui Southern Gas Company Limited (SSGCL)
iv. Inter State Gas Systems (ISGC)
v. Oil and Gas Regulatory Authority (OGRA)
vi. Oil Companies Advisory Council (OCAC)
vii. Engro Elengy Terminal Private Limited (EETPL)

The additional information was collected by literature surveys, oil refining and marketing companies, as well as from our personal data collected during several years of experience with oil and gas production companies in Pakistan.

Scope, key parameters and assumptions

The key parameters, assumptions, and data sources used in the analysis are discussed in this section. The important terms and the basic calculation framework are explained below:

- The scope of the present WtT is consistent with the scope of GREET including all parts of the fuel cycle: feedstock production and recovery, leaks and flaring, feedstock transport, fuel production, fuel storage and distribution, fuel dispensing at retail level and vehicle operation.
- The functional metrics used to describe the results are: (i) energy used (MJ/MJ), and (ii) greenhouse gases GHG emitted (in g CO_2-equivalent/MJ).
- Other WtT impact categories such as ozone depletion, acidification, eutrophication, human health, water and land use are beyond the scope of this comparative LCA.
- The secondary energy and environmental effects are not quantified. For instance, energy use and associated emissions during the production of crude oil and natural gas are quantified, but the energy used and emissions produced in the manufacturing of equipment required for oil and gas exploration and extraction and the material used in the construction of a refinery are not quantified.
- All energy contents used are on LHV basis i.e. excluding the heat generated after the combustion process by the condensation of water vapor arising from the hydrogen-content of the material.
- *Process fuel* – the term to indicate the fuel that is consumed to provide energy to the devices or facilities for performing the designated process. For example, during natural gas recovery, both diesel and electricity are mainly used as process fuels to operate facilities that extract natural gas from the well. We also define "efficiency" of a certain process as the energy of product divided by the sum of the energies of product and process fuels used in the process, as in Eq. (1). Therefore, if the efficiency of a certain process is known, the total "energy use" of process fuels to produce the unit energy of the product can be easily calculated.

$$\text{WtT Efficiency} = E_1/E_2 \tag{1}$$

where E_1 Energy of product (energy of fuel in the tank) E_2 = Energy of product of process fuel (energy of feedstock + energy expended in WTT process)

- *Process fuel share* - means the energy share of each process fuel used in the process. For example, if the total energy of process fuels used to produce the unit energy of product is 3000 kJ/GJ, and the process fuel share is 30% for diesel and 70% for natural gas, then the amounts of diesel and natural gas used are 900 and 2100 kJ/GJ, respectively. For calculating GHG emissions, the values of "combustion technology share" for each individual process fuel and "emission factor" of each combustion technology should be known as well. From the above example, if the combustion technology share of diesel fuel in the designated process is 20% for stationary engine and 80% for turbine, the energy used in the stationary engine and the turbine would be 180 and 720 kJ/GJ, respectively. Then, we can finally calculate the GHG emissions from these combustion technologies by multiplying the emission factors associated with each combustion technology and the energy uses. Emission factors are typically defined as the quantities of the relevant species emissions from the combustion of unit energy of fuel. For example, the CO_2 emission factor of diesel stationary engine and turbine are 73,366 and 74,103 g CO_2/GJ, respectively (ANL, 2016). Finally, the total emissions from the process are calculated by summing all the products of emission factors and energy uses for the combustion technologies of all the process fuels considered.
- For the greenhouse gases we considered the three major GHGs specified in the Kyoto protocol namely, CO_2, CH_4 and N_2O.
- The global warming potential of these three gases were calculated based on the latest 5th assessment report released by Intergovernmental Panel on Climate Change -IPCC 2013 (Stocker, 2014). All else being equal, the choice of time horizon for GWP greatly changes the equivalent CO_2 emissions of methane, which has a much higher GWP over 20 years than over 100 years. While most life cycle studies used 100-year GWP, short-term implications of methane emissions are increasingly of interest (Howarth, 2014). We report GHG emissions using GWP with both 100-years and 20-years. Uncertainty for both GWPs was quantified using a normal distribution based on the reported mean and 90% confidence interval. The distribution for the 100-year GWP has a mean of 36 and a standard deviation of 8.5, and the 20-year GWP has a mean of 87 and a standard deviation of 15.9. Given the wide range of uncertainty presented in AR5 and the continuing trend of increasing the GWP estimates with each assessment report, it is important to represent the complete distribution of possible values when simulating emissions. For

example, with uncertainty it is possible that the 100-year GWP of methane could be double the AR4 estimate of 25.

Pakistan's fuel mix

Before discussing the WtT fuel pathways for various transportation fuels in Pakistan, the statistical highlights of road transportation fuels are tabulated in Table 1.

Pathways and processes

As part of our study, we analyzed 10 different WtT pathways. A WtT pathway is a complete set of assumptions about the resource used, transportation and fuel production.

Crude oil based fuels pathways

In crude oil production process, recovery energy, flaring and venting emissions are the key parameters discussed in the following subsections. The crude extraction generally accompanies with natural gas, the majority of oil fields in Pakistan use this associated gas as the energy source for the operation of the extraction facilities. The amount of associated gas required for the extraction of crude, is based on the author field experience as senior production engineer in various oil fields of Pakistan. In Pakistan, on average 50 SCF of natural gas is used to extract of 1 barrel of crude oil. Similarly for the foreign crude oil, the estimation of natural gas consumption per barrel of crude oil is based on the report issued by Petroleum Energy Center (PEC), Japan (1998) which gives a figure of 50–60 SCF/bbl based on the results of a hearing survey conducted with oil fields in the UAE and Saudi Arabia. Therefore this study assumes a value of 50 SCF/bbl and 60 SCF/bbl for local oil field and foreign oil fields, respectively. In order to organize the data for both local and foreign crude oil based automotive fuel in Pakistan, the following four Well-to Tank stages are used:

- WtT Stage #1: crude oil recovery
- WtT Stage #2: crude oil transport
- WtT Stage #3: liquid fuels production
- WtT Stage #4: fuel transportation and distribution

The fuel production pathway flow for petroleum based fuels examined in this study is shown in Fig. 2. The figure depicts the flow of petroleum refining feedstocks and products of interest through the WtT stages and highlights the key activities occurring within the Pakistan and in foreign countries (exporting crude oil and diesel/ gasoline to Pakistan).

WtT Stage #1: crude oil recovery

Recovery energy includes the energy of process fuels used in injection, extraction and processing, of the crude oil in production fields. In this study, we referred to the following two references. Firstly, the GHGenius model (a Canadian life cycle modeling tool for transportation fuels) provides the scaling factors for the recovery energy in different oil fields around the world by using the US case as a reference value. For instance, the scaling factor of crude oil from Saudi Arabia is 0.91, which implies that the energy required for the recovery process of the crude oil in Saudi Arabia is 0.91 times lower than in the USA ((S&T) Consultants, 2013) Keeping in view the crude oil extraction facilities available in Pakistani oil field and by considering the regional scaling factors, the scaling factor of crude oil production in Pakistan is estimated as 0.70.

Secondly, the GREET model provides the average recovery energy of crude oil in the USA, which contains crude oil both from domestic and foreign sources. We first derived recovery energy of crude oil only from US domestic sources by combining regional scaling factors from GHGenius and the share of crude import in the USA. It is calculated that the recovery energy of US domestic crude oil is 0.011596 $MJ/MJ_{Process}$. Then, by adopting this recovery energy of the USA with the aforementioned average scaling factor for Pakistan from GHGenius, the average recovery energy of the crude oil produced in

Table 1
Statistics and sources of fuels used by Pakistan's road transport.

Description	Million TOE	MJ	Remarks
Energy consumption by road transport			
Pakistan total energy consumption	41.98	1.856×10^{12}	
Road transport share in total energy consumption	13.16	5.815×10^{11}	Road transport sector consuming 31.4% of the country total energy requirement.
Diesel share in road transport energy consumption	6.59	2.914×10^{11}	Diesel fuel share 50% of total energy consumption by road transport.
Gasoline share in road transport energy consumption	5.01	2.213×10^{11}	Diesel fuel share 38% of total energy consumption by road transport.
CNG share in road transport energy consumption	1.56	6.881×10^{10}	Diesel fuel share 12% of total energy consumption by road transport.
Crude oil based fuels			
Total crude oil processed by local refineries	12.41	5.487×10^{11}	There are 7 refineries operating in Pakistan having total crude processing capacity of 19 million tons per year.
Indigenous crude oil production	4.63	2.045×10^{11}	Currently Pakistan local crude oil production is 100,000 barrels per day.
Foreign crude oil processed by local refineries	8.61	3.807×10^{11}	27% crude oil need of local refineries is achieved through foreign crude oil mostly from Saudi Arabia.
Diesel production by local refineries	4.69	2.072×10^{11}	Sulfur content of local diesel is above 500 ppm.
Diesel imports from foreign refineries	3.45	1.523×10^{11}	Foreign crude oil is mostly imported from Saudi Arabia.
Gasoline production by local refineries	1.73	7.632×10^{10}	RON of local gasoline is 87.
Gasoline imports from foreign refineries	3.55	1.569×10^{11}	Foreign Crude oil is mostly imported from Saudi Arabia.
Natural gas based fuels			
Total ingenious natural gas production	30.01	1.326×10^{12}	
LNG import	0.47	2.088×10^{10}	1.665×10^{11} Recently Pakistan has started LNG import from Qatar.
Planned natural gas import through TAPI pipeline			The 56 in., 1600 km gas pipeline project would supply 1325 MMSCFD gas to Pakistan from Turkmenistan by the end of 2019.
Planned natural gas import through IP pipeline			The 42 in., 1931 km gas pipeline project would supply 750 MMSCFD gas to Pakistan from Iran by the end of 2018.
Total Natural gas consumption	25.69	1.136×10^{12}	
CNG Consumption	1.56	6.880×10^{10}	
Total length of Pakistan natural gas transmission lines	10,789 (km)		
Total length of Pakistan natural gas distribution lines	112,474 (km)		

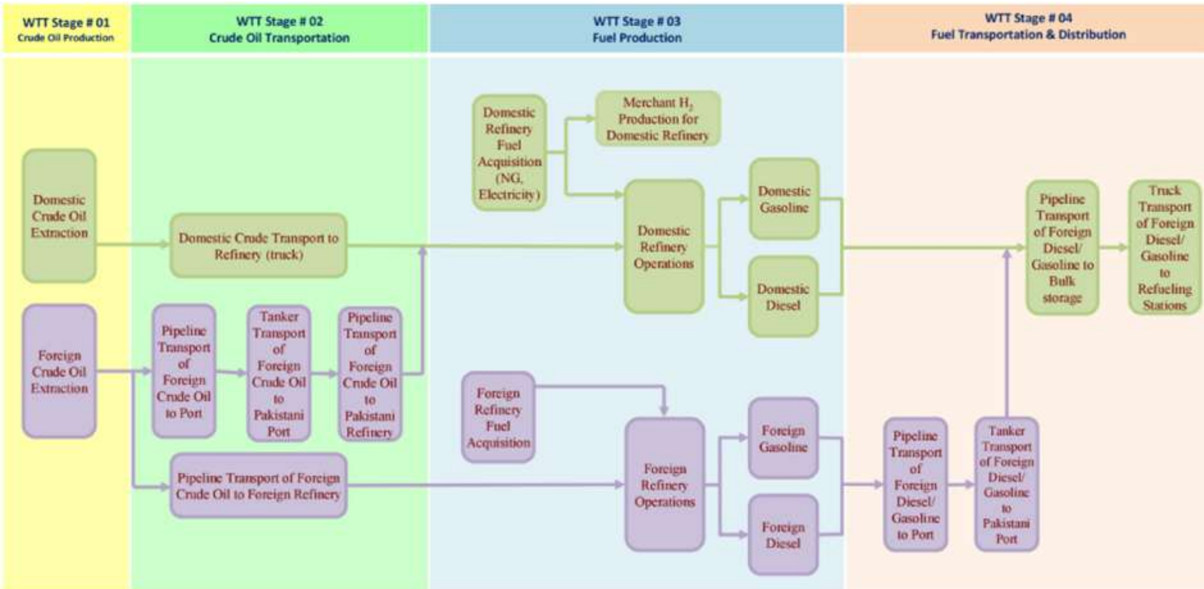

Fig. 2. Flow of petroleum refining feedstock and products through the WtT cycle stages.

Pakistan is determined as 0.0082 $MJ/MJ_{Process}$, while average recovery energy of the crude oil imported (from Middle East) in Pakistan is determined as 0.01055 $MJ/MJ_{Process}$. The corresponding values of GHGs resulted from the combustion of aforementioned recovery energy are 2.41 g CO_2eq/MJ and 3.11 g CO_2eq/MJ for Pakistani and foreign crude oil, respectively.

Flaring and venting. During the recovery process of the crude oil, considerable amount of associated gases from the oil production field are either flared or vented. Here, "flaring" is the intentional combustion of natural gas or waste gas, mainly practiced at crude oil facilities, and the combustion products of those gases are emitted to the environment. Flaring is done when there is no economic use for this associated gas. The flared gas produces carbon dioxide and possibly carbon monoxide, which are released to the atmosphere. Although the flared quantity can differ among production fields or countries, the associated GHG emission generally takes a large portion in the WtW GHG results of natural gas.

For flaring, the U.S. National Oceanic and Atmospheric Administration (NOAA) and the U.S. Energy Information Administration (EIA) publish two separate reports of the world flaring data annually (U.S. EIA, 2016; U.S. NOAA National Geophysical Data Center, 2012). NOAA estimates global flaring volume based on lights index values of image data acquired from satellites. EIA uses International Energy Statistics (IES) data which provide global CO_2 emissions from gas flaring.

These references contain the aggregate of the flaring quantities both from natural gas and crude oil production fields. Therefore, to get the flaring amount only from natural gas production, we have to allocate the whole flaring quantity into natural gas and crude oil. It is known that the flaring is typically exercised during oil production, rather than in natural gas production, because the associated gas from the oil well is usually flared during oil production due to the shortage of the NG treatment facilities near it. Therefore, the allocation share, 10% for natural gas and 90% for crude oil, is adopted in this study (Pakistan Energy Yearbook, 2015).

Venting refers to the deliberate release of associated gas or waste gas itself, without combustion, and the release of uncombusted gas in flaring (the combustion efficiency of flaring is not 100%, so some methane is left in the exhaust gas). The values assumed for venting associated with local crude oil and foreign crude oil recovery are 0.0485 and 0.0393 g $CO_2/MJ_{Process}$ respectively. To sum up the CO_2 and CH_4 emissions from flaring and venting with the crude oil production in Pakistan is derived as 1.03 g $CO_2/MJ_{Process}$ and 0.06 g $CH_4/MJ_{Process}$.

Fugitive emissions. Natural gas can be lost from crude oil production and processing systems through a variety of mechanisms. For a number of processes or pieces of equipment the operating conditions are designed to emit some natural gas; for example, some pneumatic controllers are powered using the pressure differential between high-pressure natural gas and the atmosphere, resulting in emissions upon each actuation of the controller. In addition, numerous pieces of equipment have safety systems (e.g., pressure relief valves on tanks) that vent gas when out-of-specification pressure increases could pose danger to equipment and/or workers in the vicinity. Natural gas can also be lost from underdesigned and malfunctioning equipment.

It is difficult to measure fugitive emissions. The usual practice is to base such measurements on emission factors suggested by the Canadian Association of Petroleum Producers (CAPP), the U.S. Environmental Protection Agency (EPA), and the International Association of Oil and Gas Producers (OGP). In this study, fugitive emissions were determined on the basis of CAPP emission factors (CAPP, 2002) for equipment fittings such as seals, valves, and flanges. Fugitive methane emissions associated with local crude oil production are converted to g-CO_2eq/MJ-crude to be in line with the functional unit of this study. Low, medium, and high values for fugitive CH_4 emissions are found to be 1.10, 2.50, and 6.25 g-CO_2eq/MJ-crude. The fugitive emissions values assumed for foreign crude oil is 1.65 g-CO_2eq/MJ-crude.

Because the effect of CH_4 leakage during recovery process on total GHG emissions is large, we will examine the sensitivity of the results from possible errors associated with the reference above, in Section 6.3. To sum up, the total GHG emission associated with the recovery process, Table 2 estimates the GHG values for Pakistani and foreign crude oil.

WtT Stage #2: crude oil transport

Crude oil transport includes transport of foreign and domestic crude oil from the point of extraction to the refinery. Transport emissions are based on the amount input to a transport operation (amount extracted). Losses are then assessed at the end of the transport operation. Crude oil transport from oil field to refinery requires a very small amount of energy relative to the energy contained by the crude oil. GREET model uses an efficiency of 99% (Wang, 1999) with a deviation of 0.5% for the worst and best case.

Foreign crude oil transport. Transportation of foreign crude oil to Pakistani refineries consists of three steps: (i) pipeline transport to an ocean port in the respective country (ii) tanker transport to Pakistani port, and (iii) pipeline transport to an ocean port in the respective country.

The crude is assumed to be transported 200 km via pipeline to an ocean port in the respective country. The energy intensity for pipeline transport is assumed to be 260 Btu/ton-mile and electricity is assumed to be the power source. The emissions associated with pipeline transport of imported crude oil are estimated using emissions from the Saudi Arabia power grid. The GHG emissions associated with Saudi Arabian electricity grid mix and the resulting emissions profile of crude oil imported is shown in Table 3.

All foreign crude oil sources for Pakistani refineries, is imported by ocean tankers from Middle East. In evaluating the GHG emissions associated with this process, transport distance is the most significant parameter. To estimate transport distances from foreign seaport to Pakistani seaport. Portworld distance calculator (2016) was used along with the EIA data to determine port-to-port travel distances for all crude oil shipments for the crude oil importing countries. By weight-averaging the distances with crude import quantities from those countries, the average transport distance is calculated as 1750 km.

The energy intensity of crude oil tanker is based on the oil takers which are being used by Pakistan National Shipping Corporation (PNSC) for importing the petroleum oil. The assumed study value for crude tanker transport operations is 7.3 Btu per barrel-nautical mile for oil tankers of 107,000 DWT. The heavy fuel oil (HFO) used to power tanker operations is essentially residual fuel oil and therefore the GHG emissions profile consistent with combustion of residual fuel oil in marine engines is used to determine the ship emissions during international transport. The GHG emissions from combustion of heavy fuel oil in ships engine and the resulted GHG emissions from the sea transport of imported crude oil from foreign port to Pakistani ports is shown in Table 4.

Almost the entire lot of the imported crude oil is transported via pipeline from the domestic ports to domestic refineries. Keeping in view the fraction of foreign crude oil usage of each refinery, the average pipeline length for port to refinery is assumed to 265 km. The energy intensity for pipeline transport is assumed to be 260 Btu/ton-mile and electricity is assumed to be the power source. The GHG emissions of Pakistan electricity grid mix, the resulting emission profile for the domestic pipeline transport of foreign crude oil and the total GHG emissions associated with transport of foreign crude oil from the point of extraction to Pakistani refineries is exhibited in Table 5.

Transportation of local crude oil. Local crude oil mix within the Pakistan is transported via truck while the imported crude oil is transported via pipeline from the domestic to port to domestic refinery. The Oak Ridge National Laboratory (ORNL) Transportation Energy Data Book 2016 (Davis, William, & Boundy, 2016) are used to determine energy intensity of crude truck used for crude transportation in Pakistan from oil fields to local refineries. To represent energy intensity of crude oil transportation trucks in Pakistan, the ORNL data is modified and the estimated value is 98 Btu/bbl-km. All petroleum tanker trucks in this study are assumed to be powered exclusively by diesel fuel. As most of the Pakistani oil fields are either based in Sindh (province) or KPK (province) and the corresponding distance of these oil fields from the field's gate to the nearest refinery are ranging from 200 to 300 km. Therefore an average distance of 250 km is assumed for our calculation. The emissions factors associated with the combustion of diesel fuel are summarized in Table 6 and specific transit GHG emissions associated with each of the aforementioned modes of crude oil transportation are reported in Table 7. The total GHG emissions per barrel factors are applied to all crude oil fed to Pakistani refineries.

Table 2
GHS emissions consistent with extraction of local crude oil in Pakistan and foreign crude oil exporting to Pakistani refineries.

Crude oil source	GHG emissions (g CO_2eq/MJ)
Pakistan crude oil	5.86
Saudi Arabia crude oil	4.76

Table 3
GHG emissions associated with pipeline transport of imported crude oil from point of extraction to foreign.

Source	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
2007 Saudi Arabia average electricity grid mix	227.26	226.7	7.41×10^{-3}	1.35×10^{-3}
Crude oil pipeline transport	0.154	0.1479	1.71×10^{-4}	1.91×10^{-6}

WtT Stage #3: liquid fuels production

The boundary of WtT Stage #3 starts at the entrance of the petroleum refinery with the receipt of feedstocks and ends at the entrance of the petroleum pipeline or tanker used to transport the liquid fuels to a bulk fuel storage depot. Modeling assumptions and methodology are described for both domestic refineries and foreign refineries providing imported gasoline and diesel.

Energy consumption in refining. The key parameter in the petroleum refining process is refining energy. Refineries consume electricity to power pumps, compressors, other motor-driven equipment, and the facilities, including offices, laboratories, and lighting. We assume that electricity for local refineries is supplied from refinery own power plant fueled with furnace oil. Refineries consume natural gas to supplement the fuel gas produced on-site and to provide process feed to the steam methane reforming unit that makes hydrogen. Both local and foreign refineries (Saudi Arabia) consume fuel oil to provide process heat, and, on average, around 30% of refinery fuel demand across Pakistani refineries is met by refinery fuel oil, 1–5% by natural gas, and the rest by fuel gas produced in the refinery. A typical Pakistani refinery consume about 8–9% of their own intake as processing energy.

For a typical modern refinery, the overall efficiency, regarding the energy content of total crude oil input and product output, is 94% (Royal Dutch Shell Group, 1998). Total energy consumption and accompanying CO_2 emissions are allocated among all products to determine how much is related to gasoline and diesel production. Roughly two-thirds of crude input ends up within automotive fuel ranges. A large share of the remaining will results in heavy fuel oils. The latter does not require much processing and production at 98% efficiency is assumed. Using this information, and given the fact that diesel requires less processing than gasoline, efficiency of gasoline and diesel production are estimated to be 88% and 95%, respectively.

Table 4
GHG emissions associated with sea transport of imported crude oil from foreign port to Pakistani ports (U.S. Energy Information Administration (EIA), 2007).

Source	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
HFO combustion in ships	79.49	78.8	5.7×10^{-3}	2.0×10^{-3}
Sea tanker	0.057	0.056	3.12×10^{-6}	1.16×10^{-6}

Table 5
Total GHG emissions associated with foreign crude oil transport to Pakistani refineries.

Source	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
2007 Pakistan average electricity grid mix	134.55	133.9	8.74×10^{-3}	1.53×10^{-3}
Pipeline	0.173	0.167	1.94×10^{-4}	2.17×10^{-6}
Foreign crude transportation	0.384	0.371	3.68×10^{-4}	5.24×10^{-6}

Since a refinery inherently produces multiple petroleum products in a single or combined chemical processes, it is difficult to determine the individual energy consumption for a specific product. Moreover, the details of the refining process, in general, are not open to the public, and the processes are often different among oil companies. Therefore, in many of WtT analyses, the total energy use from all the refinery processes is evaluated first and then is allocated to an individual product. The allocation can be accomplished either in the refinery level or process level. In a refinery-level analysis, the allocation can be achieved by using mass, energy content, or market price share of individual product as weighting factor. Although the refinery level allocation has the virtue of simplicity and applicability only requiring the refinery-level input and output data, it cannot reflect the detailed refining processes that can affect different products. It is therefore recommended that an allocation should be accomplished at the process level, whenever possible, by the international LCA standard ISO 14040. There have been various approaches to allocate refining energy at the process level. In this study, we referred to the U.S. National Energy Technology Laboratory (NETL) study (Skone & Gerdes, 2008), since it provides a detailed description on the allocation approaches and the raw data, and the important parameters used in the study are based on the international sources (with addition of correction factor) which can be readily applicable to Pakistani conditions.

Liquid fuels production at domestic refineries. The emissions profile associated with the current Pakistani petroleum refining operations consists of emissions from fuels acquisition, fuels combustion, hydrogen production, flaring, and venting and fugitive emissions. The GHG emissions profile associated with Pakistani petroleum refining operations consists of emissions from the following activities/sources:

i. Acquisition of fuels

- Indirect emissions associated with purchased power and steam
- Emissions associated with the acquisition of coal and natural gas purchased and consumed at the refinery as fuels
- Emissions associated with production of fuels at the refinery which are subsequently consumed as fuels (i.e. still gas, petroleum coke)

ii. Combustion of fuels at the refinery
iii. Hydrogen production (on-site and off-site)

- Upstream emissions associated with natural gas feed
- CO_2 process emissions from steam methane reforming (SMR)
- Fuel combustion and upstream emissions associated with natural gas fuel and indirect (electricity) emissions for off-site hydrogen production

iv. Flaring
v. Venting and fugitive emissions

Table 6
Crude oil transportation modes and associated emission factors.

Transport mode	Energy usage (Btu HHV/bbl of crude oil transport)	Fuel source	Emission factor (g/gal)		
			CO_2	CH_4	N_2O
Heavy duty truck	347	Diesel	10,147	0.47	0.3
Pipeline	12,997	Electricity	217[a]	0.251[a]	0.00281[a]

[a] Emission factor units are kg/MMBtu for electricity.

Table 7
GHG emissions associated with crude oil transport with Pakistan.

Transport mode	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Heavy duty truck	0.925	0.905	5.74×10^{-4}	1.18×10^{-5}

The emissions above will be organized into a refinery emissions pool and a hydrogen emissions pool and subsequently allocated between the various refinery products. There are no individual assignments of energy sources to unit operations or refinery products. For example, emissions associated with acquisition and combustion of natural gas will not be allocated based on the unit operations where the natural gas is consumed. Fig. 3 depicts the two emissions pools, refinery and hydrogen, developed in this section. Fuels for use at the refinery enter from the left of the diagram while hydrogen produced off-site enters the refinery from the right of the diagram. As shown, a portion of the emissions associated with on-site hydrogen production are embedded in the refinery emissions profile while the remaining is included in the hydrogen emissions pool. This is discussed in detail in subsequent sections.

Refinery fuels combustion. The primary source of GHG emissions at a refinery is from fuels combustion. Emissions are determined for all of the fuels consumed during the refining operations. All hydrocarbon species are assumed to be combusted in industrial-scale equipment. The following sections outline the emission factors associated with consumption of the various refining fuels. Total emissions are determined by multiplying the emission factor by the quantity of fuel consumed. Since it is not possible to accurately ascribe fuel types, combustion equipment and the resulting emissions to the various refinery operations, a composite energy usage/emissions profile was determined for all refining operations. The GHG emissions associated with the fuels consumed are allocated equivalently for each unit of energy consumed.

CO_2 emissions from refinery fuels combustion. Refinery CO_2 emissions are determined by multiplying the quantity of fuel consumed by the appropriate CO_2 emissions factor for fuel consumption. Table 8 shows the various hydrocarbon fuels consumed at refineries and lists the CO_2 emissions consistent with combustion of the individual species.

Methane (CH_4) emissions from refinery fuels combustion. Methane emissions have been quantified for standard combustion processes using finished fuels, but off-spec refinery still gas and coke combustion emission factors are not as precise and estimates vary. The Canadian National Energy Board has estimated methane emission factors for combustion of various standard and non-standard hydrocarbon fuels (NEB 1999 Canadian National Energy Board (NEB), 1999) and those values have been used to determine methane emissions consistent with refinery combustion operations. The methane emission factors utilized in this study for fuel combustion are presented in Table 8.

N_2O emissions from refinery fuels combustion. The Canadian National Energy Board has estimated N_2O emission factors for combustion of various non-standard hydrocarbon fuels (NEB 1999 Canadian National Energy Board (NEB), 1999) and those values have been used to determine N_2O emissions consistent with refinery combustion operations. The N_2O emission factors utilized in this study are presented in Table 8.

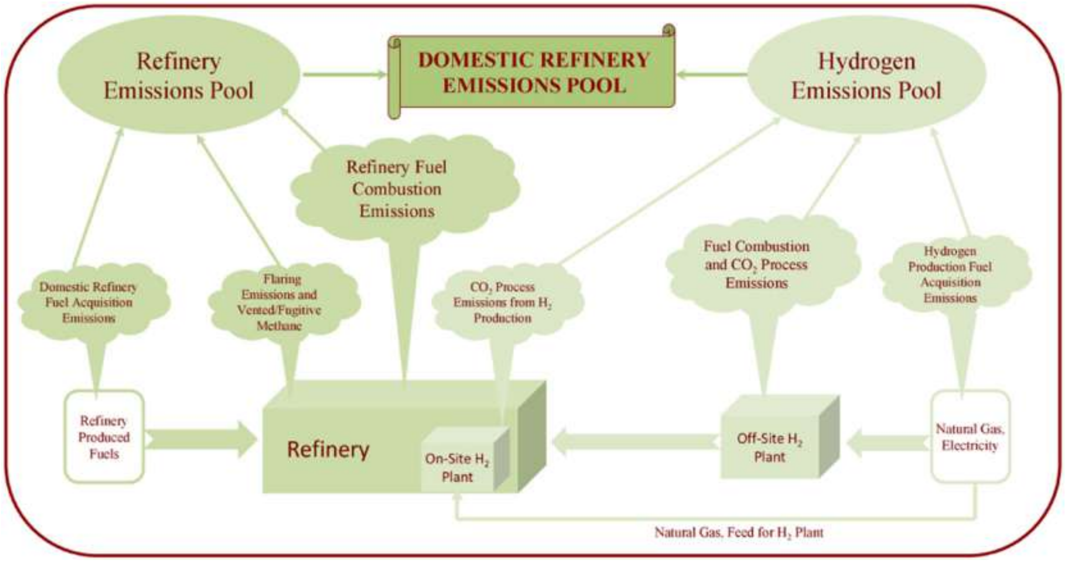

Fig. 3. Depiction of refinery and hydrogen emissions pools.

Hydrogen production. Refineries are the second highest consumer of hydrogen after fertilizer sector in the Pakistan. The primary use for hydrogen in refineries is for removal of sulfur (desulfurization) to meet product quality requirements. Hydrotreating also removes nitrogen, oxygen, halides, and metals from petroleum fractions. Pakistani refineries have the capacity to hydrotreat a combined volume equivalent to approximately 75% of the atmospheric distillation capacity. The amount of hydrogen consumed during hydrotreating is a function of the species being treated and the sulfur content of the fraction. Typical hydrogen requirements for hydrotreating for gasoline and diesel are 419 and 559 SCFB respectively. Similarly with no steam export the theoretical energy consumption for producing unit amount of hydrogen via SMR process is about 320 Btu/SCF corresponding to 94% of the theoretical efficiency (Rostrup-Nielsen & Sehested, 2003).

Hydrogen at refineries comes primarily from three different sources - hydrogen by-product from catalytic reforming, on-site hydrogen plants, and purchased hydrogen produced off-site. For this study all hydrogen produced on-site and off-site is assumed to be generated by steam methane reforming using natural gas as both a feedstock and fuel. The fuel and associated utilities for on-site hydrogen production at a dedicated hydrogen plant are also included in the refinery fuels-consumed tally, but the natural gas used as a feedstock is explicitly excluded. The energy/resource usage and environmental effects of hydrogen produced and purchased from an off-site or third party supplier are not accounted for in the refinery fuels consumed estimate. The amount of hydrogen produced at off-site hydrogen plants is assumed to be 15% of the installed hydrogen production capacity.

Hydrogen plant feedstock requirements. Based upon the natural gas composition shown in Table 9, hydrogen plant process CO_2 emissions have been calculated, consistent with the rigorous API methodology that uses the average U.S. pipeline natural gas specifications (API, 2009). Natural gas is estimated to be 76 wt% carbon (API, 2009) and CO_2 process emissions are estimated to be 0.01879 kg CO_2 per scf H_2 produced (2.855 kg CO_2 per kg of natural gas feed input). Complete combustion of natural gas is assumed and thus there are negligible methane process emissions. Using this method, the minimum CO_2 process emissions for a hydrogen plant using the standard Pakistan pipeline quality natural gas would be 0.0137 kg CO_2 per scf H_2.

GHGs emission values associated with SMR hydorgen plant are tabulated in Table 10.

Process-level allocation. As mentioned above that in this study, we referred to the U.S. National Energy Technology Laboratory (NETL) study (Skone & Gerdes, 2008), to allocate energy at process level to individual refinery products. In the NETL report (Skone & Gerdes, 2008), petroleum products are classified into seven product categories: gasoline, diesel, kerosene and kerosene based jet fuel, residual oil, coke, light ends, and heavy ends. The light ends include still gas, refinery gases, special naphtha, and petrochemical feedstocks, while the heavy ends refer to asphalt and road oil, lubricants, waxes, and miscellaneous matters. In evaluating refining energy of each product category, the total energy use is divided into two energy pools, i.e., the energy use except for hydrogen production and the hydrogen production energy. Then, to calculate the refining energies of the individual products, they use certain allocation factors that are based on the analysis of the detailed

Table 8
Refinery fuels and associated CO_2, methane and N_2O emissions from fuel combustion (NEB 1999 Canadian National Energy Board (NEB), 1999).

Refinery fuel	CO_2 emissions (kg CO_2/MMBtu)	CH_4 emissions (kg CH_4/MMBtu)	N_2O emissions (kg N_2O/MMBtu)
Liquefied petroleum gas (LPG)	62.3	0.00118	0.00950
Distillate fuel oil	73.2	0.00545	0.00351
Residual fuel oil	78.8	0.00432	0.00326
Still gas	64.2	0.00134	0.00065
Petroleum coke	102.1	0.00299	0.00322
Natural gas	53.1	0.00134	0.00057

Table 9
Composition of a typical Pakistan pipeline quality natural gas.

Component	Mole %
Methane	85
Ethane	5
Propane	2
Butane	1
Higher hydrocarbons	1.5
Carbon dioxide	2
Nitrogen	3.5

Table 10
Cradle-to gate GHG emissions inventory for hydrogen production via SMR in Pakistan.

Description	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
SMR H_2 production	74.4	71.3	0.106	3.60×10^{-4}

processes in refinery. In this regard, the NETL compiles the data for the specific energy use of a certain refining process and the energy consumption shares of individual products in the designated process, by investigating substantial references, such as those reported in the Hydrocarbon Processing, Oil and Gas Journal and various handbooks (Gary, Handwerk, & Kaiser, 2007; Meyers, 2004). These data along with the nationwide daily operating quantities of the individual refining processes can lead to the allocation factors.

In the first and second rows of Table 11, the resultant energy use fractions of individual products divided by their production volume fractions in the USA are shown for both energy pools, i.e., refining energy except hydrogen production and hydrogen production energy, respectively. Then, the volume fractions of Pakistani refinery products are multiplied to the values in the first and second rows, which again are renormalized to give the energy use fractions as shown in the fourth and fifth rows in the table. Since the ratio of the energy use fraction over volume fraction implies the efficiency of making a product, the above calculation is based on the assumption that the Pakistani and the US refineries will have the same ratios among refining efficiencies of individual products. By combining the total energy use in Fig. 3 and the fractions in the fourth and fifth rows of Table 11, the energy uses of individual products in Pakistani refineries can be calculated as in the last row of Table 11.

As a result of the allocation, heavy ends are estimated to be most energy-intensive. It is known that the manufacturing process for lubricating oil in the heavy ends category is the most energy-intensive process in a refinery. Gasoline has the second largest refining energy intensity, mainly because the alkylation and the isomerization processes are predominantly attributed to gasoline product. The two processes have the highest level of specific energy requirement, about three times larger than that of atmospheric distillation (Skone & Gerdes, 2008). On the contrary, the refining energies of kerosene and residual oil are relatively low because these products need the less energy-intensive processes such as distillation and hydrotreating.

Flaring operations. Flaring operations and associated emissions are not generally tracked for petroleum refineries across the Pakistan. For this study, Pakistani refinery flare operations and emissions have been estimated by taking data from three major Pakistani refineries through personal communication with process department of the concerned refinery. For this study, the average Pakistani refinery flare gas flow is assumed to be 5.45 per unit of atmospheric distillation capacity (SCFB) while the value 6.15 SCFB is assumed for foreign refinery.

CO_2 emissions. Given that the composition of flared gas is unknown, it is necessary to estimate CO_2 combustion emissions without an understanding of the composition of the gas. The minimum CO_2 emissions consistent with flaring would result from the combustion of flare gas composed entirely of natural gas (since it has the lowest carbon-to-hydrogen ratio). For a flare gas flow rate of 5.45 SCFB, using the natural gas energy content and emission factor for combustion shown in Table 8, refinery CO_2 emissions from flaring would be 0.297 kg CO_2 per barrel of atmospheric distillation capacity. This represents the minimum CO_2 emissions produced by flare activities.

Methane emissions. Assuming that the refinery flare gas is natural gas, the estimated refinery methane emissions was assumed to Extrapolating the methane emission data from two air quality districts in California the estimated methane emission for Pakistani refineries is 1.62×10^{-4} per bbl of distillation capacity.

N_2O emissions. For a flare gas flow rate of 5.45 SCFB, using the natural gas energy content and emission factor for combustion shown in Table 8, refinery N2O emissions from flaring would be 3.28×10^{-6} kg N_2O per barrel of atmospheric distillation capacity.

Vented/fugitive emissions. The primary source of methane emissions from refineries is vented emissions, with smaller amounts of unburned CH_4 in process heater stack emissions and unburned CH_4 in engine exhausts and flares. No information is available regarding data for estimates of vented/fugitive emissions. Keeping in view the poor regulation appliance to GHGs emission in Pakistani refineries, the total methane emission resulting from the flaring and fugitive emissions is assumed to 2.35 g CO_2eq/MJ.

Refinery emissions profile. The resulting emissions profile for the transportation fuels of interest produced at domestic refineries are shown Table 12.

Emission profile of foreign refineries. Determining emissions consistent with refining operations for foreign entities is not a trivial matter due to the inherent variability in feedstocks and technologies employed, as well as different product emphasis and environmental regulations. Information extracted from foreign studies of gasoline and diesel production vary widely due to differences in study assumptions, system boundaries, and information sources. Due to unavailability of energy consumption and refinery emission data for Saudi Arabian refineries, we used the mean average of a very recent study (Elgowainy et al., 2016) pertaining to a comprehensive lifecycle analysis of 43 US refineries conducted by Argonne National Laboratory in 2016. The assumed values of GHGs emissions for foreign refineries are listed in Table 12.

WtT Stage #4: transport of liquid fuels to vehicle refueling station

Stage #4 begins where liquid fuels exit foreign or domestic refineries and at refueling stations. Liquid fuel transport includes transport of imported gasoline and diesel fuel from the Middle East to the Pakistan as well as domestic transport of both imported fuels and domestically produced gasoline and diesel fuel. Firstly, petroleum products are transported from refineries to oil storage depots which are located near the major cities and then products are distributed from oil storage depots to refueling stations. In calculating the average distribution distance, the regional petroleum consumption and refinery location data, provided by Pakistan Oil Companies Advisory Council (OCAC) are used with the assumption that products will be delivered to each oil refueling station from the nearest refinery/depot. The average

Table 11
Calculation of refining energy using NETL results.

	Gasoline	Diesel	Kerosene	Residual oil	Coke	Light ends	Heavy ends
NETL energy use fraction (without H_2 production) / product volume fraction	1.075	0.954	0.604	0.682	1.193	0.748	2.015
NETL H_2 use fraction/product volume fraction	1.052	1.084	0.680	0.716	1.003	0.668	1.757
Pakistani refineries product volume fraction	0.138	0.380	0.015	0.324	0.000	0.103	0.041
Pakistani refineries energy use fraction	0.165	0.403	0.010	0.245	0.000	0.085	0.092
Pakistani refineries H_2 use fraction	0.154	0.439	0.011	0.247	0.000	0.073	0.077
Pakistani refining energy (with H_2 production) [kJ/GJ]	68,526	56,662	36,693	36,107	36,076	51,705	109,433

Table 12
GHG emissions for transportation fuels produced in Pakistani and foreign refineries.

Source	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Conventional gasoline by local refineries	7.74	7.69	7.97×10^{-4}	1.34×10^{-4}
Conventional gasoline by foreign refineries	7.92			
Conventional diesel by local refineries	6.72	6.45	8.59×10^{-3}	1.17×10^{-4}
Conventional diesel by foreign refineries	6.85			

distribution distances of both gasoline and diesel are calculated as 225 km, respectively. For the calculation a mix of the different transportation modes has been used according to the actual share of each mode in Pakistan. The average shares of various distribution modes are assumed to 30% for pipeline and 70% for truck. The specifications of the distribution modes and GHGs associated with each means of distribution are assumed to be the same as in the USA (ANL, 2016) without better data available in Pakistan. Although depots and refueling stations also account for small energy consumption, essentially in the form of electricity but this study do not consider the energy consumption by depots and liquid fuel refueling stations.

Transportation of imported diesel and gasoline. The transportation of imported diesel and gasoline includes tanker transport of imported products to the Pakistan receiving port. Emissions associated with tanker are the primary GHG emission sources. The imported gasoline and diesel are assumed to be shipped an average of 200 km by pipeline to a port for ocean transport. The energy intensity for pipeline transport is assumed to be 0.172 MJ/ton-km (ANL, 2016) and electricity is assumed to be the power source. The emissions associated with pipeline transport are estimated using emissions from the Saudi Arabia power grid as a surrogate profile for that of foreign countries.

By using the information described in Section 5.1.2, the associated GHG emissions with the transportation of imported gasoline and diesel is exhibited in Tables 13 and 14 respectively.

Transportation of local diesel and gasoline. Liquid fuels are transported within the Pakistan via two primary mechanisms: pipeline and truck. Tables 15 and 16 summarizes the GHG emissions associated with the local transportation and distribution of local production gasoline and diesel fuels.

Natural gas based fuel pathways

This section discusses the gaseous automotive fuel extracted from natural gas i.e. CNG. This study explores the energy consumption and GHGs emissions associated with pathways of CNG from the following three different natural gas sources:

i. CNG from indigenous natural gas sources
ii. CNG from foreign natural gas sources imported via pipeline
iii. CNG from foreign natural gas sources imported via LNG

Table 13
GHG emissions associated with transport of imported gasoline to refueling stations.

Transport mode	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Pipeline (from foreign refinery to port of shipment)	0.013	0.0125	1.44×10^{-5}	1.61×10^{-7}
Sea tanker	0.187	0.185	1.35×10^{-5}	4.70×10^{-6}
Pipeline (from domestic port to oil depot)	0.016	0.0156	1.81×10^{-5}	2.01×10^{-7}
Heavy duty truck	0.878	0.859	5.45×10^{-4}	1.12×10^{-5}
Total	1.094	1.072	5.91×10^{-4}	1.63×10^{-5}

Table 14
GHG emissions associated with transport of imported diesel to refueling stations.

Transport mode	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Pipeline (from foreign refinery to port of shipment)	0.015	0.0143	1.65×10^{-5}	1.84×10^{-7}
Sea tanker	0.190	0.189	1.37×10^{-5}	4.78×10^{-6}
Pipeline (from domestic port to oil depot)	0.0187	0.0179	2.06×10^{-5}	2.03×10^{-7}
Heavy duty truck	0.893	0.873	5.54×10^{-4}	1.14×10^{-5}
Total	1.117	1.094	6.05×10^{-4}	1.66×10^{-5}

WtT Stage #01: natural gas extraction and processing

Natural gas recovery energy. Natural gas is produced from either dedicated fields or as associated gas in oil fields. Roughly 80% of the domestic natural gas production in Pakistan comes from dedicated natural gas fields, while the rest comes from oil fields. Extraction of natural gas is very efficient and depends on field pressure and gas quality. When impurities are low, and field pressure is high, energy demand can be negligibly small. More difficult extraction sites can result in an energy consumption up to 5% of the energy content of the extracted gas, including flaring and losses (ANL, 2016). The extraction efficiency varies between 95% and 100%. Currently no reliable data source is available to predict the energy efficiency for NG extraction in Pakistan; hence we used our professional experience within various Pakistan's natural gas fields to estimate the NG extraction efficiently of a typical Pakistani gas field. The calculated value is 98% which is slightly higher than the value of 96.4% predicated by China Automotive Technology and Research Center (2007) for Chinese gas fields. The reason for assuming the higher value than Chinese gas field is due to relatively high productivity index (PI) of natural gas wells in Pakistan. Most of the energy for NG extraction is supplied directly in the form of natural gas (typically through an on-site gas Gen-set).

Fugitive emission at well-site. Natural gas contains mainly methane, a major GHG. Consequently, methane leakage during NG extraction and processing contributes substantially to GHG emissions. The level of this leakage affects the energy efficiency and emission reduction performance of NG fuels as alternative vehicle fuels.

Considerable differences were exhibited between the studies (Howarth, Santoro, & Ingraffea, 2011; Venkatesh, Jaramillo, Griffin, & Matthews, 2011) for fugitive emissions at the well site (0.7–5 g CO_2eq/MJ) with smaller differences at the processing plant (0.4–1.7 g CO_2eq/MJ). The review of the studies did not provide any clear reasons why there is a large range of estimates for this emission category. Thus, keeping in view the work practices (low awareness among the natural gas producer about the GHG potentials of methane) and lack of stringent of environmental regulations for the production and processing natural gas in Pakistan, our best estimate distribution was taken as the studies' average and min/max: (0.7, 2.3, 5.0).

Table 15
GHG emissions associated with transport of domestic gasoline to refueling stations.

Transport mode	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Pipeline (from domestic refinery to oil depot)	0.016	0.0156	1.81×10^{-5}	2.01×10^{-7}
Heavy duty truck	0.878	0.859	5.45×10^{-4}	1.12×10^{-5}
Total	0.894	0.875	5.63×10^{-4}	1.14×10^{-5}

Table 16
GHG emissions associated with transport of domestic diesel to refueling stations.

Transport mode	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Pipeline (from domestic refinery to oil depot)	0.0187	0.0179	2.06×10^{-5}	2.03×10^{-7}
Heavy duty truck	0.893	0.873	5.54×10^{-4}	1.14×10^{-5}
Total	0.912	0.891	5.74×10^{-4}	1.16×10^{-5}

Processing. After extraction, raw natural gas is transported to natural gas processing plant for refining it. The processing efficiency of NG processing plat is normally in range of 94% to 97.5% (ANL, 2016) and the process fuel share is 2% for diesel and 98% for natural gas in Pakistan. The energy associated with processing varies considerably with the producing region in Pakistan. This reflects different gas qualities, practices and climatic conditions. Processing can take place near the wellhead or, as is common in Pakistan, at a central location where light hydrocarbons can be readily used as chemical feedstocks. Based on the various sources of information available we have used a median figure of 2.5% of the processed gas energy with a range of 1 to 4%.

Raw NG may contain carbon dioxide in concentrations ranging from very low to sometimes significantly more than 10% which need to be removed before being delivered to the pipelines. As shown in Table 17, the maximum allowable concentration of CO_2 in natural gas should not be more than 3 mol%. Most of raw natural gas being produced in Pakistan meets the allowable limit of CO_2 concentration, therefore for the simplicity this study assume that the CO_2 concentration in natural gas is less than 3% and can be ignored.

Specifically, GHG emissions from gas processing result from:

- Combustion emissions from the use of a glycol re-boiler in the dehydration step;
- Fugitive emissions;
- Flaring/venting emissions and;
- Gas-fired reciprocating compressors at the end of the gas processing segment.

Dehydration and GHG emission. Dehydrators are used to remove water from the associated gas. There are various gas dehydration methods, and they vary from field to field. For simplicity the study assumes that glycol dehydrators are used to remove water for all gas fields in Pakistan. Reboiler heaters and pumps are the consumers of energy in glycol dehydrators. The reboiler heat duty can be calculated from the regenerator duty and the amount of water removed and is found by the equation below, where H is the regenerator duty in MJ/kg of H_2O and q is the glycol-to-water ratio in m^3/kg, which is assumed to be 0.0167. The regenerator duty is calculated using the following (Eq. (2)) as rule of thumb:

$$H = 2.1 + 269.58 \cdot q \quad (2)$$

The heat required for the glycol dehydrators is assumed to be supplied by natural gas with a heater efficiency of 80%.

Table 17
Approved specification for pipeline natural gas in Pakistan.

Gas specification	Unit	Accepted level
Sulfur (max)	Grains/100 scf	3.5
Hydrogen sulfide - H_2S (max)	Grains/100 scf	0.24
Carbon dioxide - CO_2 (max)	Mole percentage (%)	3
Nitrogen - N_2 (max)	Mole percentage (%)	7
Net calorific value (min)	BTU/scf	900
Wobbe index		1180 (with ±5%)
Water contents (max)	lbs/MMSCF	7
Pressure (min)	psi	950

Globally as well as in Pakistan, glycol dehydration units are used to remove water from the raw NG. Reboiler heaters and pumps are the consumers of energy in glycol dehydrators. To determine combustion emissions, it is necessary to calculate reboiler energy use on a 'mass unit of natural gas consumed' per 'mass unit of natural gas dehydrated.' This is derived through assumptions of the glycol flow rate, reboiler duty factor, and the amount of water removed. This study assumes that the extracted natural gas is water saturated at the wellhead at a proportion of 49 pound (lb) MMSCF of gas, and is dehydrated to 7 lb per MMSCF of gas in order to meet Pakistan pipeline gas specifications. Assumptions for the glycol flow rate and re-boiler duty were sourced from published EPA data (EPA, 2006). The calculated reboiler energy use figure is then multiplied by combusted emission factors for reboilers, sourced from the API compendium (API, 2009). The estimated natural gas consumption of a typical Glycol dehydration plant in Pakistan is assumed as 0.04 MMSCF for dehydrating 1 MMSCF of natural gas. Although there are also few natural gas production fields in Pakistan with sour gas which is processed by Amine Gas Sweetening Plant to remove H_2S and make it acceptable for pipeline gas specifications. However to make our calculation simple, we considered the entire stream of indigenous natural gas as sweet.

Flaring, venting and fugitive emissions in processing. After the extracted gas is sufficiently dehydrated, GHG emissions generated from gas processing in the boundaries of this analysis include other point source emissions from processing equipment that is combusted via flaring, fugitive emissions from pneumatic devices and other processing equipment not accounted for elsewhere, and combustion emissions produced via the reciprocating compressors that allow the processed gas to enter the pipeline transportation gate. Cumulatively, these processing steps result in the loss or use of 0.0419 MMSCF of natural gas per MMSCF of natural gas processed.

A gas-fired glycol regenerator drives water from the glycol by heating the glycol in a reboiler. A minor amount of methane is absorbed by the glycol along with the excess water, resulting in fugitive methane emissions released directly to the atmosphere during the heating of the glycol in the reboiler, or regeneration, step. Fugitive methane emissions during the glycol regeneration step and fuel use to power the glycol reboiler during the dehydration step together result in the loss or use of 1.46×10^{-4} MCF of gas per MCF of natural gas dehydrated.

Vented emissions occur as well, but these emissions are included in the fugitive emissions category discussed in the preceding section. Fugitive GHG emissions originating from dehydration are presented along with the other sources of fugitive emissions in Table 18 below.

Table 18
Summary of energy use and GHG emissions from gas dehydration.

Description	Unit	Value
Reference unit & resource requirements		
Reboiler NG use	kg/kg of dehydrated NG	1.40×10^{-4}
Fugitive/vented	kg/kg of dehydrated NG	5.37×10^{-6}
Total NG requirements	kg/kg of dehydrated NG	0.00015
Key assumption & inputs for dehydration step		
Glycol (TEG) flow rate	gal/lb water	3
Reboiler duty	BTU/gal TEG	1124
Water in raw NG	lb/MMSCF NG	49
Water in dehydrated NG	lb/MMSCF NG	7
Reboiler energy use	BTU/kg NG	7.43
Reboiler CO_2 emission factor	kg/kg of dehydrated NG	3.95×10^{-4}
Reboiler CH_4 emission factor	kg/kg of dehydrated NG	7.68×10^{-9}
Reboiler N_2O emission factor	kg/kg of dehydrated NG	2.14×10^{-9}
Dehydration plant fugitive/vented CH_4 emission factor	kg/kg of dehydrated NG	5.37×10^{-6}
Total emission of TEG unit	kg/kg of dehydrated NG	
CO_2eq	kg/kg of dehydrated NG	5.57×10^{-6}
CO_2	kg/kg of dehydrated NG	3.95×10^{-4}
CH_4	kg/kg of dehydrated NG	5.38×10^{-6}
N_2O	kg/kg of dehydrated NG	2.14×10^{-9}

Natural gas compression at the processing plant. Prior to finished process gas entering the pipeline transportation gate, processed gas must be compressed to 950 psi to meet the pressure requirement of Pakistan pipeline gas quality. In Pakistan reciprocating compressors are utilized at the gas processing plant. Reciprocating compressors generate GHG emissions via the combustion of natural gas to power their operation.

The first step in determining GHG emissions from compressors at the processing stage entails estimating the relevant compressor heat rate, i.e. the required power output for a compressor per unit of gas throughput. The amount of power required is contingent upon the compression ratio, which is the ratio of outlet to inlet pressures. This analysis assumes an inlet pressure of 50 psig and an outlet pressure of 950 psig. Utilizing a compressor horsepower selection chart published by GE Oil and Gas (2005), which shows the relationship among power, fuel throughput, and the compression ratio, compressor brake horsepower was determined to be 193 hp per MMCF of gas throughout. This figure was then converted to 1.84 × 10–4 MWh per kg of gas throughput. The estimate of compression power requirements presented above should be considered conservative due to some facilities being designed to utilize several stages of pressure letdown in the condensate or oil recovery process; such facilities feed considerable portions of gas into the compression system at a higher pressure, requiring less total compression power for the same amount of gas.

In this analysis, fuel use from compressors during the processing stage results in the loss of 4.07×10^{-2} MCF of natural gas per MCF of natural gas processed, representing 96.7% of the total natural gas loss or use from the processing stage. A summary of the GHG emissions occurring from reciprocating compressors during the processing stage is provided in Table 19, and includes resource requirements, key assumptions and inputs, and GHG emissions by source and product.

Summary of WtT Stage #1 GHG emissions profiles. GHG emissions associated with the production and processing of natural gas is summarized in Table 20.

WtT Stage #02: pipeline transportation

After extraction and processing, natural gas is transported to various locations via large pipelines. The locations considered in this work are distributed CNG refilling stations. For this step, natural gas travels through the pipeline at pressures between 120 and 1000 psi and as the natural gas travels along the pipeline, the pressure within the pipe drops primarily due to friction losses along the pipe. Therefore, compressor stations are installed along the pipeline. The exergy loss from compression is approximately 2.4–4.5% depending on the number of compressor stations. There are two types of compressors: grid power electric compressors and natural gas-fueled compressors, with natural gas compressors (powered by compression station own natural gas fueled power plant) being the prevalent choice in Pakistan. We thus only consider turbine/engine driven electric compressors, which have an electric motor energy efficiency ranging from 0.94 to 0.98. The study assumes the efficiency of 96.5% for electric motor driven reciprocating compressor at intermediate compression stations.

Two categories of transport distance are assumed in this paper: 300 km for pipeline transport from gas fields to nearby cities (representing cases in some gas-rich regions like Sindh province) and 750 km for transport from various gas fields in the provinces of Baluchistan and Sindh provinces to Punjab province.

Emissions from pipeline transport occur from pipeline fugitive emissions and the use of compressors at compressor stations. Although Pakistan has a widespread infrastructure of natural gas transmission and distribution pipeline network with total length of 10,789 km and 112,474 km respectively (Pakistan Energy Yearbook, 2015), but the integrity of this network is very poor. According World Bank report, the UFG (unaccounted for gas) of Pakistan natural gas pipeline network is over 10% which is well above the international standard of 2%. Pipeline leakages share the 30% of total UFG losses, which becomes 3% total gas transmitted through pipelines.

Natural gas needs to be constantly repressurized at intervals of 65 to 160 km while being transported through a pipeline. The first step in estimating GHG emissions from compressors is determining the natural gas fuel use factor, which is expressed on a mass-unit-of-fuel-use per mass-distance-unit-of-gas-transported basis. This calculation requires analyzing total pipeline compressor fuel use.

Using the data from the two gas transmission and distribution companies in Pakistan (SNGPL and SSGC), we estimated that 0.75% of transported gas is used as compressor fuel by dividing total compressor station fuel use by the total amount of delivered gas on 28 major interstate pipelines, which collectively represented 81% of total natural gas transmission in 2009. The analysis resulted in a fuel use factor of 1.02×10^{-5} MCF of natural gas use per MCF-km of natural gas transported.

In this analysis, fugitive pipeline emissions and fuel use for compression systems during transportation to the CNG station in the loss of 4.87×10^{-3} MCF per MCF of natural gas transported. The processing plant to liquefaction plant gate is assumed to be 320 km, and the regasification plant to power generation plant gate is assumed to be 1000 km. A summary of the GHG emissions generated from pipeline transportation is provided in Table 21.

WtT Stage #03: CNG compression

To use natural gas as a vehicle fuel, it should be compressed to a required pressure at CNG refueling station. For converting the pipeline gas to CNG, the modeling approach in GREET assumes that the natural gas is initially compressed to a pressure of 276 bar to allow for pressure losses caused by cooling during vehicle refueling to a tank at 248 bar. In Pakistan the maximum allowable pressure for vehicle's CNG cylinder is

Table 19
Summary of GHG emissions and relevant inputs from natural gas processing.

Description	Unit	Value
Venting	kg/kg NG processed	6.57×10^{-6}
Fugitive	kg/kg NG processed	8.56×10^{-4}
Other venting	kg/kg NG processed	3.82×10^{-4}
Total fugitive/venting during NG compression at plant	kg/kg NG processed	1.25×10^{-3}
Compression combustion	kg/kg NG processed	4.07×10^{-2}
Energy for reciprocating compressor	kg NG/MWh	221
Total CO_2eq emissions during NG compression at plant	kg/kg NG processed	0.168
Total CO_2 emissions during NG compression at plant	kg/kg NG processed	0.109
Total CH_4 emissions during NG compression at plant	kg/kg NG processed	1.99×10^{-3}
Total N_2O emissions during NG compression at plant	kg/kg NG processed	$1.92 \cdot 10^{-8}$

Table 20
GHG emissions associated with recovery and processing of natural gas.

Parameter	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Recovery	2.098	0.436	5.92×10^{-2}	1.26×10^{-5}
Processing	3.078	0.894	7.79×10^{-2}	1.07×10^{-5}
Total	5.177	1.330	0.1372	2.33×10^{-5}

Table 21
GHG emissions associated with transportation and distribution of domestic natural gas.

Transport mode	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Pipeline transport of natural gas	8.290	1.257	0.251	2.14×10^{-5}

Table 22
GHG emissions associated with the compression of natural gas to CNG.

Transport mode	GHGs emissions (g/MJ)			
	CO_2eq	CO_2	CH_4	N_2O
Natural gas compression	4.82	3.127	5.71×10^{-2}	5.51×10^{-7}

200 bar. Therefore we assume that inlet pressure of compressor is 8 bar which gas is initially compressed to 230 bar and is stored in the vehicle at 200 bar. The key assumption with refueling stations is the compressor efficiency, which Argonne National Laboratory found to range between 91.7% and 97% (Mansour & Haddad, 2017). As per our Pakistan CNG refueling station survey, majority of CNG compressor were Chinese origin/electric driven and their average efficiency was 93%. We also found that the typical inlet pressure for the compressor was 8 bar. Therefore, with inlet pressure 8 bar, outlet pressure 230 bar, compressor efficiency 93%, compressor isentropic efficiency 65%, the required work to perform this compression, we get 0.0473 MJ/MJ as the required energy consumption which represent the overall efficiency of CNG production as 95%.

A summary of the GHG emissions generated from converting pipeline natural gas to CNG at refueling station is provided in Table 22.

Pathways of foreign natural gas sources

Due to depleting indigenous reserves of natural gas sources and rising demand for natural gas, Pakistan is facing severe natural gas supply crisis. To bridge the supply-demand gap for gas, government has been pursuing different options, including inter-state gas pipeline projects (TAPI, IP) and import of LNG.

IP gas pipeline project

The Iran-Pakistan (IP) gas pipeline project having the gas supply capacity of 750 mmcfd, start from South Pars gas field in Iran and end at Nawabshah (a city of Pakistan), covering a distance of around 1820 km with 1115 km portion in Iran and 705 km in Pakistan. The project is expected to commission by the end of 2018.

TAPI gas pipeline project

Turkmenistan-Afghanistan-Pakistan-India (TAPI) pipeline project having the gas supply capacity of 3178 mmcfd, begins from the Galkynysh gas field in Turkmenistan passes through Afghanistan, Pakistan and concludes at Fazilka in India. The total length of the pipeline is 1800 km while Pakistan will share 1600 km of the project. The pipeline will deliver its first gas supply in December 2019.

GHG emissions profile of imported pipeline gas

GHG emissions associated with the production, processing, and transport of natural gas supply through the above mentioned pipeline projects is shown in Table 23. As both the aforementioned projects are in progress, so for calculating GHG associated with the transportation of foreign gas we use the data of European interstate gas pipeline (Edwards et al., 2014) which are currently being used for supply natural gas to Europe.

LNG - liquefied natural gas

Pakistan is currently importing 3.75 million tons LNG per annum (equivalent to 600 mmcfd of natural gas) from Qatar. LNG is other alternative to transport natural gas; it is transported at −160 °C temperature and ambient pressure. This method is the most economic option for transporting gas over long distances (above 4000 km) when compared with pipeline projects. LNG production and long distance shipping is a well-established route widely used throughout the world. Gas is extracted and cleaned up before being liquefied in a cryogenic plant. For Pakistan application, after being processed, natural gas is transported to liquefaction plant in producing countries (Qatar for this study), where it is liquefied to LNG, and then transported to Pakistan by LNG carrier. For automotive application, the regasified natural gas is transported to CNG refueling stations where it is compressed to the required pressure. Fig. 4 illustrates the WtT process for CNG using LNG as gas source. For the stages: extraction, preprocessing and pipeline transportation (before liquefaction and after regasification) we have assumed the same figure as for foreign gas sources as discussed in Section 5.2.1.

The literature on WtT for LNG was found less in agreement due to the different LNG production and shipping technologies, and several sources are taken in consideration. The JEC (Edwards, Larivé, Rickeard, & Weindorf, 2014) study estimates the emission intensity for LNG production (extraction, liquefaction) in 9.5 g CO_2eq/MJ_{LNG} of which 1.05 g CO_2eq/MJ_{LNG} of LNG venting. Kofod and Stephenson (2013) estimated it to be in the range of 4.5–7.6 (g CO_2eq/MJ_{LNG}), with an average of 7.0 g CO_2eq/MJ_{LNG}, based on the Chevron report (Australia C, 2009). Okamura, Furukawa, and Ishitani (2007) estimated the average emission intensity as 8.1 g CO_2eq/MJ_{LNG} based on existing technologies, and Barnett (2010) estimated the average emission level for the most recent and efficient liquefaction facilities at 5 g CO_2eq/MJ_{LNG}, based on the Wood Mackenzie oil and gas database for Year 2010 (Mackenzie, 2014). Arteconi, Brandoni, Evangelista, and Polonara (2010) reports similar values in the range of 7.44–8.9 g CO_2eq/MJ_{LNG}.

Processing

Once the gas enters the liquefaction plant gate, it is treated, cooled, and condensed to LNG for tanker transport. The boundaries of the liquefaction segment begin once the gas exits the pipeline and enters the liquefaction facility's treatment plant which includes acid gas treatment using activated methyl diethanol amine for CO_2 removal and dehydration using molecular sieves. It ends after the LNG is produced and stored in tanks, from which it is eventually loaded onto a LNG tanker for marine transport. Excepting power generation, the liquefaction segment generated the most GHG emissions in this life cycle analysis, accounting for 7.2% (low GHG case) to 10.1% (high GHG case) of total GHG emissions. Additionally, the liquefaction segment accounts for 41.8% (low GHG case) to 76.9% (high GHG case) of total

Table 23
GHG emissions associated with pipeline transportation of imported gas from foreign country to domestic central manifold.

Transport mode		GHGs emissions (g/MJ)			
		CO_2eq	CO_2	CH_4	N_2O
IP gas pipeline project	Recovery & processing	4.66	1.197	0.124	2.11×10^{-5}
	Interstate pipeline transportation	4.33			
	Domestic transportation & distribution	1.658	0.252	5.02×10^{-2}	4.28×10^{-6}
TAPI gas pipeline project	Recovery & processing	4.41	1.131	0.117	1.98×10^{-5}
	Interstate pipeline transportation	3.82			
	Domestic transportation & distribution	1.4093	0.214	4.27×10^{-2}	3.64×10^{-6}

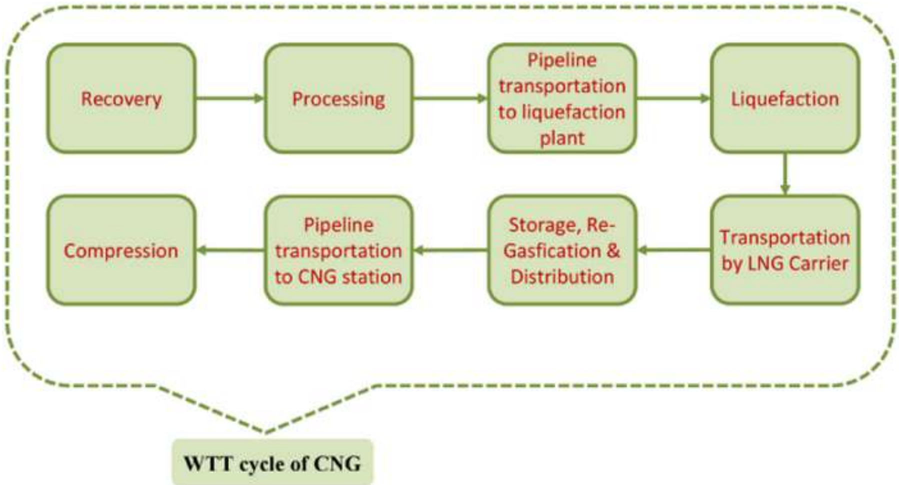

Fig. 4. WtT cycle of CNG using LNG as source gas in Pakistan.

natural gas loss or use over the life cycle analysis, representing the largest amount of any segment.

The major causes of GHG emissions in the processing stage of LNG are attributable to:

- fuel consumption for driving turbines/primary motors needed to operate the equipment;
- combustion of waste gases in flares;
- gas losses from venting (e.g. associated with pretreatment processes or losses from equipment and pipes).

The main liquefaction technologies for LNG plants can be categorized into six:

- Propane Pre-Cooling Mixed-refrigerant C3MR (Licensed by Air Products and Chemicals Inc. APC);
- Propane Pre-Cooling Mixed-refrigerant C3MR/Split MR (Licensed by Air Products and Chemicals Inc. APC);
- Optimized cascade (Licensed by ConocoPhillips);
- C3MR with a nitrogen refrigeration cycle AP-X (Licensed by Air Products and Chemicals Inc. APC);
- Ethane/Propane Pre-Cooling Dual mixed refrigerant DMR (Licensed by Shell);
- Propane Pre-Cooling Mixed Fluid Cascade MFC ((Licensed by Linde);

The C3MR process developed by APCI has been the workhorse of the LNG industry for more than 30 years. Currently this process holds the greatest share at 41%, followed by the Optimized Cascade (22%), C3MR/SplitMR (16%) and AP-X (13%). Share of each type liquefaction technology installed by 2016 is shown in Fig. 5 (2016 World LNG Report - International Gas Union (IGU), 2016). As currently LNG in Pakistan is being importing LNG from Qatar LNG plants which are based on AP-X liquefaction technology, so we consider AP-X as basis for our calculation. The AP-X process is an improved version of the C3MR/Split MR process

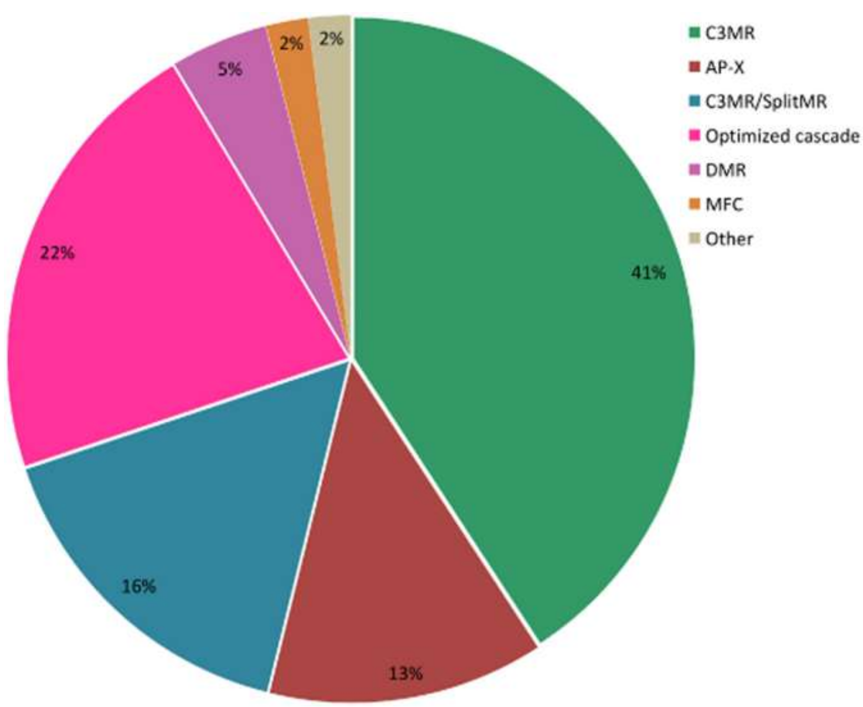

Fig. 5. Liquefaction capacity by type technology 2016.

that includes a sub-cooling process having nitrogen as working fluid. Fig. 6 illustrates the AP-X LNG process with NGL recovery integration.

After it is liquefied, LNG is stored for a few days before being shipped out. Because the boiling point of natural gas is −162 °C, LNG tends to boil off inside the storage chamber. Although LNG storages are specially designed for maintaining low temperature, it is impossible to stop boiling off completely. Some portion of this boiloff-gas (BOG) is recovered to LNG, while the rest is vented to the air. To calculate the amount of LNG venting during the storage, the required parameters are duration of storage, boil-off-rate (BOR), and recovery rate. In this study we assume 4 days average duration of storage at producing country (Qatar). To evaluate the BOR, we refer to Gastransport & Techinigaz Inc. (GTT), which is a dominant company in LNG storage market. According to GTT, 0.1%/day is appropriate for the BOR of LNG storage constructed in land. Finally, 80% of recovery rate is assumed with the uncertainty from 75% to 90%. Therefore, the remaining 20% that is not recovered is vented to the air, and the value is 20.39 g $CH_4/GJ_{Process}$.

Transportation

After the gas is liquefied and stored, it must be loaded onto tankers and shipped in its liquid state to its destination market. LNG is transported on large ocean going vessels with capacities ranging from 75,000 to 265,000 m^3 of LNG. The boundaries for the LNG shipping segment begin once the LNG exits the liquefaction facility's storage tanks and is loaded onto the LNG tanker. The segment ends after the ship concludes its ballast voyage and returns to the original loading location. Calculated emissions from LNG shipping in this analysis include ship loading, the laden voyage, ship offloading, and the ballast voyage. Emission sources from LNG shipping include the venting of unconsumed and un-reliquefied boil-off gas (BOG) during voyage, combustion emissions from power generation, venting from the compressors used to recover the BOG, fugitive emissions from compressors, emissions from fuel combustion used for ship propulsion, emissions for other vessels, e.g. tugs, used to position the LNG ship near or at port, and combustion emissions from the power plant used to power the ship's other systems.

Most of LNG carriers have the boil-off gas problem which takes place during storage, loading or discharging and the ship's voyage. In order to keep the LNG in a liquid state at atmospheric pressure, it must be maintained at temperature below its boiling point temperature (−162 °C). As a result of imperfect insulation, the heat enters the cargo tank during storage and transportation. So, a portion of LNG cargo evaporates gas which is called Boil-Off Gas (BOG). The boil-off gas ranges from 0.1%–0.25% of stored LNG per day depending on the size of the tank and the materials and methods of construction. There are two methods of handling the BOG generated during LNG transportation i.e. (i) using the BOG as fuel for the propulsion system of LNG carrier and (ii) re-liquefaction of BOG to LNG with on-board re-liquefaction plant and injecting back to cargo tank of the LNG carrier. Traditionally, LNG tankers run on steam engines powered by boil off gas (BOG). In this study we consider the modern Q-Flex LNG carrier pioneered by Qatargas. These tankers are equipped with on-board reliquefaction plants that collect the BOG, cool it to below −162 °C so that it becomes LNG, and inject the LNG back into the cargo tanks. Each Q-Flex vessels have a cargo capacity ranging from 210,000 m^3 to 217,000 powered by slow speed diesel engines which are more thermally efficient than steam turbines and therefore burn less fuel, which will produce 30% lower overall emissions compared to traditional existing LNG carriers (Pratt, Onder, & Raja, 2009). To calculate the energy use and the GHG emission during transportation by LNG carrier, it is necessary to know energy intensity (kJ/ton km), transport distance, cargo payload, and process fuel share for LNG carrier. Energy intensity is calculated from energy consumption (kJ/hp h), horsepower requirement of LNG carrier, load factor, average speed (km/h), and cargo payload of LNG carrier, as in Eq. (3). Here, the load factor is the percentage of installed horsepower that is used for the trip.

$$E_I = \frac{E_C \text{ x } HP_R \text{ x } L_F}{V_{avg} \text{ x } CP} \quad (3)$$

where

E_I energy intensity (kJ/ton km)
E_C energy consumption (kJ/hp h)
HP_R required horsepower (hp)
L_F load factor
V_{avg} average ship speed (km/h)
CP cargo payload (ton)

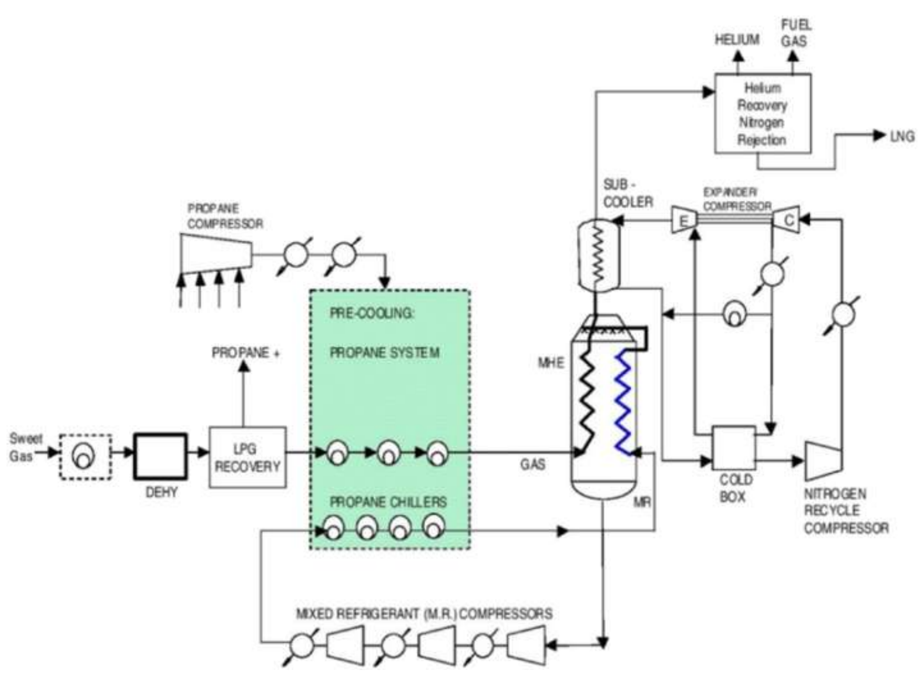

Fig. 6. Simplified process flow diagram of AP-X LNG process.

For calculating energy consumption (kJ/hp h), we consider the engine specification of Q-Flex LNG carrier. The values are 2835 kJ/hp h with LNG onboard from Qatar to Pakistan and 2643 kJ/hp h without LNG for the other way. Pakistan LNG Importing Company provided the data for the cargo payload of 60,950 tons, and then the required horsepower for LNG carrier is calculated by Eq. (4) and the calculated value is 14,812 hp.

$$\text{Horsepower} = 9070 + 0.101 \times \text{Cargo payload} \quad (4)$$

For the load factor, we use 80% when LNG carrier moves from Qatar to Pakistan, and 70% when LNG carrier moves back. The difference between these two load factors are mainly due to the weight of LNG, i.e., more horsepower is required when LNG is loaded than otherwise. We used 30.58 km/h for the average speed. By using the above data and Eq. (4), energy intensity is calculated as 32.8 kJ/ton km for the trip from Qatar to Pakistan and 28.8 kJ/ton km for the return. Using the web-based, Portworld software, the calculated transportation distances 1617 km is obtained. The last source of methane leakage from bunkering operations is the purging of liquid and vapor from the fueling hoses of LNG delivery tankers after filling on-site storage tanks. It is estimated that for the modern LNG tankers, the maximum volume of purged methane would be about 0.02% of the total LNG tanker's capacity.

Regasification

Regasification is necessary to return the LNG back into a pressurized, gaseous state so it is suitable for pipeline transportation to reach end users. This analysis assumes that the only processes the regasification plant will perform are pumping, compression and vaporizing LNG (Fig. 7). Regasification generates a low amount of GHG emissions in the context of the LNG life cycle analysis. In the low GHG case, GHG emissions were calculated to be 5.39 × 10–3 kg of CO_2-eq per kg of regasified fuel. In the high GHG case, GHG emissions were calculated to be 1.71 × 10–2 kg of CO_2-eq per kg of regasified fuel. For the total life cycle analysis, regasification accounts for 0.2% (low GHG case) to 0.4% (high GHG case) of total life cycle GHG emissions. The BOG generated while the gas is stocked at the terminal is assumed to be recovered in the regasification process. It is assumed that the BOG handling system of the LNG import terminal in Pakistan would capture 95% of BOG and that 5% would be released. To determine the BOG from the storage tanks, we considered the capacity of the storage tanks of current sole LNG terminal (owned by Engro Elengy Terminal Private Limited - EETPL) in Pakistan and calculated the BOG as 0.15% of the total capacity stocked on a daily basis. The mean time spent by the LNG in storage, estimated on Pakistan natural gas demand data (Pakistan Energy Yearbook, 2015), was 2 days. The total energy use and the GHG emission during the three processes of receiving terminal i.e. pumping, compression and vaporizing LNG, is estimated to 0.01743 MJ/MJ and 0.433 g CO_2eq/MJ. According to EETPL, the process fuel share is 90% for natural gas and 10% for electricity. Finally, we average the CH_4 fugitive emissions values from storage and regasification process, which results in 5.08 × 10–2 g CH_4/MJ with an uncertainty range from 2.82×10^{-2} to 83.12×10^{-2} g CH_4/MJ.

Results

We have conducted a WtT analysis on 10 different combinations of transportation fuels in Pakistan. Using GREET, key assumptions were modified in accordance with Pakistani conditions. The results will be discussed under two different headings: energy impact and environmental impacts. The energy consumption and GHG emission at various stages of the fuels are described as MJ/MJ and g CO_2eq/MJ respectively.

WtT energy use

The WtT energy use for a fuel represents the total amount of energy consumed in the WtT processes to produce a particular quantity of fuel. This data is presented in Fig. 8. It can be seen that the total WtT energy consumption by CNG production from local natural gas is roughly 32% and 25% less than for the gasoline and diesel production from local crude oil, respectively. CNG compression, which consumes electricity with an energy efficiency of about 98%, is relatively a small emission source, accounting for about 40%, 28% and 19% of the total WtT energy consumption for local natural gas, imported natural gas via interstate-pipeline and LNG respectively. In case LNG, liquefaction is responsible for over one third of total WtT energy consumption. Similarly CNG production from imported natural gas in the form of LNG consumes 53% more energy than the CNG production from local gas. Gasoline and diesel production in Pakistani refineries are consuming slightly high energy than imported gasoline and diesel fuel. Also, it can be seen that the refining operation stage is the single largest contributor to energy consumption for both gasoline and diesel fuel, accounting for 54–60% of total energy consumption. In the whole WtT process, the only significant difference between gasoline and diesel comes from the refining process. The energy consumption in the refining process of diesel is 18% less than that of gasoline. The refining energy of gasoline and diesel fuel produced by local refineries is less than foreign refineries. The possible reason for this is that the diesel fuel produced at local refineries contain high amount of sulfur (above 800 ppm) while the diesel fuel produced by foreign refineries are having sulfur contents in the range of 50 ppm. Due to the energy-intensive sulfur removal process, the low sulfur diesel used produced at foreign refineries requires significantly more energy upstream than the high sulfur

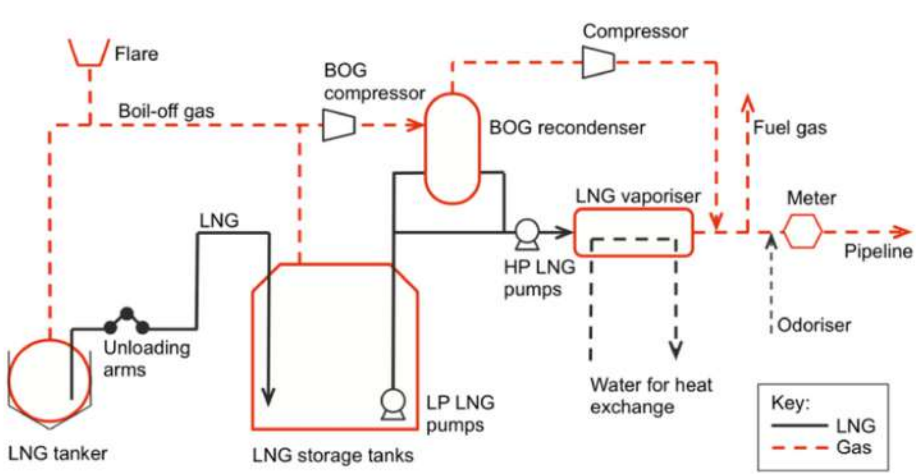

Fig. 7. Process flow of a typical LNG receiving and regasification terminal.

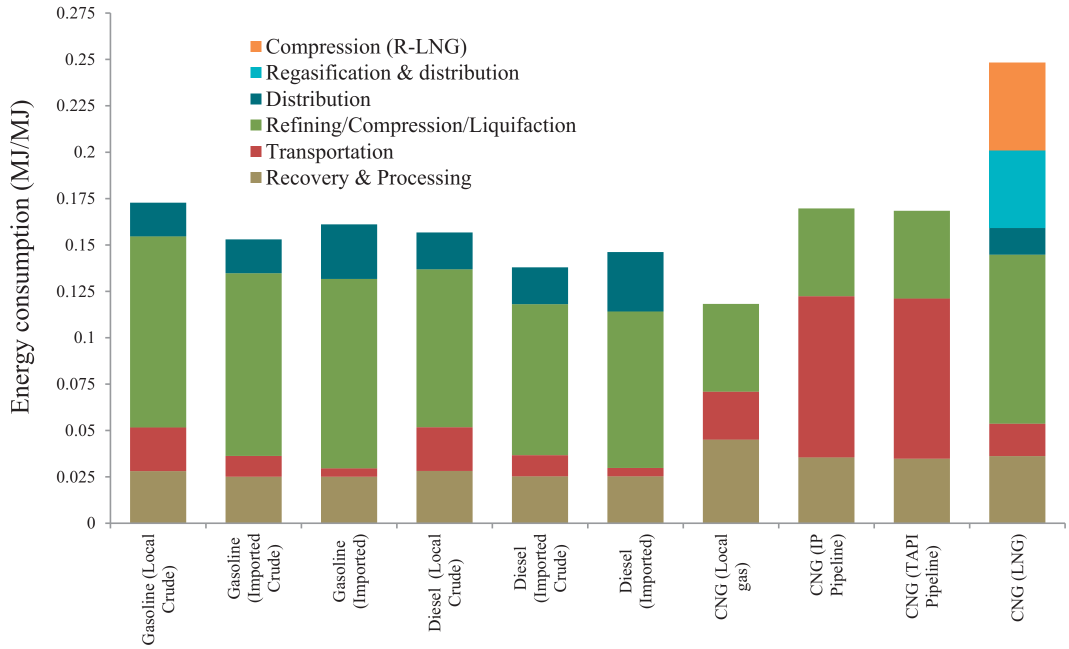

Fig. 8. WtT energy consumption for the selected pathways.

diesel produced by Pakistani refineries. Similarly although the gasoline produced by Pakistani refineries are having research octane number (RON) in range of 90 which is quite low from the research octane number 92 of imported gasoline.

Increasing the gasoline octane rating can improve a vehicle engine's energy efficiency by allowing an increase in the engine compression ratio. Keeping in view the prevailing compression ratio (10.1:1) of the SI engine technologies available in Pakistan, each point increase in the compression ratio (e.g., from 10:1 to 11:1) requires a corresponding increase in the fuel's research octane number (RON) of 2.5 to 6, depending on attributes of the engine technology (e.g., direct injection, turbocharging, advanced spark control) (Hirshfeld, Kolb, Anderson, Studzinski, & Frusti, 2014). Therefore any increase in the RON of regular gasoline would offer a negligible benefit for existing vehicles (with CR = 10.1:1), resulting in a significant waste in refining effort until most of the LDV (light duty vehicle) fleet is replaced. Presently we can assume a policy where the government of Pakistan adopts a RON standard for regular and premium gasoline, with minimum RON ratings that correspond approximately to those of existing grades, 92 RON for regular and 98 RON for premium (high RON). Then, vehicle manufacturers introduce new vehicles which require the 98 RON gasoline. Over time, these vehicles will make up an increasing fraction of the LDV fleet, and refineries will produce larger proportions of premium gasoline to satisfy the fuel demand from these vehicles. By introducing vehicles that utilize higher-octane gasoline in this manner, a gradual increase in the average RON can be realized without requiring the introduction of a new fuel grade. Below we present why the energy consumption of Pakistani refineries is lower than the foreign refineries.

Producing high-octane fuel (HOF) requires changes in refinery operation, which may increase the energy and greenhouse gas (GHG) emission intensity of the gasoline product. For example producing HOF can be achieved via increased production of high RON blending components, such as reformate, alkylate, and isomerate. In addition to experiencing volumetric loss during their production, high-RON blending components are also energy intensive (Elgowainy et al., 2014), so producing more of them increases refining GHG emissions. Estimating the net change in GHG emissions associated with introducing HOF vehicles requires a detailed assessment of HOF production impacts on refinery operations, by using a linear programming (LP) model, and a subsequent allocation of refinery emissions to various refined products. Such analysis is beyond the scope of this study. In the U.S., octane needs have been met by changes in refinery production to increase aromatic content and/or branched chain hydrocarbon percentage, and also by the use of oxygenated fuels (ethanol, methanol, MTBE). In developing countries, Methylcyclopentadienyl Manganese Tricarbonyl (MMT) is the cheapest means of improving the octane level of gasoline. In developed countries, due to its harmful effects on human health and the vehicle's, MMT is either used rarely (e.g. in US allowable limit is 8.3 mg/lit, European Union 2 mg/lit while in State of California, Japan, Germany etc. its usage is banned) or voluntarily stopped by major refiners.

In Pakistan, following the promulgation of new directives in October 2016, which forced refiners to increase the octane number of locally produced gasoline from 87 to 92 RON. As mentioned earlier the MMT is the cheapest way of enhancing the octane rating, therefore the implementation of new directives resulted in the increased reliance on MMT for raising octane number in unleaded gasoline. Refineries have been using MMT because it does not need any special changes to operation and production procedures of the refineries as well as equipment. On average a single drop of MMT in a liter of fuel can increases octane number by 3 (HiTEC® 3000 Fuel Additive: Octane Improver and Emissions Reducer for Unleaded Gasoline, 2016). Unlike developed countries, where usage of MMT as gasoline additive is banned, there is no legal guideline for the permissible use of MMT. Very recently (Nov. 2017), Honda (a major auto-maker in Pakistan) in its complaint to government have pointed that local gasoline has MMT levels as high as 54 mg/kg which severely damages the catalytic converter of their vehicles. This is an extremely high number if we compare it with any international acceptable standards of MMT use. Until now, many car owners have completely removed the catalytic converter from their cars, which is again a very serious problem in terms of emissions.

Refineries need to make changes to their operations and production processes instead of using a cheap method of obtaining the required octane grades. They should prepare a roadmap for all the necessary modifications needed to produce fuel without any metal additives. They should not enhance the octane number by cutting their cost. Refineries and the government must ensure the protection of public health, as well as new technologies for emission control systems in vehicles that are not adversely affected by their products.

WtT GHG emissions

We report results of the WtT GHG emissions of the case study fuels in Fig. 9. These results are based on 100-year GWPs, the baseline estimate of emissions, and are presented in the functional unit of equivalent CO_2 emission per unit of energy of production. The results are broken according various stages of WtT cycle of the corresponding fuel. The CO_2 emissions are calculated in GREET using the carbon balance method. Therefore, the trends in CO_2 emissions are in accordance with those of fuel energy consumed. The total GHG emission, expressed in CO_2 equivalent, is the sum of CO_2, CH_4 and N_2O emissions by considering global warming potentials. The results suggest that imported diesel fuel provide the lowest GHG emissions across all pathways considered. Similarly highest WtT GHG emissions can be observed for CNG fuel produced from imported LNG. Total GHG emissions associated with the LNG based CNG fuel is 21.3 g CO_2eq/MJ of which about one third comes from liquefaction process. WtT GHG emission associated with CNG produced from indigenous natural gas sources are 16% and 21% higher than the gasoline and diesel fuel produced from ingenious crude oil, respectively. It is surprising to note that 45% of GHG emission comes from transporting local natural gas from gas fields to CNG refueling stations. As discussed in Section 4.2.2, it is because of very amount of gas leakages from the Pakistan's natural gas transmission and distribution network. As natural gas contain mostly contain of methane which has 28% higher GWP over the 100 year time horizon. As shown in Section 6.3, the situation would become even more alarming if we consider 20 year time horizon for GWP of methane. Additionally for the CNG fuel pathway, it can be noted that the upstream NOx emissions are the another major contributor to WtT emissions, mostly due to compressors used for long distance natural gas transmission pipelines to the refueling stations for CNG production. However, as transmission pipelines are not often in heavily populated areas, hence in case of WtW cycle of CNG fuel, the benefit from lower vehicle emissions is likely more impactful to human health than the higher WtT emissions.

Among the natural gas based fuels, CNG produced from the interstate gas pipeline projects produces the lowest GHG emission. It can be seen that the GHG emission of local crude oil based fuels are about 13% higher than that of foreign based crude oil fuels. The two possible reason for this are the comparatively high energy content of foreign crude oil and low emissions associated with the pipeline and sea transportation in contrast to truck (with older engine technology) transportation.

GWP time horizon and sensitivity analysis

In this section, we estimate GHG emissions using GWPs with different time frames of 20-years and compared the results with the with 100-year GWP (baseline scenario). A sensitivity analysis was then performed to explore the effect of variability and uncertainty on our estimates of WtT GHG emissions. Estimates using both 100-year GWPs (solid filled left bars) and 20-year GWPs (pattern filled right bars) are presented side by side for each pathway in Fig. 10. Using the 20-year GWP, the results demonstrate that the WtT GHG emissions of crude oil pathways increase by 21–41% compared to emission estimates with 100-year GWP. Similarly applying 20-year GWP baseline scenario to natural gas pathways, the results demonstrate that GHG emissions increase in the range of 80–113%. The obvious reason for this surprising GHG emission increase is the high risk of methane emission in natural gas fuel pathways. In case of 20-year baseline, the GWP of methane become three times the GWP value of methane in 100-year life cycle analysis.

To quantify the uncertainty in our WtT GHG estimates, the GREET stochastic tool was employed. The GREET model contains hundreds of

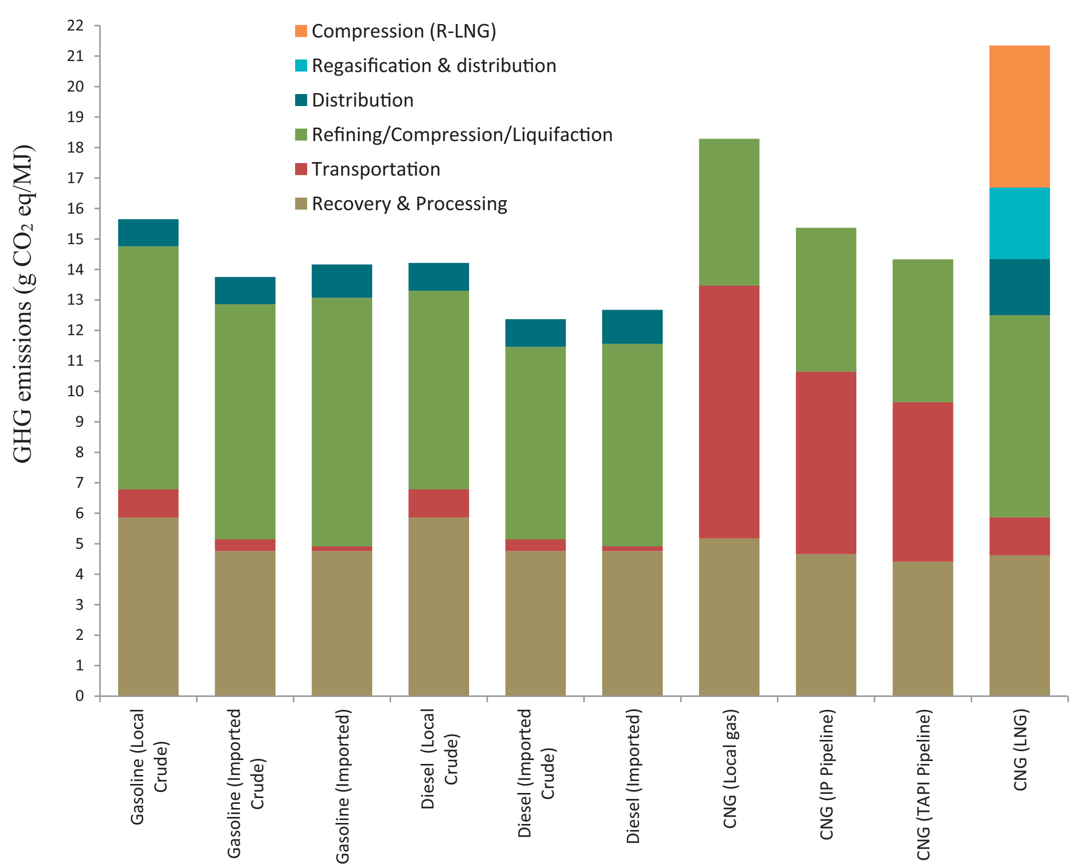

Fig. 9. WtT GHG emissions for the selected pathways.

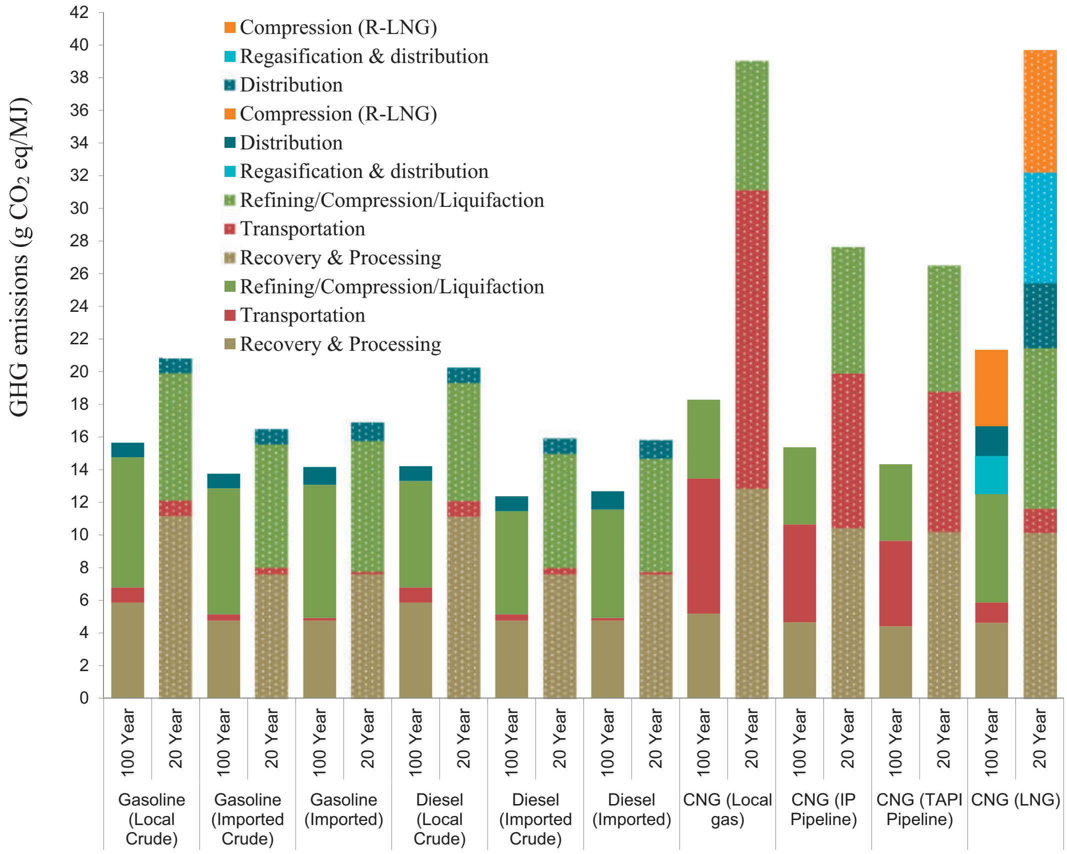

Fig. 10. Comparative WtT GHG emissions for the selected pathways using 100-year and 20-year GWP baseline.

built-in distribution profiles to quantify uncertainty. The parameters with built-in-profiles include fuel properties, emission factors, and process efficiencies. In our analysis, we adjusted the recovery and refining distribution profiles to match the ranges of our data and added profiles for venting and flaring. The stochastic tool was run once for each fuel pathway using the GREET default Hammersley Sequence Sampling technique. The resulted range of key parameters' values for crude oil and natural gas based fuels are listed in Tables 24 and 25 respectively. Here, the minimum and maximum values of the parameter mean those that lead to the lowest and highest GHG emissions. For example, the larger value for the liquefaction efficiency is shown in the minimum value column, because it results in the lower GHG emissions. The result of the sensitivity analysis on the parameters of crude oil and natural gas pathways are shown in Fig. 11. It is demonstrated that crude oil fuel pathways have sensitivities of less than 3%. However, the amount of CH_4 leakage in Pakistan in natural gas based fuel pathways and CO_2 venting during natural gas processing in the producing countries show relatively large sensitivities around 5.5%.

Table 24
List of key parameters for the sensitivity analysis of crude oil fuel pathways.

Key parameters	Min	Determined	Max
Recovery energy (MJ/MJ)	0.0075	0.0082	0.01159
Recovery efficiency (%)	95	93	92
Flaring and venting CO_2 during processing (g CO_2/MJ)	1.0345	1.0785	1.123
Flaring and venting CH_4 during processing (g CH_4/MJ)	0.039248	0.0892	0.223
Gasoline refining energy (MJ/MJ)	0.0851	0.0895	0.1029
Diesel refining energy (MJ/MJ)	0.0615	0.0645	0.0781
Distribution distance (km)	200	225	400

We acknowledge that there are several limitations to this study. Our analysis focuses on GHG emissions and we use the global warming potential of non-CO2 gases. Recent literature suggests that GWP has serious limitations. For instance, GWP treats all emissions as if they are pulse emissions at the beginning of the time horizon considered, thus completely ignoring different effects of emissions happening at different time (Alvarez et al., 2012). Further, while GWP is closely related to radiative forcing, GWP does not consider other drivers of climate change, such as the rate of change, and variations in surface temperature response (Kendall, 2012; Shindell et al., 2009). Some research is ongoing to develop more appropriate climate impact metrics, (Shindell et al., 2009) but there is no consensus about the use of these metrics for LCA and a comparison of such metrics is beyond

Table 25
List of key parameters for sensitivity analysis of natural gas pathways fuels.

Key parameters	Min	Determined	Max
Recovery energy (MJ/MJ)	0.0254	0.02665	0.0295
Recovery efficiency (%)	99	98	96
NG processing plant efficiency (%)	97.5	96	94
CO_2 in recovery and processing of NG (g CO_2/MJ)	1.12	1.677	1.95
Flaring and venting CH_4 during recovery and processing (g CH_4/MJ)	0.0625	0.125	0.27
CH_4 leakage during transportation from gas field to refueling station (g CH_4/MJ)	.115	0.251	0.298
CO_2 in Inter-state pipeline gas transportation (g CO_2eq/MJ)	3.82	4.33	5.75
LNG Liquefaction efficiency (%)	1.14	1	0.9985
LNG recovery rate in LNG liquefaction plant (%)	90	80	75
LNG recovery rate in LNG carrier (%)	95	90	85
Duration of LNG storage in foreign country (days)	3	4	5
Pipeline transportation distance (km)	250	300	750
CNG stations compressor efficiency (%)	97	93	91.5

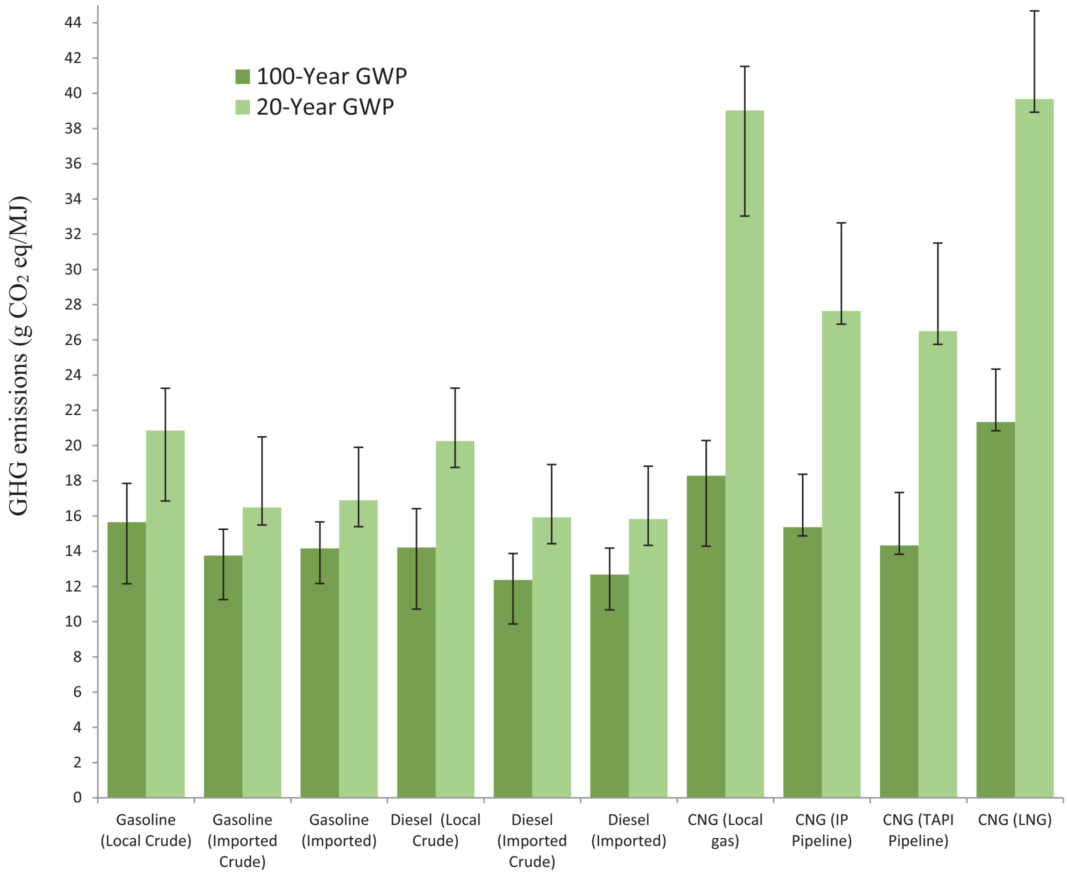

Fig. 11. Sensitivity analysis of WtT GHG emissions of crude oil and natural gas fuels pathways using 100-year and 20-year GPW baseline.

the scope of this study. In the future, as more appropriate metrics are identified, we can use the inventory results in this paper to re-evaluate the climate impacts of crude oil and natural gas-based transportation fuels. Moreover in the present study, the refining energy of individual products is allocated on the process-level allocation method based on the Pakistani refinery data and the NETL result; it would be desirable to have more detailed process-level data from Pakistani refineries to further improve the accuracy of the WtT results.

Comparison of WtT results with other studies

The WtT energy use and GHG emissions results of various studies and the present study are represented in Fig. 12. The comparison clearly shows that the WtT energy consumption obtained in the current study for Pakistan is 28% and 21% less than the similar studies of European and US market respectively. Interestingly the WtT GHG emission results for CNG produced from the indigenous gas sources in Pakistan is 29% and 45% higher than the corresponding values of the studies specific to European and US markets, respectively. As mentioned earlier this is due to high rate of fugitive GHG emission during pipeline transmission and distribution of natural gas. Similarly for gasoline and diesel fuel, the comparison clearly shows that the current study for Pakistan follows the general trend regarding WtT GHG emission when compared with earlier studies for other countries. However in contrast to other studies the values for energy consumption for gasoline and diesel fuel of this study are remained lower. This is mainly due to lower octane value of gasoline and higher sulpher value of diesel fuel produced by Pakistani refineries. Both of these factors (i.e. low octane value and high sulpher contents) can significantly decrease the processing energy of the corresponding fuel.

Conclusion

This study reports results of the first-ever analysis of WtT energy use and GHG emissions for various automotive fuels in Pakistan. The findings of the study are highly region specific, and thus cannot be directly applied to other locations. The study evaluated the GHG emission and the energy use for every process of the whole WtT fuel cycle of 10 different fuel pathways in the Pakistani context.

Key finding are listed below:

1. The CNG production from local natural gas is observed to be most efficient and least energy consuming among all fuel pathways. The WtT energy consumption by CNG pathway is roughly 32% and 25% less than for the gasoline and diesel production from local crude oil, respectively.
2. Inspite of having comparatively low energy content of Pakistani local crude oil (3.3% less than imported crude), the refining energy of required to produce unit amount of gasoline and diesel fuel is compatible to refining energy of foreign crude oil. This is due to low quality of gasoline and diesel fuel produced at Pakistani refineries.
3. The imported diesel fuel and CNG fuel produced from imported LNG provides the lowest and highest GHG emission respectively among the all case study fuel. WtT GHG emission associated with CNG produced from indigenous natural gas sources are 16% and 21% higher than the gasoline and diesel fuel produced from ingenious crude oil, respectively. About half of the WtT GHG emissions associated with indigenous gas based CNG fuel resulted from the pipeline transportation of natural gas from gas fields to refueling stations.
4. The GHG emissions of domestic pipelines transportation of natural gas to refueling stations is about 40% higher than international level.

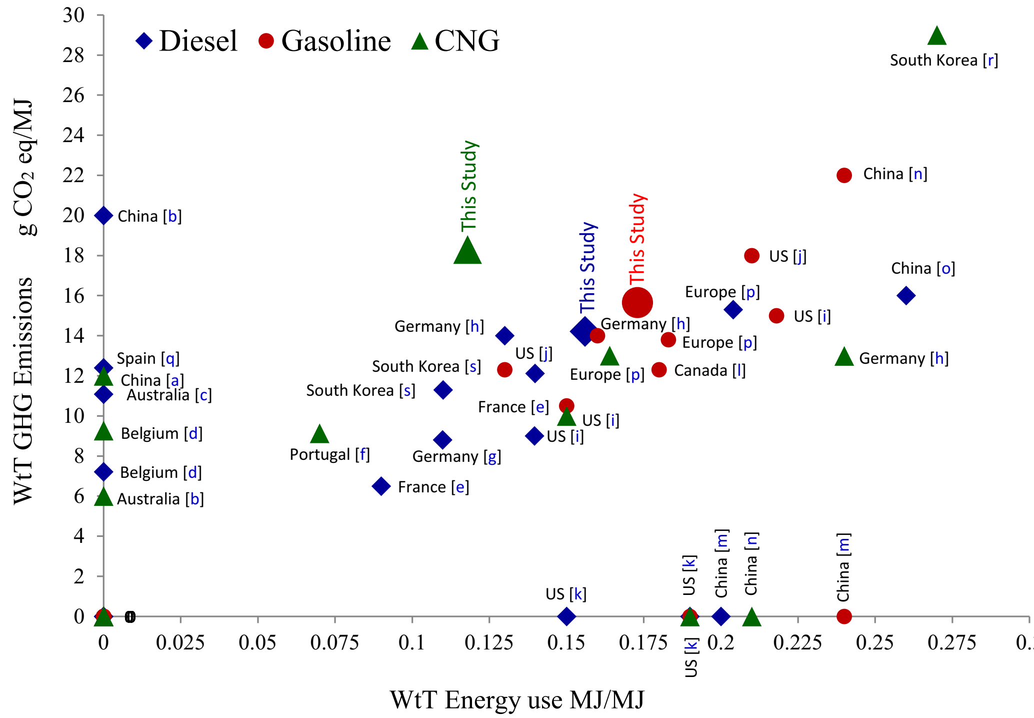

Fig. 12. A comparison of WtT energy use from the present study with those reported in the literature (see the supplementary file for the reference of studies mentioned in this figure).

5. The GREET default WtT emissions for conventional gasoline and diesel are approximately 22% higher than our results for gasoline and diesel fuel produced by Pakistani refineries from local crude oil.
6. The GREET default WtT emissions for CNG are within the range of our results for CNG produced from indigenous natural gas.
7. The sensitivity analysis show that most of the parameters associated with crude oil pathways are of little importance to the final result, but for natural gas pathways there are several parameters with relatively high sensitivities, i.e., CO_2 venting during processing, CH_4 leakage in Pakistan, and CH_4 leakage during recovery, which would require further investigation to improve the overall accuracy of the analysis. It is important that policy-makers consider uncertainty and variability when they set policy goals based on relative or absolute emissions associated with WtT emissions of natural gas pathways.
8. In addition to payload, the choice of GWPs and methane emission estimates are other important factors for absolute emission levels and relative rankings of natural gas fuel pathways. Using 20-year GWPs instead of 100-year GWPs increases WtT GHG emissions by 80–113% for natural gas pathways.

Nomenclature

ANL	Argonne national laboratory
API	American petroleum institute
bbl	Barrel
BOG	Boil-off gas
BTU	British thermal unit
CAPP	Canadian association of petroleum producers
CH_4	Methane
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2eq	CO_2 equivalent
DMR	Dual mixed refrigerant
DWT	Dead weight of tanker
EETPL	Engro elengy terminal private limited
EIA	Energy information administration
EPA	Environmental protection agency
GHG	Greenhouse gas
GREET	Greenhouse emissions and energy use in transportation
GWP	Global warming potential
HDIP	Hydrocarbon development institute of Pakistan
HEV	Hybrid electric vehicle
HFO	Heavy fuel oil
IC	Internal combustion
IES	International energy statistics
IP	Iran Pakistan
ISGS	Interstate gas systems
LCA	Life cycle analysis
LHV	Latent heat of vaporization
LNG	Liquefied natural gas
MCF	Thousand cubic feet
MJ	Megajoule
MMSCFD	Million cubic feet per day
N_2O	Nitrous oxide
NETL	National energy technology laboratory
NG	Natural
NG	Natural gas
NGV	Natural gas vehicle
NOAA	National oceanic and atmospheric administration
OCAC	Oil companies advisory council
OGP	Oil and gas producers
OGRA	Oil and gas regulatory authority
ORNL	Oak ridge national laboratory
PEC	Petroleum energy center
PNSC	Pakistan national shipping corporation
ppm	Parts per million
RON	Reteach octane number
SCFB	Standard cubic feet per barrel
SNGPL	Sui northern gas pipelines limited
SSGCL	Sui southern gas company limited
STEP	Sustainable transport energy program

TAPI Turkmenistan-Afghanistan-Pakistan-India
TOE Ton of oil equivalent
WtT Well-to-Tank

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2017.12.004.

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Annexure-L

Khan, M.I., Shahrestani, M., Hayat, T., Shakoor, A. and Vahdati, M., 2019. Life cycle (well-to-wheel) energy and environmental assessment of natural gas as transportation fuel in Pakistan. Applied Energy, 242, pp.1738-1752.

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Life cycle (well-to-wheel) energy and environmental assessment of natural gas as transportation fuel in Pakistan

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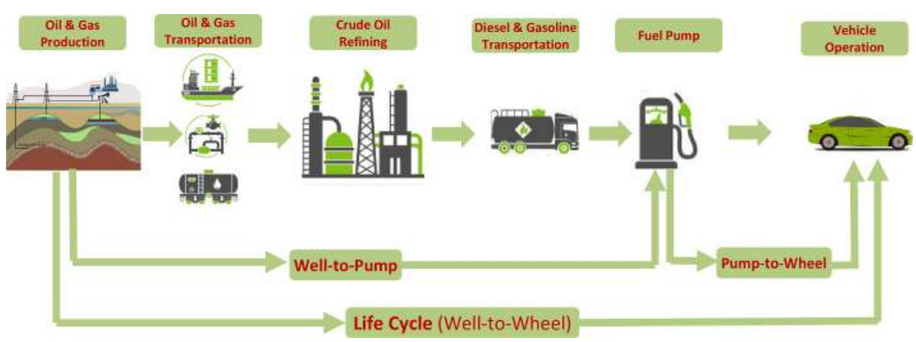
HIGHLIGHTS

- Well-to-Wheels analysis of energy consumptions and GHG emissions.
- Analysis covers 25 combinations of automotive fuel and matching power-train systems.
- Well-to-Tank stage analysis conducted using GREET model.
- Tank-to-Wheel stage analysis conducted using AVL Cruise vehicle simulator.
- A 20% reduction of GHG emissions may be realized by switching from gasoline to NGV.

GRAPHICAL ABSTRACT



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ABSTRACT

Consumers and organizations worldwide are searching for low-carbon alternatives to conventional gasoline and diesel vehicles to reduce greenhouse gas (GHG) emissions and their impact on the environment. Natural gas as an alternative transportation fuel has made significant inroads in the light and heavy duty vehicles market over the last fifteen years. In a sustainable development view, both vehicle emissions and energy supply chain analysis from well-to-wheel must be addressed. The aim of this research is to provide a Well-to-Wheel (WtW) assessment of energy consumptions and GHG emissions for 25 combinations of automotive fuel and matching powertrain systems, with a special focus on the natural gas pathways. Although several well-to-wheel studies available in literature are comprehensive in relation to developed countries' conditions, it is problematic to apply the results to developing countries fuel markets, since the local fuel conditions and respective vehicle powertrain technologies are considerably different. This study deal with a comparative well-to-wheel analysis of natural gas, diesel and gasoline fuels looking at the Pakistanis situation but the models and approaches for this study can be applied to other countries having similar characteristics, as long as all the assumptions are well defined and modified to find a substitute automotive energy source and establish an energy policy in a specific region. The well-to-tank step was made using the GREET model, developed by the U.S. Argonne National Laboratory while tank-to-wheel analysis was performed using AVL Cruise, a commercially-available backward vehicle simulator. Later both stages were integrated in a well-to-wheel stage where relevant indexes were proposed and discussed. The results indicate that natural gas vehicles are 5–17% and 23–36% less fuel efficient, depending on the engine technology employed as compared to gasoline and diesel powertrain, respectively.

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Natural gas appears as an environmental efficient pathway regarding GHG emissions, especially compared to gasoline. In addition, using 20-year GWPs instead of 100-year GWPs increases WtW GHG emissions by 19–26% for natural gas pathways.

Nomenclature

AFR	air fuel ratio
ANL	Argonne national laboratory
ATT	after-treatment technologies
API	American petroleum institute
BEV	battery electric vehicle
BTU	British thermal unit
CAPP	Canadian association of petroleum producers
CH_4	methane
CI	compression ignition
CN	Cetane number
CNG	compressed natural gas
CO_2	carbon dioxide
CO_2eq	CO_2 equivalent
DISI	direct injection spark ignition
DICI	direct injection compression ignition
DPF	diesel particulate filter
DOC	diesel oxidation catalyst
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
g/km	gram per-kilometer
GREET	greenhouse emissions and energy use in transportation
GWP	global warming potential
H/C	hydro-carbon ratio
HEV	hybrid electric vehicle
IC	internal combustion
ICE	internal combustion engine
IP	Iran Pakistan
IPCC	intergovernmental panel on climate change
IVE	International Vehicle Emissions
JRC	joint research center
Km	kilometer
kW	kilowatt
kWh	kilowatt hour
LCA	life cycle analysis
LHV	latent heat of vaporization
Lit	liter
LNG	liquefied natural gas
LNT	lean NOx traps
MJ	megajoule
MMSCFD	million cubic feet per day
NDCs	nationally determined contributions
NEDC	new European drive cycle
Nm	Newton meter
N_2O	nitrous oxide
NG	natural gas
NGVs	natural gas vehicles
PISI	port injection spark ignition
RON	reteach octane number
rpm	revolutions per minute
SCFB	standard cubic feet per barrel
SCR	selective catalytic reduction
SI	spark ignition
SNGPL	Sui northern gas pipelines limited
SSGCL	Sui southern gas company limited
STEP	sustainable transport energy program
TAPI	Turkmenistan Afghanistan Pakistan India
TOE	ton of oil equivalent
TtW	Tank-to-Wheel
TWC	three-way catalyst
WtT	Well-to-Tank
WtW	Well-to-Wheel
U.S.	United States

1. Introduction

The Paris Agreement – the first-ever universal, legally binding global climate deal – was adopted by 195 countries at the Paris Climate Conference (COP21) in December 2015. The Paris Agreement requires all Parties to put forward their best efforts through "nationally determined contributions" (NDCs) to greatly reduce greenhouse gas (GHG) emissions. Being the world's 6th most populated nation, its energy requirement establishes Pakistan as a major contributor of GHG emissions; therefore, the reduction of the GHG emissions in Pakistan has attracted substantial local attention. The energy consumption of the road transportation sector accounts for 33% of the total energy consumption in Pakistan [1] and is responsible for a significant share (around 25%) of GHG emissions nationwide [2]. Therefore the reduction of GHG emissions in the transportation sector is a top priority of the government [3].

Emissions and energy consumption are often measured at the point of use. This does not, however, account for the overall emissions and energy consumption. To evaluate the impact of fuels and energy carriers the whole supply chain has to be considered [4]. To evaluate and assess the energy consumption, emissions, and economic effects of automotive fuels and vehicle technologies, a holistic or comprehensive approach has to be considered. The approach, often referred to as life cycle approach, or life cycle assessment (LCA), which must include all the steps required to produce a fuel, to manufacture a vehicle, and to operate and maintain the vehicle throughout its lifetime including disposal and recycling at the conclusion of its life cycle. A lifecycle analysis of energy consumed and emissions generated is especially important for technologies that employ fuels with different primary energy sources and fuel production processes. A typical life cycle of a vehicle technology is shown in Fig. 1. The life cycle can be classified into two major categories: the fuel cycle and the vehicle cycle. The fuel lifecycle analysis, also known as well-to-wheel analysis is vital for selecting vehicle fuels and technologies for the future.

The well-to-wheel analysis indicates the study of the energy use and GHG emissions in the production of the fuel and its use in the vehicle or engine, hereinafter called WtW analysis. Compared to Life Cycle Assessment (LCA) a WtW analysis can have the same system boundaries but does not consider energy or emissions involved in the construction of the facilities, the vehicles, consumption of other materials, water, and end of life disposal [5]. The whole WtW cycle is comprised of two independent stages, as shown in Fig. 2. These include (i) a Well-to-Tank (WtT) stage, which includes the recovery or production of the feedstock for the fuel, transportation and storage of the energy source through conversion of the feedstock to the fuel and the subsequent transportation, storage, and distribution of the fuel to the vehicle tank, and (ii) a Tank-to-Wheel (TtW) stage, which refers to the vehicle in utilizing the fuel for traveling purposes throughout its lifetime.

The rest of this paper is structured as follows: Section 2 reviews the existing literature. Section 3 defines the key assumptions and parameters used in well-to-wheel analysis including functional unit, GHG coefficients, fuel pathways, and methane slip/leakage and vehicle

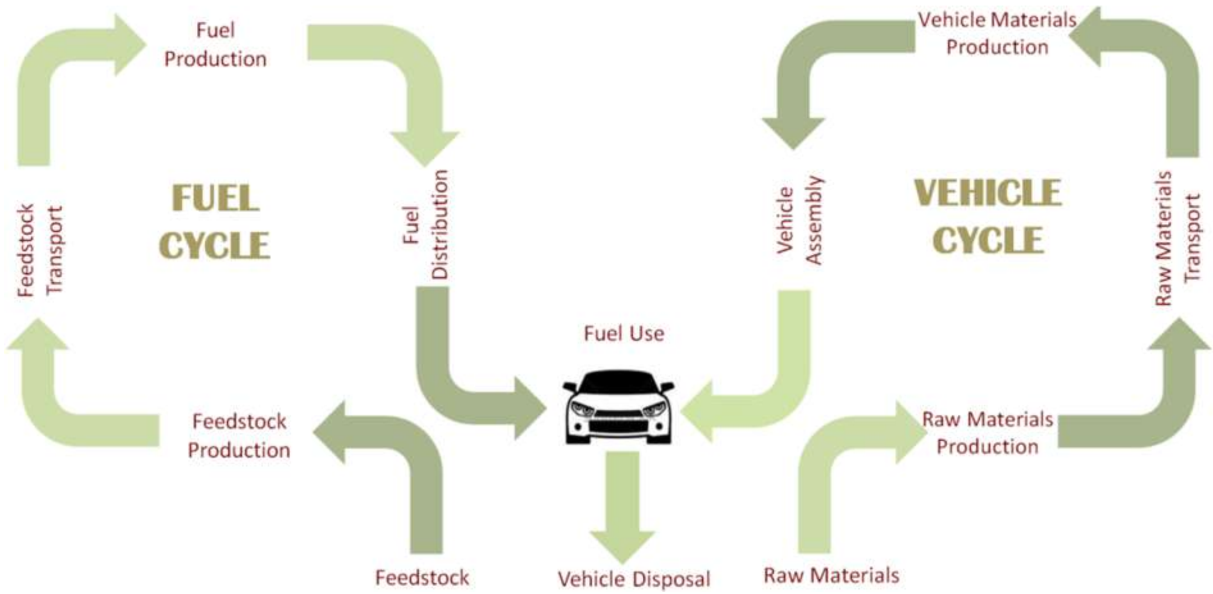

Fig. 1. Typical life cycle of a vehicle technology.

technologies. Section 4 describes the research methodology and data. The results and discussion are reported in Section 5. A comparative analysis of this study with previous studies is presented in Section 6. Section 7 concludes the outcomes of the study.

2. Review of the state-of-the-art

Many variations of WtW studies [6–18] have been proposed in the literature to capture different aspects of the fuel life-cycle of transportation fuels for various propulsion in different regions of the world. However WtW studies on CNG vehicles haven't got much academic interest and only a few analyses have been conducted targeting the CNG fuel, with often varied and even contrasting results. In this section, we have presented a brief review of those WtW studies pertaining to CNG.

The first comprehensive WtW analysis study [19] was performed by General Motors and Argonne National Laboratory. The analysis based on the U.S. market which includes a set of 75 different fuel pathways and 15 vehicle powertrains, aimed at informing the public and private decision 65 makers on the impact of diverse fuel/vehicle systems. GREET was used for the WtT tank stage, while proprietary 66 GM models were used to compute TtW energy consumption and emissions. The results revealed that on WtW energy basis CNG consumes 4% and 25% more energy than gasoline and diesel fuel vehicle respectively. Similarly, for GHG emission the study estimated that CNG produces 8% less GHG emission than gasoline while 6% more than conventional diesel fuel. Another WtW study in US setting was conducted by Waller et al. [20]. This study compares the current and theoretical maximum well-to-wheels energy efficiencies of passenger vehicles using natural gas in three different ways: via direct use in a CNG vehicle, for production of hydrogen used in a fuel cell vehicle, and to generate electricity for a battery electric vehicle. The study reveals the best current and theoretical maximum WTW energy efficiencies corresponding to 31%/63%, 25%/87% and 44%/84% for CNG, FCEV, and BEV pathways respectively. In the European context, the Joint Research Center (JRC) has recently published WtW study based on 2010 vehicle-fuel specific data with predictions for the period beyond the year 2020 [21]. This study considered a C-segment 5-seater sedan as a reference vehicle and simulated vehicles on NEDC (New European Drive Cycle) for TtW evaluations. For TtW analysis, a wide range of fuel-powertrain combinations were considered. The major fuels considered were: gasoline, diesel, LPG, CNG, hydrogen and bio-diesel. For CNG fuel two pathways were considered i.e. (i) imported natural gas via 4000 km pipeline and (ii) natural gas from imported LNG. The results show that on WTW basis CNG is less energy efficient than gasoline and diesel fuel. Similarly, for GHG the study shows that CNG produces less emission than gasoline and more emission than diesel fuel. Another study by Torchio et al. [22] described a WtW analysis in the European context introducing a new global index by assigning costs to energy, emissions and other factors. This study concludes that usage of natural gas-based fuels and hybridization as promising options compared to conventional gasoline and diesel fuel vehicles. Similarly, a WtW analysis by Yazdanie et al. [23] concerned the operation of conventional and alternative passenger

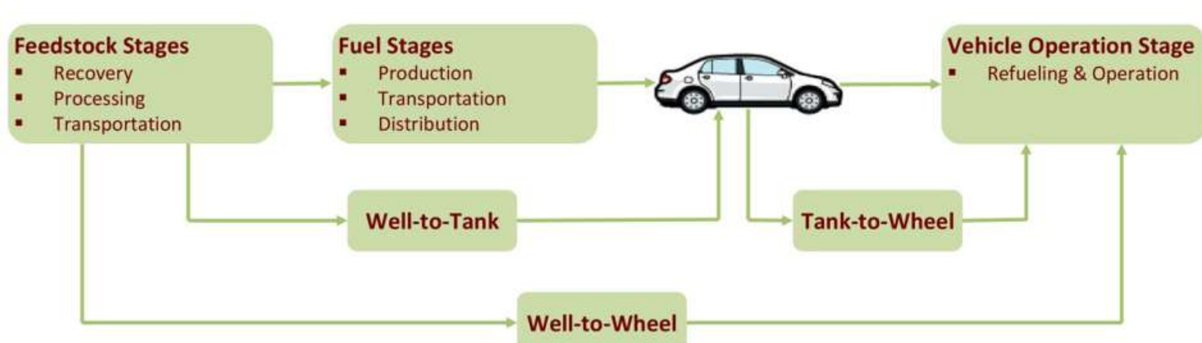

Fig. 2. System boundary of well-to-wheel analysis of the case study fuels.

vehicles in Switzerland. This analysis showed that HEVs using alternate fuels particularly biogas and CNG resulted in remarkable reductions in WTW energy and GHG emissions over a conventional gasoline-powered IC engine vehicle. In Australia, as part of the Sustainable Transport Energy Program (STEP), Ally et al. [24] did an LCA comparison of bus fleets powered by diesel, CNG and hydrogen fuel cell respectively. They showed that CNG required more energy per distance traveled and resulted in slightly higher GHG emissions compared to diesel driven vehicles. However, vehicles driven by CNG showed lower emissions related to smog, acidification, and soil/water contamination (NOx, CO, SO_2, and non-methane volatile organic compounds) for Western Australia. In Canadian setting, Rose et al. [25] carried out a comparative LCA with GHGenius (LCA model developed for Canadian Transport system) on refuse collection vehicles powered by diesel and CNG and found that a 24% reduction of GHG emissions was achieved by switching from diesel to CNG. In the US context, Tong et al. [26,27] WtW GHG emissions of light-duty and heavy-duty vehicles fueled by natural gas were examined and compared to their gasoline and diesel counterparts, and vehicle fuel efficiency and methane leakage rate of the natural gas supply chain were found to be major drivers to the relative GHG emission performances of NGVs. In China, Karman et al. [28] presented the results from an assessment of WtW GHG emissions from buses fuelled with diesel and CNG in the city of Beijing. The model employed was the 'China version' of 'GHGenius', created by using specific data and estimates wherever China-specific information was available to replace its default data for North America. It was found that GHG emissions 'per vehicle-kilometer driven' for CNG were slightly lower than those for diesel. In another study, Ou et al. [29] employed Tsinghua-CA3EM model to compare the WtW performance of alternative fuel buses with conventional buses specific to China. They showed that CNG buses consume 14% less energy and produce 28% less GHGs than a counterpart diesel vehicle. Likewise, Patil et al. [30] conducted a country-specific WtW analysis of automotive fuels for India. Specifically, 28 vehicle/fuel configurations of a subcompact passenger car were selected for detailed analysis in the Indian context. The results revealed that on WtW basis CNG produces ~26% less GHG emission than gasoline while ~7% more than conventional diesel fuel. Curran et al. [31] used the GREET model to analyze the WtW energy use and GHG emissions from natural gas pathways. They specifically compared CNG vehicles and electric vehicles charged with natural gas-based electricity and found that the latter is better.

It is clear from the above literature that most of the WtW studies mostly focus on developed countries. The nature of choices and assumptions made in these WtW studies are likely to be subjective. Therefore results of WtW studies focused on developed economies like USA, Europe may not be appropriate for developing countries applications. It is problematic to apply the results of LCA studies conducted for developed countries to developing countries fuel markets like Pakistan, since the local conditions and respective vehicle powertrain technologies are considerably different. To the best of our knowledge, no comprehensive WtW assessment of transportation, especially for fuels with commercial availability, has been fully investigated in the developing countries. WtW modeling for different fuel pathways in the developing countries using a unified but comprehensive and systematic computing platform is problematic because: (1) relatively limited data are available, (2) cooperation between related research institutes is weak, and (3) funding for long-term research has been insufficient. Moreover, most of the WtW studies available in the literature used the GREET model to estimate the emission reduction potentials and the fuel efficiency of natural gas pathways compared to petroleum fuels. However, these studies failed to include a comprehensive set of pathways and used outdated data with regard to natural gas upstream emissions and global warming potential (GWP). In addition, they largely ignored uncertainty and variability, especially those related to fugitive methane emissions from natural gas systems. The present study addresses these limitations and provides an independent emission inventory in addition to the GREET model.

Therefore the aim of this study is to construct the first comprehensive WtW GHG database of petroleum-based automotive fuels commercially available in Pakistan that will be essential to meet the rising stringent emission standards and to evaluate the best fuel option for Pakistan. The study presents a detailed WtW analysis to compare vehicles fueled with CNG, gasoline and diesel. The comparison is based on two indicators: (i) primary energy consumption, and (ii) GHG emissions. Instead of simply listing the comparisons, this paper discusses the reasons that cause the changes in the efficiencies and emissions that are brought about by automotive fuels.

This study is designed with the view of helping policy makers to answer the following questions:

- Based on the evaluation of the WtW cycles of automotive fuels specific to Pakistan, which fuel option among the selected fuel/power types would have the least harmful environmental impact overall?
- Which life cycle phase contributes the most to each of the different possible environmental impacts?
- Which uncertainties in life cycle analyses could most drastically affect the environmental performance of CNG vehicles?

This study distinguishes itself from previous efforts in the following ways:

- This is the first study to consider a detailed WtW analysis of CNG fuel with three different pathways (i.e. domestic natural gas, interstate gas pipeline and LNG) in developing and energy importing countries like Pakistan. Moreover, this study is the first initiative in the developing countries to consider TtW analysis for a C-segment passenger car equipped with gasoline (PISI and DISI), diesel, dedicated CNG (PISI and DISI) and bi-fuel CNG engine (PISI and DISI) technology. This combined with the variety of fuel pathways considered makes this, to the best of our knowledge, the most comprehensive WtW analysis of fossil fuels available to date
- Other than being the first comprehensive country-specific WtW study for Pakistan, the novelty of this work lies in the use of a consistent framework across multiple powertrain types with the same operating conditions to assess energy consumption and operating emissions.
- The study integrates the microscopic base emission model AVL Cruise coupled with the macroscopic base emission model GREET for WtW analysis under specific regional conditions.
- This study reports a comparison of WtW GHG emissions for CNG, diesel and gasoline vehicles using global warming potential (GWP) with both 100-years and 20-years based on the latest 5th assessment report released by Intergovernmental Panel on Climate Change (IPCC 2013) [32]. All else being equal, the choice of the time horizon for GWP greatly changes the equivalent CO_2 emissions of methane, which has a much higher GWP over 20 years than over 100 years.

3. Methodology and data

As mentioned above the WtT cycle consist of two stages i.e (i) WtT stage, and (ii) TtW stage. The WtT stage of study has been covered in part-1 [33] of this two-part study. In this paper, the Well-to-Tank (WtT) results observed in part-1 [33] are combined with the TtW (Tank-to-Wheel) results reported in this present paper to provide the comprehensive WtW (Well-to-Wheel) results for the operation of conventional and CNG passenger vehicle drivetrains specific to Pakistan.

Tank-to-Wheel phase of the Well-to-Wheel cycle considers the energy use and emissions associated with the operation of a vehicle. Different factors affect emissions from motor vehicles, including travel, driver, facility, vehicle, fuel and overall environmental characteristics.

Travel-related factors include vehicle engine operating modes or temperatures (cold and hot starts, hot stabilized periods), speeds, accelerations and decelerations. Significant impacts on emission levels are also influenced by those driver behaviors causing speed variations in response to specific traffic conditions, vehicle and fuel types, thus imposing heavy loads on the engine. Facility-related factors, which include infrastructure engineering features and traffic signals, are supposed to encourage low-emitting speeds or operating modes. Emission rates further depend on vehicle-related factors such as age, mileage, maintenance conditions, weight, size, engine power, fuel delivery system, emission control system. Furthermore, environmental factors (air temperature, altitude, humidity) play an important role in affecting emissions.

The review of existing methods provides evidence that generally a computer-based emission model is used to incorporate the effects of the above-mentioned factors in the measurement of energy consumption and emissions during the operation of a vehicle. The literature encompasses the two general approaches (i.e. Macroscopic models and Microscopic models) used to estimate vehicle emissions and fuel consumption. The macroscopic modeling approach uses average aggregate network parameters to estimate network-wide emission rates according to high-level relationships among density, flow, and speed of traffic flows on urban road networks [34]. These models develop emission and fuel consumption factors based on macroscopic activity, like transport productivity or Vehicle Travel Kilometers (VTK). For macroscopic emissions models, only a macroscopic emission estimation approach can be applied, since detailed individual vehicle data is not available in these models. This type of models is generally used in case of modeling emissions of transportation systems in a large scale strategic level, like national road network or regional scale. The popular example of this type includes MOBILE, EMFAC, COPERT, IVE Model [35].

The microscopic models describe individual vehicle movements through the traffic simulation model. In these models, each vehicle moves through the traffic network with an updated character which is determined by speed, acceleration, time, and individual driver behavior. The driver behavior is determined by a set of models such as car following, lane changing, acceleration noise and etc. Its application envelope covers conventional vehicle powertrains through to highly-advanced hybrid systems and pure electric vehicles. Examples of this type include MOVES, CMEM, PHEM, ADVISOR, Autonomie, and AVL CRUISE.

To estimate the comparative tank-to-wheel energy use and emissions associated with the operations of CNG, gasoline and diesel vehicle specific to Pakistan, this study used AVL Cruise, a commercially-available backward vehicle simulator for GHG emission and energy use [36]. AVL CRUISE is an example of a micro-scale instantaneous emission model based tool which enables the user to design a specific passenger vehicle and simulate fuel consumption and emissions under different operating conditions. It is considered to be one of the industry's most powerful, robust and adaptable software for vehicle system and driveline analysis with advanced simulation and optimization features [37]. It helps efficiently developing the right decisions leading to competitive vehicles with respect to fuel efficiency, emissions, performance and driveability [38]. In AVL Cruise the architectures of any kind of drivetrain can be modeled by using the available component blocks e.g. IC engines, clutches, transmission elements, controls, shafts, wheels/tires, electrical components, brakes, auxiliaries, curb weight and others. So it can simulate any passenger vehicle commercially available in the market. The engine's performance, fuel consumption, emissions etc. are all based on stationary measured curves and maps. This means it does not really know what type of engine you are simulating and what fuel you want to use as an energy source. What it needs is a full load characteristic of the engine, a motoring curve of the engine and then the fuel consumption map, where you input the fuel consumption either as volume flow or mass flow depending on Engine speed and Engine torque or Power. It also facilitates the user to input the emission maps for NOx, CO, HC and Soot. Due to these structured interfaces and advanced data management concept, AVL Cruise has established itself as a

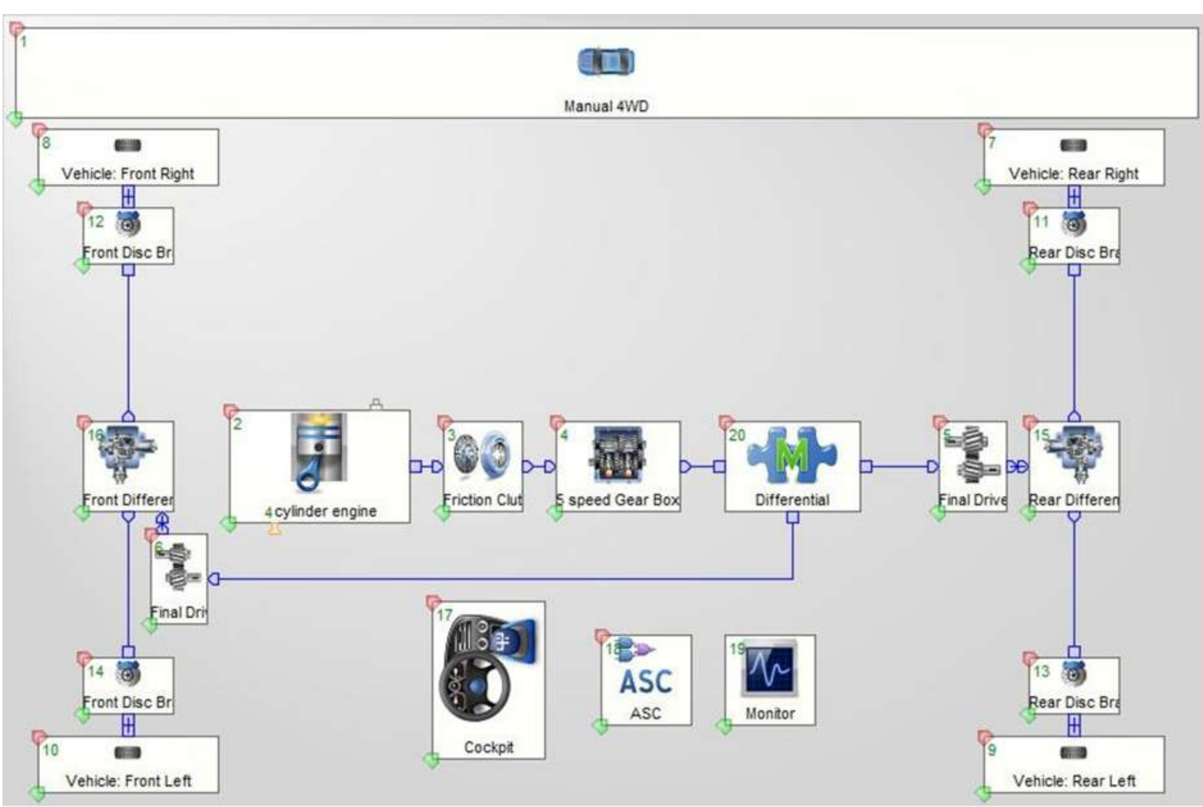

Fig. 3. Template topology for conventional vehicles in the AVL CRUISE environment.

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data communication and system integration tool for different teams within world-leader OEM's and their suppliers [39]. CNG vehicles are not included in AVL Cruise. To include this technology, an adhoc CNG vehicle model has been implemented in AVL Cruise using experimental data provided by a Pakistani OEM automaker. In order to simulate a vehicle, a template model structure (Fig. 3) has been developed. It consists of components that actual vehicles have (such as IC engine, gearbox, wheels, brakes, etc.), functions that control the operation of each component and the necessary connections between them. Each component is described by a number of parameters and is configurable in such an extent that it can reproduce most of the representative vehicles (e.g. diesel, gasoline, CNG) selected for this study. The connections can be either mechanical, allowing mechanical power flow (for example ICE → clutch → gearbox), electrical (battery → starter), or informational (control functions). All vehicle models assessed in this study are simulated over the New European Driving Cycle (NEDC) for predicting fuel economy and carbon dioxide emissions.

4. Key assumptions and parameters

Following are key parameters and assumptions used in this study:

4.1. Function unit

This study used the following important function units:

- WtT stage energy consumption is calculated on a megajoule per megajoule (MJ/MJ) basis.
- TtW and WtW stage energy consumption is calculated on a megajoule per-kilometer (g/km) basis.
- WtT stage emissions are calculated on a gram per megajoule (g/MJ) basis.
- TtW stage emissions are calculated on a gram per-kilometer (g/km) basis.
- WtT results are combined with TtW results and overall WtW energy consumption and GHG emission are calculated on g/MJ and g/km, respectively. The different functional units associated with WtT and TtW stages, are linked through formulas:

$$WtT\ \ energy\ \ in\left[\frac{\text{MJ}}{\text{km}}\right] = WtT\ \ energy\ \ in\left[\frac{\text{MJ}}{\text{MJ}}\right] \times TtW\ \ energy\ \ in\left[\frac{\text{MJ}}{\text{km}}\right] \tag{1}$$

Similarly

$$WtT\ \ GHG\ \ in\left[\frac{\text{g}\ \ \text{CO}_2\text{eq}}{\text{km}}\right] = WtT\ \ GHG\ \ in\left[\frac{\text{g}\ \ \text{CO}_2\text{eq}}{\text{MJ}}\right] \times TtW\ \ GHG\ \ in\left[\frac{\text{g}\ \ \text{CO}_2\text{eq}}{\text{km}}\right] \tag{2}$$

4.2. GHG coefficients

The CO_2 equivalence is applied to the non-CO_2 greenhouse gases according to the 100 year and 20 year conversion coefficients recommended by the latest 5th assessment report of the Inter-governmental Panel for Climate Change (IPCC 2013) [32] tabulated below (Table 1).

4.3. Vehicle emission control technologies

In developed countries today, the vehicles' emissions compliance is accomplished through engine management, along with a suite of advanced catalyst technologies, including: three-way catalyst (TWC), diesel particulate filter (DPF), diesel oxidation catalyst (DOC), selective catalytic reduction (SCR), and lean NOx traps (LNT). However, in developing countries like Pakistan, these vehicle emission after-treatment technologies (ATT) are still very rare. Therefore in this study, all the vehicle technologies are modeled without ATT.

4.4. Pakistan's fuel mix

Before discussing the WTT fuel pathways for various transportation fuels in Pakistan, the statistical highlights of road transportation fuels are presented in Appendix A.

4.5. Fuel pathways

The study considers three types of fuels (CNG, gasoline & diesel) extracted from 10 different fuel pathways. Table 2 illustrates the fuel pathways considered in this study.

4.6. Reference vehicle and vehicle technologies

All simulations are based on a generic or "virtual" reference vehicle, representing a common Pakistani C-segment 5-seater sedan, comparable to e.g. a Toyota GLI or Honda City or others in that class. This reference vehicle is used as a tool for comparing the various fuels and associated technologies covered in this study. Base vehicle characteristics and vehicle technologies considered in this study are given in Table 3. Combining the fuel pathways shown in Table 2 with the vehicle technologies listed in Table 3, results in 25 powertrain configuration (Table 4).

5. Results and discussion

In this study, a WtW analysis on 25 combinations of automotive fuel and matching powertrain systems available in Pakistan was conducted.

5.1. WtT energy consumption and GHG emissions

In the first part [33] of this two-part study, a WtT analysis was conducted on 10 different combinations of transportation fuels in Pakistan (Table. 2). The resulting energy consumption and GHG emission obtained in part-1 [33] of this study are reproduced in Fig. 4 and Fig. 5, respectively.

5.2. TtW analysis

TtW analysis was conducted on seven different vehicle technologies highlighted in Table 4. The vehicle energy efficiency and GHG emissions results in MJ/km and g CO_2eq/km, respectively are presented and discussed.

5.3. TtW energy consumption

The TtW energy efficiency for all powertrains is shown in Fig. 6.The energy efficiency for a diesel-powered vehicle is expectedly better as compared to vehicles powered with gasoline, and CNG. This is due to the higher efficiency of the CI engine technology when compared to SI engine. It is observed that direct injection in SI engine can reduce TtW energy consumption by about 4.5–8%. By injecting the fuel directly into

Table 1
IPCC GWP values of greenhouse gases.

GHG	GWP value	
	100-year time horizon	20-year time horizon
CO_2	1	1
CH_4	28	84
N_2O	265	265

Table 2
Fuel Pathways considered in this study.

Fuel Type	Symbol	LHV MJ/kg	RON/CN	CO_2 Emission factor g/MJ
Gasoline (produced at local refineries from indigenous crude oil sources)	F1	43.2	93	73.4
Gasoline (produced at local refineries from imported crude oil sources)	F2			
Gasoline (imported from the Middle East)	F3			
CNG (produced from indigenous gas sources)	F4	45.1		56.2
CNG (produced from imported gas through IP Pipeline)	F5			
CNG (produced from imported gas through TAPI Pipeline)	F6			
CNG (produced from imported LNG)	F7			
Diesel (produced at local refineries from indigenous crude oil sources)	F8	43.1	51	73.2
Diesel (produced at local refineries from imported crude oil sources)	F9			
Diesel (imported from the Middle East)	F10			

each cylinder of the engine, better control of fuel's behavior can be achieved, improving the accuracy of air/fuel ratio during engine's dynamic performance, permitting use of higher compression ratios, and reducing the losses resulting from throttling the airflow in the standard port-injected SI engine [40]. The injected fuel, evaporates in the cylinder and causes to cool the intake charge. The cooling effect permits higher compression ratios and increasing of the volumetric efficiency and thus higher torque is obtained [40]. The dedicated DISI natural gas vehicles show significantly improved fuel economy results as compared to bi-fuel CNG and gasoline vehicles using PISI & DISI technology. The improvement in the TtW energy efficiency for DISI dedicated CNG vehicles can be attributed to the direct injection advantage over port injection and higher octane number of natural gas as compared to gasoline. Moreover dedicated CNG vehicles have SI engines that are operated only on natural gas. So compression ratio of these engines is optimized to utilize the advantage of high octane number (1 2 0) of natural gas which enhances engine thermal efficiency of about 10% above than that of gasoline engine [41]. Owing the above mentioned attributes, DISI engine technology provides significant improvements in fuel economy. However direct injection systems are more expensive as it requires costly and technically difficult modification to engine structure especially due to the need for an extra hole for the fuel injector. One other contributing factor toward the power loss in CNG engines is the stoichiometric air to fuel ratio (AFR) of natural gas. Natural gas has AFR of 17, compared to approximately 14.6 for diesel and gasoline. Since the mass of air inducted into the engine is limited, a

Table 4
Combination of WtW fuel pathways and vehicle technologies combination.

WtT Fuel Pathway (F)	TtW Powertrain (P)	WtW Combination (FP)
F_1	Gasoline PISI (P_1)	F_1P_1
F_2		F_2P_1
F_3		F_3P_3
F_1	Gasoline DISI (P_2)	F_1P_2
F_2		F_2P_2
F_3		F_3P_2
F_4	CNG Dedicated PISI (P_3)	F_4P_3
F_5		F_5P_3
F_6		F_6P_3
F_7		F_7P_3
F_4	CNG Bi-fuel PISI (P_4)	F_4P_4
F_5		F_5P_4
F_6		F_6P_4
F_7		F_7P_4
F_4	CNG Dedicated DISI (P_5)	F_4P_5
F_5		F_5P_5
F_6		F_6P_5
F_7		F_7P_5
F_4	CNG Bi-fuel DISI (P_6)	F_4P_6
F_5		F_5P_6
F_6		F_6P_6
F_7		F_7P_6
F_8	Diesel DISI (P_7)	F_8P_7
F_9		F_9P_7
F_{10}		$F_{10}P_7$

Table 3
Specification of reference vehicle technologies.

Description	Unit	Vehicle technology						
		PISI			DISI			DICI
		Gasoline	CNG (Bi-fuel)	CNG (dedicated)	Gasoline	CNG (Bi-fuel)	CNG (dedicated)	Diesel
Curb wright (including fuel)	kg	1275	1275	1275	1275	1275	1275	1275
Weight class	kg	1360	1360	1360	1360	1360	1360	1360
Length	mm	4507	4507	4507	4507	4507	4507	4507
Width	mm	1735	1735	1735	1735	1735	1735	1735
Height	mm	1477	1477	1477	1477	1477	1477	1477
Drag coefficient	–	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Vehicle front area	m^2	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Tyre size	–	195/65 R15	195/65 R15	195/65 R15	195/65 R15	195/65 R15	195/65 R15	195/65 R15
Transmission	–	Synchromesh 5 forward speed – 1 reverse Manual						
Engine displacement	liter	1.3	1.3	1.3	1.3	1.3	1.3	1.3
No. of cylinder	–	4	4	4	4	4	4	4
Compression ratio	–	10.5:1	11:01	12.7:1	10.5:1	11:01	12.7:1	17.6:1
Specific power	kW/lit	64		57	64	58	64	55
Maximum power	kW @rpm	63 @6000	86 @6000	99 @5750	90 @4300	95@4800	99 @ 4300	92 @ 4000
Maximum torque	Nm @rpm	121 @4400	123 @ 4000	170 @3500	200 @1750–4000	140@4200	220 @1750–4000	200@ 1750
BSFC @ 2000 rpm/2 bar	g/kWh	395	385	365	385	380	355	305
BSFC minimum	g/kWh	240	235	225	244	238	214	210
Fuel economy	km/lit	14	13.8	15.27	14.53	14.32	16.74	19.1

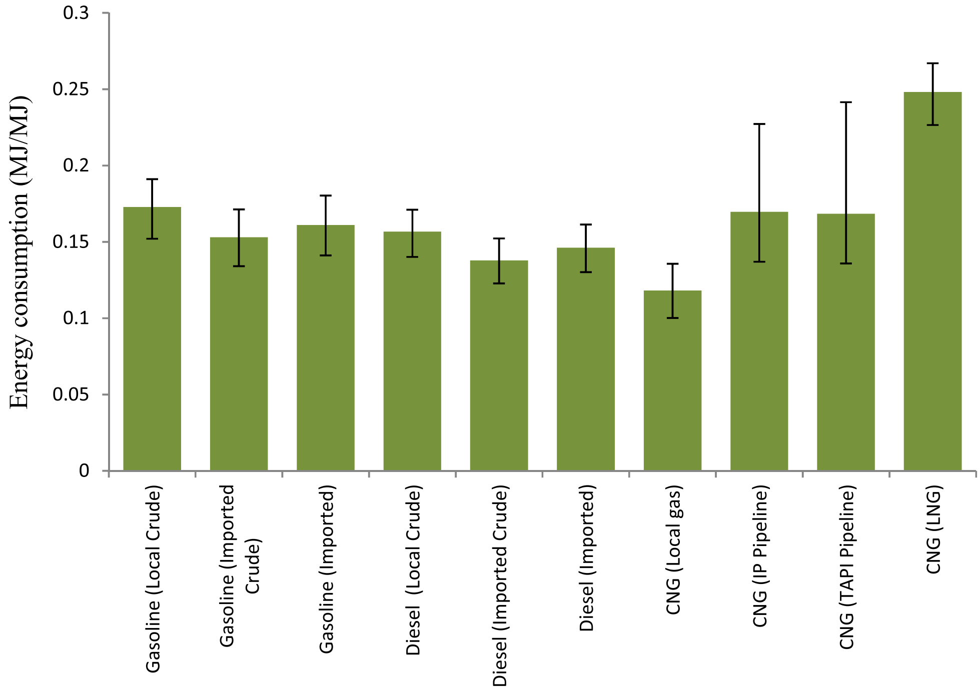

Fig. 4. WtT energy consumption for the selected pathways.

higher AFR means less energy into the engine and lower peak power.

Bi-fuel PISI CNG vehicles show the worst TtW performance in terms of energy use, due to relatively low flame propagation of natural gas and loss in volumetric efficiency. Due to the low densities, gaseous fuels occupy 4–15%of intake passage volume resulting in a significant reduction of volumetric efficiency when compared to liquid fuels. Therefore lesser volumetric efficiency and flame propagation of natural gas reduce bi-fuel CNG engine power by 10% when compared to gasoline.

Although due to high octane value, the SI engine running on natural gas can be expected with relatively high thermal efficiency but retrofit Bi-fuel CNG engines will not have the advantage of high octane value of natural gas as the compression ratio will be set to the level required for gasoline. It can be observed that in contrast to conventional PISI

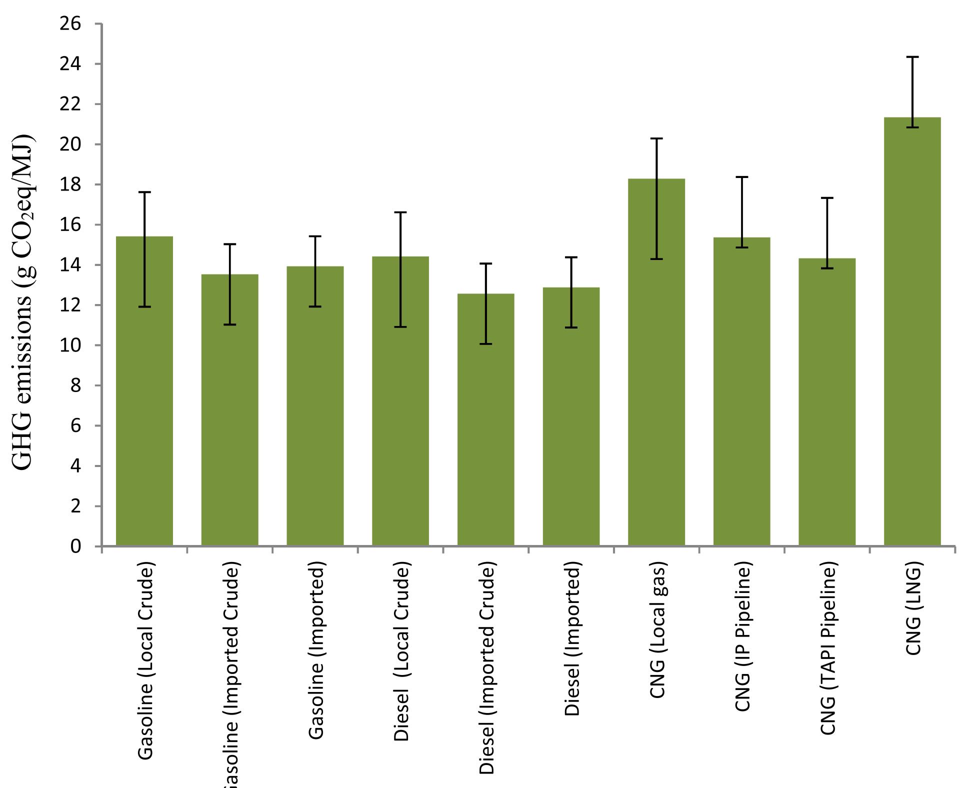

Fig. 5. WtT GHG emissions for the selected pathways.

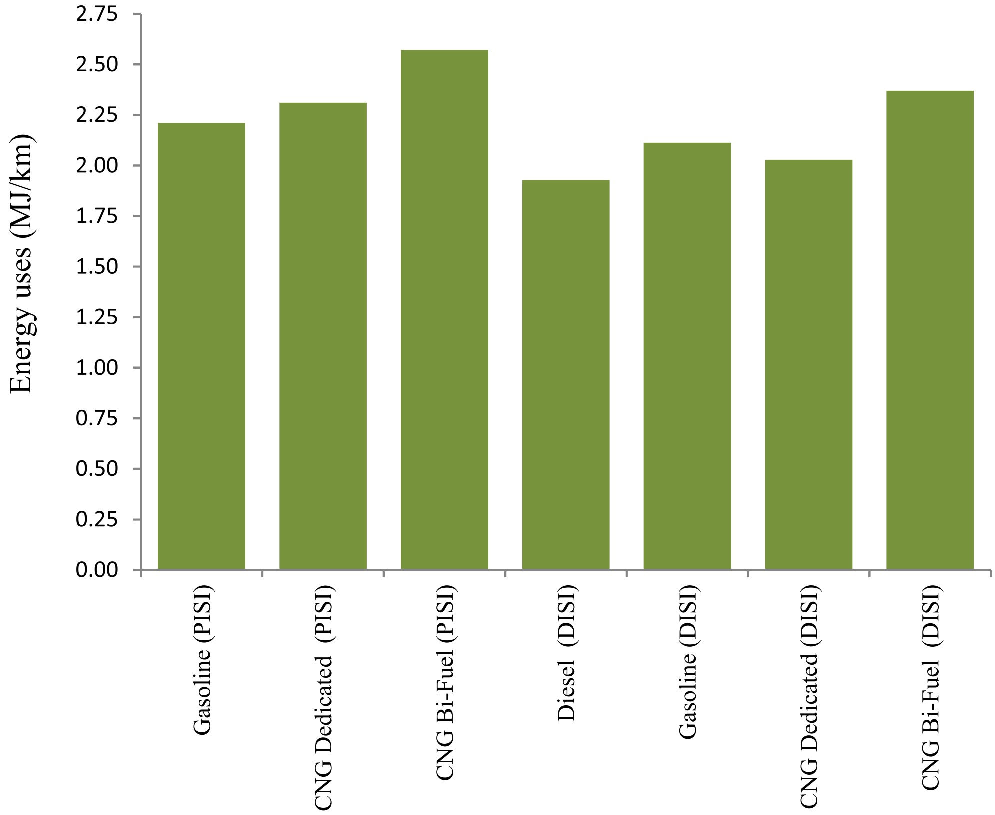

Fig. 6. TtW energy uses for the selected powertrain technologies.

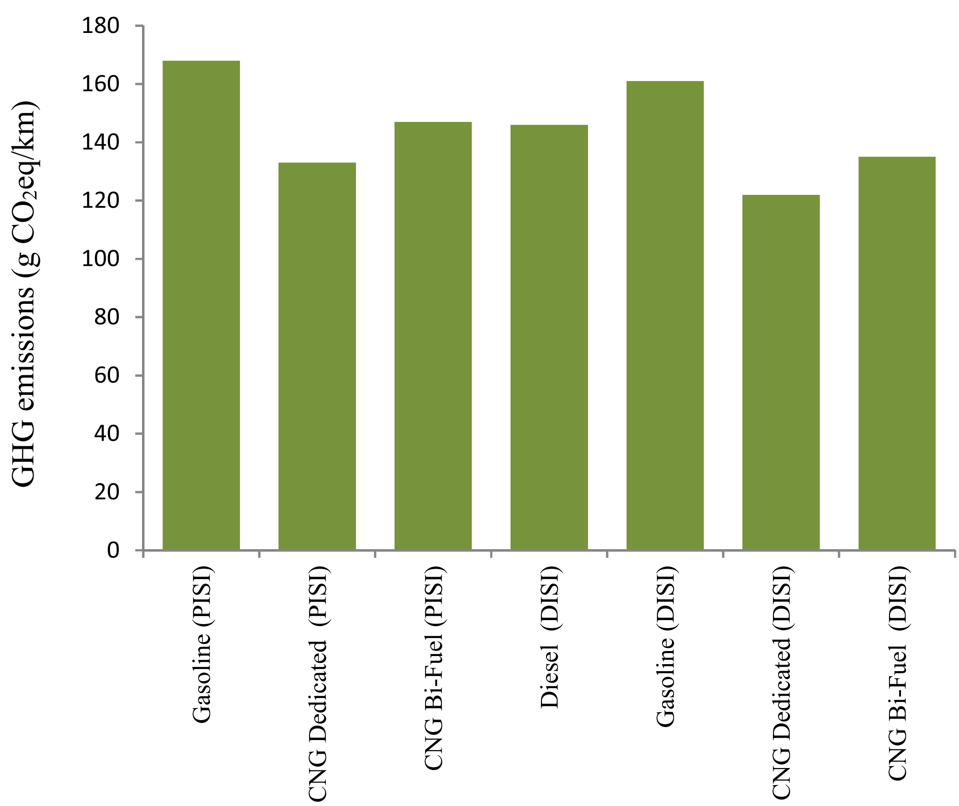

Fig. 7. TtW GHG emission for the selected powertrain technologies.

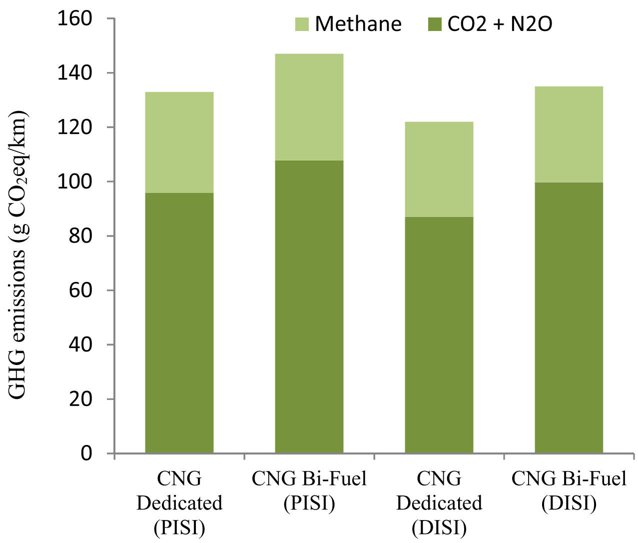

Fig. 8. Share of methane emission in TtW GHG emissions for natural gas-fueled powertrains.

gasoline powertrain, bi-fuel CNG system will still be 6.3% less energy efficient even if it is equipped with a direct ignition system which shows that the engine's thermal efficiency has a significant impact on TtW energy efficiency.

5.4. TtW GHG emission

The GHG emissions results are presented in Fig. 7. A powertrain that run on natural gas emit less TtW GHG emissions than their peers, achieving 12.4–27% reductions compared to gasoline vehicles and 0–16.5% reduction versus their diesel counterpart. Thanks to the large fuel efficiency benefits, diesel-powered vehicles achieve 9.3–13% GHG emission reductions over gasoline and 0.5% to bi-fuel PISI natural gas vehicles.

The comparatively low GHG emission of natural gas fueled powertrain is primarily due to the fact that the main constituent of CNG is methane (CH_4), the simplest alkane with only one carbon atom and consequently no carbon-to-carbon bonds. The simple chemical structure of methane makes it an inherently clean burning fuel than any other fossil fuel [42]. For instance, when combusted, natural gas releases 28 percent less carbon dioxide per unit of heat than diesel fuel [41]. But on the other hand, methane is 28 times more potent greenhouse gas than carbon dioxide (CO_2) and its leakage from the engine can offset the emission benefits of CNG. Moreover being a major constituent of natural gas, the hydrocarbons emitted from a CNG engine are mainly composed of methane which is much harder to ignite in the after-treatment system then the heavier hydrocarbons associated with gasoline and diesel as it requires a much higher temperature of 540 °C when compared to gasoline (258 °C) or diesel (316 °C) [43]. For this reason, minimizing engine-out emissions of unburned methane is of great importance.

Methane is also emitted from gasoline and diesel vehicle but its quantity is much low (~23% at the level of NGVs [44] as compared to CNG vehicles. Methane is released in the engine due to incomplete or partial fuel combustion, which produces CH_4, CO, PM along with other unburned hydrocarbons. This usually occurs when the ratio of air to fuel in the combustion chamber is too low for complete combustion i.e. there is inadequate oxygen to convert all CH_4 present in the fuel to CO_2 and H_2O and heat. Based on the literature review, crankcase and tailpipe emissions are the two largest sources of methane loss from natural gas vehicles and can be calculated by Eq. (3) [45].

$$\text{Methane Loss}(\%) = \left[\frac{\text{Mass } CH_4 \text{ tailpipe} + \text{Mass } CH_4 \text{ crankcase}}{\text{Mass Fuel}}\right] \times 100 \quad (3)$$

Tailpipe methane emissions can be estimated from available literature. For example, Patrick et al. [46] report CNG tailpipe emission factors of 0.015 g of methane/ton-mile. Under the simplified assumption that natural gas composition is 100% methane (i.e., one mole of CO_2 is produced per mole of fuel burned), 0.05% of the fuel is lost through the tailpipe. Similarly, Carder et al. [47] estimated tailpipe methane loss at 0.21% for stoichiometric natural gas engines. Dunn et al., [48] report that 15L HD HPDI natural gas engine dynamometer tests over the Supplemental Emissions Test (SET) cycle reveal tailpipe methane at 0.65–0.75 g per kilowatt-hour (kWh), which translates to a 0.48% methane loss. In another study Frazier [49] registers methane levels at 1.7 g/bhp-h, which translates to a 0.92% tailpipe methane loss. We estimate the tailpipe methane emissions for natural gas vehicles in the range of 0.45–0.6% depending upon the engine and fuel injection type e.g. dedicated CNG engine, PISI, DISI.

Crankcase emissions, also known as "blow-by" emissions, are released directly from the engine into the atmosphere through a vent. Literature values for crankcase emissions are scarce. Researchers from West Virginia University's Center for Alternative Fuels, Engines, and

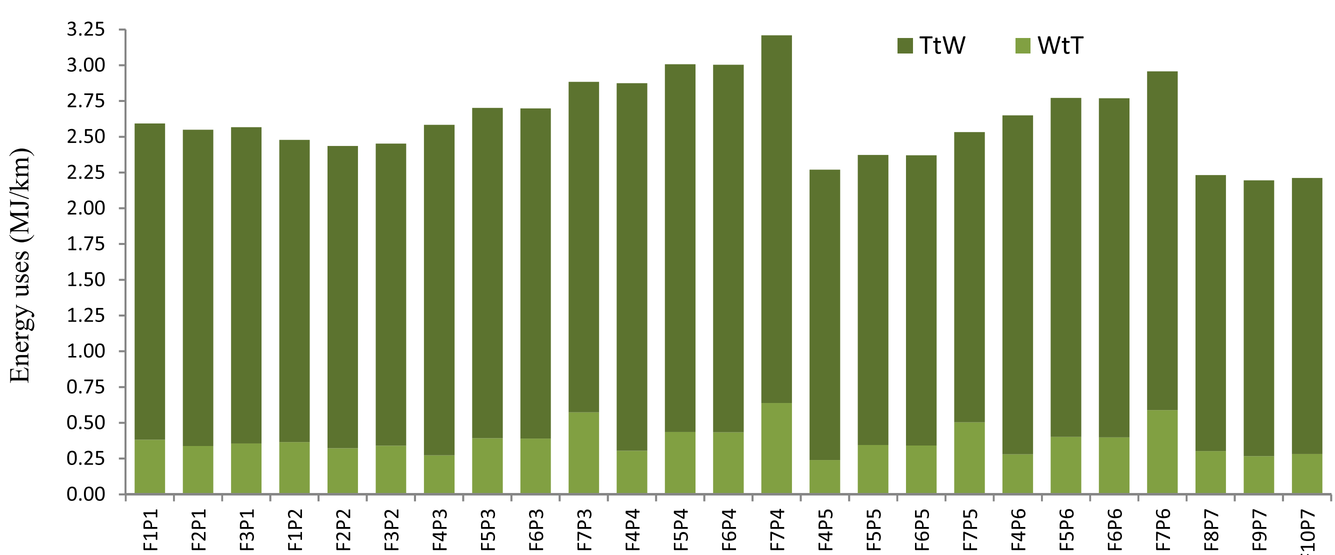

Fig. 9. WtW energy uses for the selected powertrain technologies.

Emissions (CAFEE) [50] recently conducted methane leak and loss audits of large-bore gas engines at five different gas compressor stations and the resulted crankcase emissions represent a loss of 0.1–0.6%. US EPA 2014 GHG certification data [51] for natural gas engines show that combined (tailpipe and crankcase) methane emissions for stoichiometric natural gas engines range from 0.6 to 1.2% of the fuel (US EPA, 2014). Ebner and Jaschek [52] concluded that typical piston ring blow-by losses are in the range of 0.5–1%. Keeping in view the engine technologies available in Pakistan we approximate the crankcase methane emissions at a level of 0.8%.Fig. 8 reports the share of methane (in gram of CO_2 equivalent per km) in total TtW GHG emission for natural gas-fueled powertrains. In can be noted that in terms of global warming potential, the share of methane emission varies from 26% to 28% in TtW GHG emissions of NGVs.

5.5. WtW analysis

As mentioned above the WtT cycle consist of two stages i.e (i) WtT stage, and (ii) TtW stage. The WtT stage of study has been covered in part-1 [33] of this two-part study. In this paper the Well-to-Tank (WtT) results observed in part-1 [33] are combined with the TtW (Tank-to-Wheel) results reported in this present paper to provide the comprehensive WtW analysis of 25 combinations of automotive fuel and matching powertrain systems.

5.6. WtW energy use

The WtW energy use in MJ per kilometer of distance traveled is shown in Fig. 9. The analysis indicates that for all powertrains, a major contribution (80–89%) of energy used in the overall WtW analysis comes from the TtW component. The diesel vehicles are the least energy consuming due to relatively lower energy use in the TtW phase as compared to gasoline and CNG vehicles. On the other hand, WtW energy consumption of NGVs remain highest among all powertrains considered in this study. For NGVs the contribution of the TtW energy used is about 80% of the total WtW energy use. It is interesting to note that the indigenous natural gas has the lowest WtT energy consumption among all fuel pathways but in terms of WtW energy consumption, it is above the diesel and gasoline vehicles. It is mainly due to low energy density of natural gas which conduces to 10–15% power loss during vehicle operation stage. The dedicated DISI natural gas vehicles resulted in 1.5–12.5% and 3–8.5% less energy consumption as compared to PISI gasoline and DISI gasoline vehicles, respectively. It is mainly because of ~20% increase in the compression ratio (12.5) of dedicated DISI natural gas engine as compared to 10.5 compression ratio of a conventional gasoline engine. Conventional dedicated PISI natural gas-fueled vehicles are unable to compete with the conventional PISI gasoline WtW energy demand via imported LNG and interstate pipeline natural gas pathways due to a lower overall energy conversion efficiency chain. However, indigenous natural gas pathways for dedicated NGVs offer efficiency gains with the potential to bridge the gap between gasoline and NGVs WtW performance. In general dedicated CNG vehicles are currently slightly less efficient than equivalent gasoline vehicles while diesel vehicles enjoy a net advantage.

5.7. WtW GHG emissions

The GHG emissions during different WtW stages of CNG, gasoline and diesel powered light duty vehicles are shown in Fig. 10. For all powertrains, the majority of GHG emissions (73–86%) are produced in the TtW stage. It can bee see that the gasoline vehicles are the most GHG-emitting configuration followed by bi-fuel PISI natural gas vehicles and diesel vehicles. The dedicated CNG vehicles equipped with DISI engine technology show the lowest GHG emissions among all powertrains. To make the WtW GHG emission of natural gas powertrains on a par with their diesel equivalents, ~11% reduction in WtW GHG emission would be needed which can be achieved by converting bi-fuel CNG vehicle to dedicated CNG vehicle. Though the energy consumption for dedicated CNG vehicles is higher as compared to diesel vehicles, the GHG emissions for CNG are comparable with those of diesel vehicles due to the less carbon content in CNG fuel which produces lower CO_2 in the TtW stage. Also, it can be seen that the total WtW GHG emissions emitted by dedicated DISI CNG powered vehicles are roughly 8% less than for the diesel-powered vehicles. In general for natural gas powertrain, the higher relative WtW GHG emissions reductions in this study are mainly from the vehicle operation phase where recent advances in CNG engine technology are expected to improve the environmental value proposition of such vehicles. However, considering GHG emissions associated with the diesel powertrain as the baseline, operating conventional gasoline engine with CNG fuel offers a

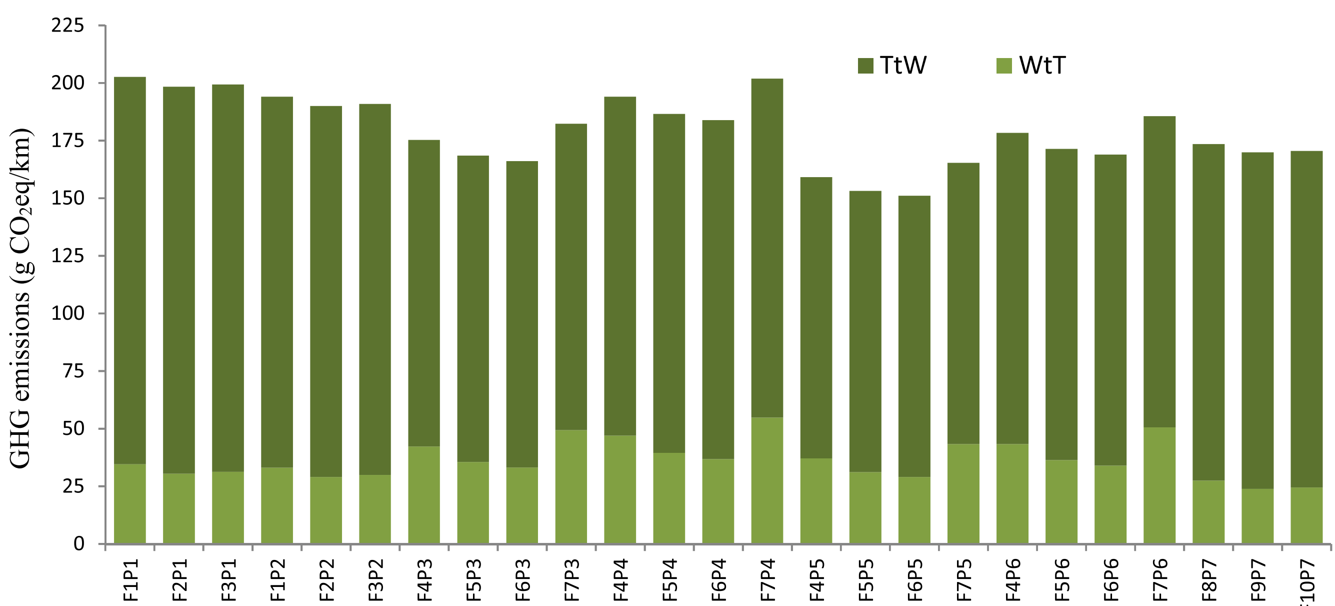

Fig. 10. WtW GHG emissions for the selected powertrain technologies.

limited advantage in terms of GHG emissions reductions. Overall the distributions of WtW GHG emissions from natural gas pathways are found to be wider than those from petroleum pathways.

5.8. GWP time horizon and sensitivity analysis

In this section, GHG emissions' estimates are conducted using global warming potentials (GWPs) of non- CO_2 greenhouse gases with time frame of 20-years and compared the results with the with 100-year GWP (baseline scenario). A sensitivity analysis was then performed to explore the effect of variability on our estimates of WtW GHG emissions.

In the previous life-cycle studies [15,20,21,24], there is a persistent use of the 100-year impact of methane on global warming, a factor about 28 times that of CO_2. However, the current scientific consensus on climate change, summarized in IPCC AR 5 [32], says that we only have about 20–30 years before we reach the warning zone of temperature rise that could lead to climate tipping points. We can't wait for 20–30 years to start decreasing CO2eq emissions from fossil fuels. Over a 20-year period, the consensus impact factor for methane is about 84. There is no scientific justification for the use of a 100-year period. The choice of GWP value could have serious impacts on the actual and relative results of this study. As methane is the major contributor to the life cycle GHG emission of natural gas so we will concentrate our discussion on the natural gas pathways only.

Estimates using both 100-year GWPs and 20-year GWPs are presented side by side for each powertrain technology in Fig. 11. It can be observed that the choice of GWP time horizon could have serious impacts on the WtW GHG emission results of this study. Using 20-year GWP, increases the WtW emissions of natural gas pathways from 179 g CO_2eq/km to 253 g CO_2eq/km (ranging between 64 and 77 g CO_2eq/MJ), an increase of about 19–26% from the baseline estimates of 100-year GWP. The obvious reason for this significant increase in the GHG emission is associated with a high risk of methane emission in natural gas fuel pathways mainly in the WtT stage. It is observed that by using 100-year GWP, the GHG emission results for natural gas pathways was comparable to the corresponding results of diesel fuel while superior to that of gasoline powertrains. But in the case of 20-year GWP, natural gas pathways worst performance in terms of WtW GHG emissions.

Considering the WtW results of this study, two factors largely determine whether the NGVs provide WtW GHG emission reductions as compared to their diesel and gasoline counterparts: NGVs relative fuel economy and methane emission leakage during the WtT and TtW stages. Using methane emission by 50% above the reference case, increase the WtW GHG emission by 8–10% across natural gas pathways. However, if 20-year GWPs and high methane emission (i.e. 50% above the reference case) assumptions are jointly considered, WtW GHG emissions increase between 37 and 47% across natural gas pathways.

The results of this study, as well as those in the literature [53,54], suggest that methane leakage rate of natural gas pathways is the most important factor influencing whether natural gas fuel pathways achieve net emission reductions. Given the importance of this factor, we derive the break-even methane leakage rate of natural gas vehicles relative to baseline gasoline and diesel fuel vehicles. The break-even rate is the methane leakage rate at which WtW GHG emissions from a natural gas pathway equals that of conventional gasoline or diesel. Considering diesel vehicle as baseline, our analysis indicate that natural gas vehicles offer GHG emissions reductions to its counterpart powertrains i.e. diesel and gasoline if the WtW methane leakage rate is lower than 2.9% (using the 100-year GWP) or 1.1% (using the 20-year GWP) and 1.8% (using the 20-year GWP), respectively. A shorter time horizon (such as 20 years), which considers a higher warming potential of methane, requires a lower break-even rate than a longer time horizon (such as 100 years).

6. Comparison with other studies

The WtW energy use and GHG emissions results of various studies and the present study are represented in Fig. 12. Generally speaking, detailed comparisons cannot be made among the findings of WtW analysis of similar fuel due to different methods of modeling, types of input data used, system boundaries, engine parameters etc. Different methodologies and assumptions in different studies make scenario comparison difficult or impossible. Therefore the comparison of absolute results from these studies and our study are less meaningful, mainly because of different locale-specific data and baseline hypotheses. However, comparison of the relative change in the results among these studies should improve our understanding of the range of energy and emission benefits of advanced vehicle technologies and alternative transportation fuels. We only compared our results to studies that explicitly reported CO_2, CH_4 and N_2O emissions, thereby allowing for the

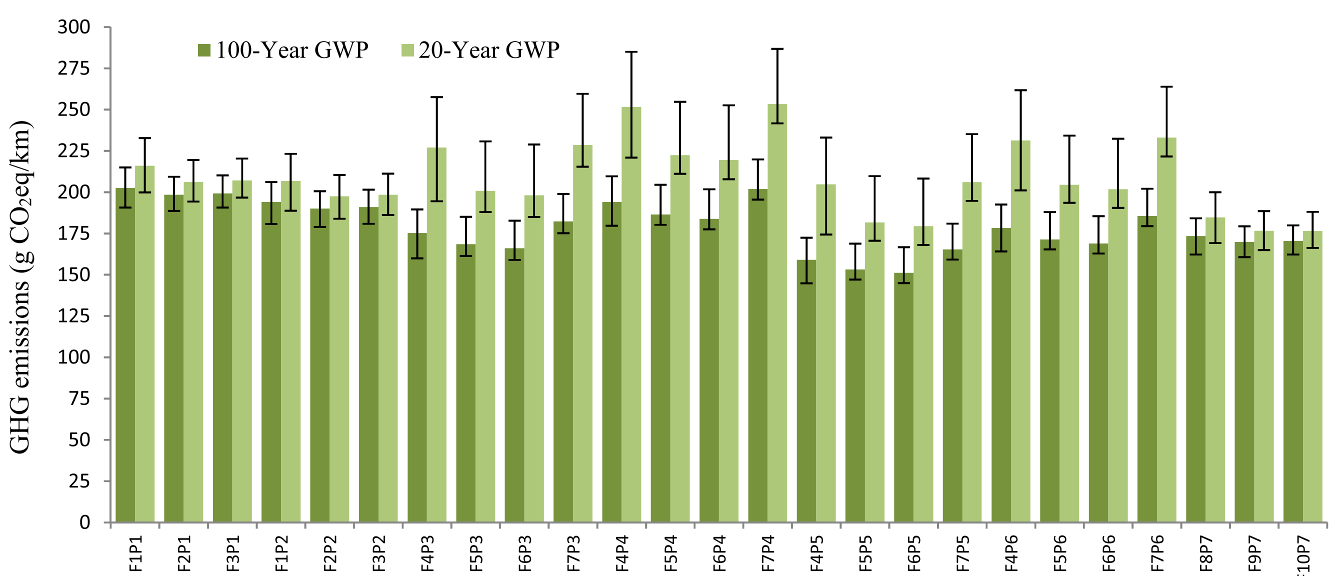

Fig. 11. Uncertainty analysis of WtW GHG emissions for the selected pathways using 100-year and 20-year GWP baseline.

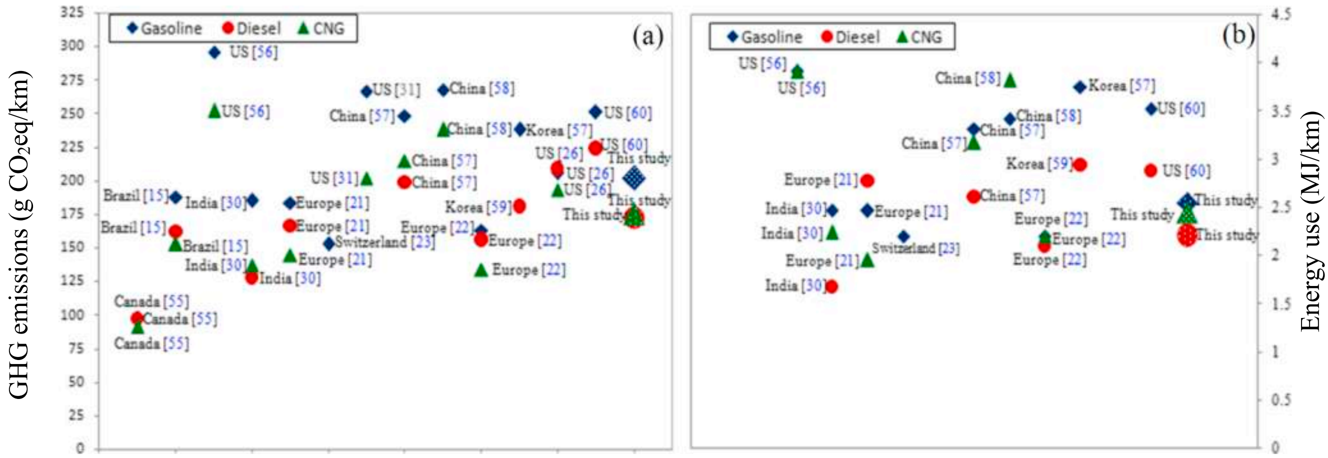

Fig. 12. Results comparison of the present study with those reported in the literature (a) WtW GHG emission (b) energy use. (See above-mentioned references for further information.)

expression of all study results in terms of 100-y GWPs reported in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). The comparison clearly shows that the current study for India follows the general trend (regarding the change in WtW energy use with change in fuel-powertrain) when compared with earlier studies for other countries. The comparison shows that our estimate of WtW GHG emissions associated with natural gas pathways is between the values reported for the European and Chinese market. The WtW GHG emission values of NGVs of this study are 20% higher than the WtW values for similar type vehicle reported in WtW study conducted by Europe's Joint Research Centre (JRC) [21] in 2014. This is mainly due to the high rate of fugitive GHG emission during pipeline transmission and distribution of natural gas in Pakistan as compared to that of Europe. Similarly, for gasoline and diesel fuel, the comparison clearly shows that the current study for Pakistan follows the general trend regarding WtT GHG emission when compared with earlier studies for other countries. Similarly, for gasoline and diesel fuel, the comparison clearly shows that the current study for Pakistan follows the general trend regarding WtW GHG emission and energy use when compared with earlier studies for other countries.

7. Conclusions

The present study has been conducted to provide detailed WtW assessment of energy consumptions and GHG emissions of natural gas, gasoline and diesel fuel pathways at the Pakistan and energy importing developing countries levels. The results of the present study can be used as an input to the strategic decision-making process for future transport energy policy and also to identify key areas of interest for further technology research and development of the Pakistan transport system. Furthermore, it could also provide an important tool for policy makers to better understand the trade-offs between energy and environmental effects for the most effective use of regional energy resources.

This study presents a comprehensive comparison of operational WtW analysis for 25 combinations of automotive fuel and matching powertrain systems. The key findings are listed below:

- In contrast, natural gas-fueled vehicles are at a disadvantage from the standpoint of energy consumption e.g. on WtW basis, NGVs are 5–17% and 23–36% less fuel efficient, depending on the engine technology employed as compared to gasoline and diesel powertrain, respectively.
- Natural gas appears as an efficient pathway regarding GHG emissions, especially compared to gasoline. Dedicated NGVs equipped with direct injection technology is even more efficient and may result in 20% and 12% less GHG emissions as compared to gasoline and diesel pathways, respectively. The environmental and energetic assessments of NGV appear to be very favorable to this technology (i.e. dedicated DISI) and make CNG a promising fuel for light-duty road transport vehicles. However, WtW GHG emissions of the prevalent bi-fuel NGVs are 12% higher than those of their diesel counterparts with the baseline estimates of 100-year GWP.
- In terms of WtW GHG emissions, natural gas pathways can attain better or comparable performance as compared to petroleum pathways, however, retrofitted bi-fuel engine technology and Methane leakage during gas fuel production and vehicle operation stage, can negate the benefits of using NGVs. Thus without significant improvements in both methane leakage and engine efficiency, using natural gas in light-duty transport will not provide large GHG benefits. There are cost-effective technologies to reduce methane leakages in natural gas pathways. For instance, natural gas engine with closed crankcase design that has reached the market can significantly reduce the TtW part of methane emission. Similarly, the potential way to reduce the methane from WtT pathway, technologies are now available with help of which methane vented during gas production and processing can be captured and sequestered or used for energy at no net cost.
- A larger uncertainty and variability was observed in WtW GHG emissions of natural gas pathways as compared to conventional gasoline and diesel fuel. Moreover, the choice of GWPs and methane emission estimates are other important factors for absolute emission levels and relative rankings of natural gas fuel pathways. Using 20-year GWPs instead of 100-year GWPs increases WtW GHG emissions by 19–26% for natural gas pathways.
- While this paper focuses on GHG emissions, natural gas based fuels may provide other environmental benefits, such as the reduction of other air pollutants as well as a significant economic advantage over petroleum-based pathways but these issues are outside the scope of this work and will be addressed in future research.
- The results of this study serve as valuable inputs not only for policy decision-makers in Pakistan, but analysis would also be applicable to other countries having similar characteristics, i.e., oil-importing developing countries with their own or easy access to natural gas resources (e.g., via relatively short distance pipelines); some countries in Latin America, Africa and Southeast Asia would seem to fit this description.

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Appendix A. . Statistics and sources of fuels used by pakistan's road transport [1]

Description	Million TOE	MJ	Remarks
Energy consumption by road transport			
Pakistan total energy consumption	50.12	2.216×10^{12}	
Road transport share in total energy consumption	16.51	7.297×10^{11}	Road transport sector consuming 33.93% of the country total energy requirement
Diesel share in road transport energy consumption	7.83	2.914×10^{11}	Diesel fuel share 47.46% of total energy consumption by road transport
Gasoline share in road transport energy consumption	7.09	3.138×10^{11}	Gasoline fuel share 43% of total energy consumption by road transport
CNG share in road transport energy consumption	1.57	6.956×10^{10}	CNG fuel share 9.53% of total energy consumption by road transport
Crude oil based fuels			
Total crude oil processed by local refineries	12.78	5.649×10^{11}	There are 7 refineries operating in Pakistan having total crude processing capacity of 19.37 Million Tons per year
Indigenous Crude oil Production	4.33	1.914×10^{11}	Currently Pakistan local crude oil production is 100,000 barrels per day
Foreign crude oil processed by local refineries	8.95	3.958×10^{11}	27% crude oil need of local refineries is achieved through foreign crude oil mostly from Saudi Arabia
Diesel production by local refineries	4.81	2.129×10^{11}	Sulfur content of local diesel is above 500 ppm
Diesel imports from foreign refineries	3.99	1.764×10^{11}	Foreign Crude oil is mostly imported from Saudi Arabia
Gasoline production by local refineries	1.98	8.754×10^{10}	RON of local gasoline is 90
Gasoline imports from foreign refineries	4.89	1.161×10^{11}	Foreign Crude oil is mostly imported from Saudi Arabia
Natural gas based fuels			
Total Ingenious Natural Gas Production	30.18	1.335×10^{12}	
LNG Import	4.46	1.970×10^{11}	Since 2014 LNG is being imported mainly from Qatar
Planned natural gas import through TAPI pipeline			The 56 in., 1600 km gas pipeline project would supply 1325 MMSCFD gas to Pakistan from Turkmenistan by the end of 2019
Planned natural gas import through IP pipeline			The 42 in., 1931 km gas pipeline project would supply 750 MMSCFD gas to Pakistan from Iran by the end of 2018
Total Natural gas consumption	29.30	1.295×10^{12}	
CNG Consumption	1.57	6.956×10^{10}	
LNG share in total CNG consumption	0.38	1.658×10^{10}	
Total length of Pakistan natural gas transmission Lines	10,789 (km)		
Total length of Pakistan natural gas Distribution Lines	112,474 (km)		

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