

Energy transitions in Sub-Saharan Africa: policy recommendations for charcoal trade, solar PV adoption, and sustainability in rural Zambia

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Published Version

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Chanda, H., Mohareb, E. ORCID: <https://orcid.org/0000-0003-0344-2253>, Peters, M. ORCID: <https://orcid.org/0000-0002-4324-6559>, Harty, C., Green, M., Kasanda, E. B. and Shibata, N. (2026) Energy transitions in Sub-Saharan Africa: policy recommendations for charcoal trade, solar PV adoption, and sustainability in rural Zambia. *Energy Policy*, 208. 114936. ISSN 1873-6777 doi: 10.1016/j.enpol.2025.114936 Available at <https://centaur.reading.ac.uk/125303/>

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To link to this article DOI: <http://dx.doi.org/10.1016/j.enpol.2025.114936>

Publisher: Elsevier

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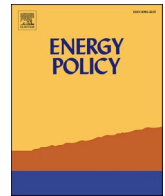
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"Energy transitions in Sub-Saharan Africa: Policy recommendations for charcoal trade, solar PV adoption, and sustainability in rural Zambia"

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1. Introduction and background

Sub-Saharan Africa (SSA) faces a critical energy paradox: while the region possesses vast renewable energy potential, including abundant solar resources, its populations remain heavily dependent on traditional biomass fuels such as charcoal and firewood for basic energy needs (Kaoma and Gheewala, 2020). In Zambia, this contradiction is acutely evident. Approximately 98 % of rural households rely on biomass as their primary energy source, with charcoal remaining the dominant fuel despite its well-documented environmental and public health consequences (Kaoma and Gheewala, 2020). The continued use of charcoal is not solely a cultural or habitual phenomenon; rather, it reflects structural energy poverty and persistent policy limitations that restrict access to viable clean energy alternatives such as solar photovoltaic (PV) technologies (Chambalile et al., 2024; Tomala et al., 2021). Globally, reliance on biomass contributes significantly to household air pollution (HAP), which is associated with respiratory and cardiovascular illnesses. Approximately four million premature deaths annually are linked to exposure to HAP (Clean Cooking Alliance, 2025). Children under the age of five are particularly affected, with over 700,000 deaths attributed to air pollution in 2021 alone (State of Global Air, 2024). Within SSA, the health burden is disproportionately high due to poor ventilation, limited health infrastructure, and entrenched energy practices (Roomaney et al., 2022; Simkovich et al., 2019).

In the Zambian context, this health crisis is compounded by systemic energy shortfalls. Although the country relies heavily on hydropower for electricity generation, its capacity is increasingly undermined by climate variability (Malange et al., 2021). This has heightened interest in off-grid solar PV solutions, especially in rural areas, where grid extension remains economically unfeasible. Despite Zambia's favourable solar irradiation levels, averaging 5.5 kWh/m² per day, the uptake of

solar PV technologies remains limited due to high initial costs, low consumer awareness, and underdeveloped infrastructure (Chambalile et al., 2024; Mfuno and Boon, 2008). These constraints highlight the broader challenge of energy transition in SSA as regards how to reconcile technical potential with the socio-economic conditions that shape energy access and sustainability. This article investigates this tension by examining how policy frameworks can be designed to support an inclusive and sustainable energy transition in Zambia. It specifically focuses on the dual dynamics of charcoal dependency and solar PV adoption, offering policy recommendations grounded in the socio-economic realities of rural communities.

1.1. Charcoal's socio-economic and environmental role

Charcoal production continues to serve as a critical livelihood strategy in rural Zambia. For many households, it provides both income and energy security, especially in areas with limited access to employment and modern energy services (Chanda et al., 2025a; Steel et al., 2022). Urban demand for charcoal has intensified its production, creating an informal yet lucrative market (Ngoma et al., 2019; Rose et al., 2022). However, this growth has come at significant environmental cost. Charcoal production has led to widespread deforestation and ecological degradation, particularly in regions surrounding major urban centres. The expansion of production zones has altered forest ecosystems, increasing carbon emissions and threatening biodiversity (Nansikombi et al., 2020a; Sedano et al., 2022). Despite its economic benefits, the charcoal sector remains largely informal and under-regulated. Approximately 98 % of charcoal entering Zambia's urban markets is unlicensed and untaxed, contributing to major losses in government revenue (USAID A2C, 2024). For rural producers, this informality is both an opportunity and a constraint as it allows access to

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<https://doi.org/10.1016/j.enpol.2025.114936>

Received 9 March 2025; Received in revised form 12 September 2025; Accepted 14 October 2025

Available online 20 October 2025

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markets but lacks safeguards, regulation, and support systems. With limited access to alternative livelihoods or clean energy options, many rural communities remain locked into a “charcoal trap” that undermines both economic and environmental sustainability (Kutsch et al., 2011).

1.2. Solar PV's role and barriers

As a renewable energy solution, solar PV offers considerable promise for expanding energy access in off-grid rural areas of Zambia. The country's high solar potential positions it well for the deployment of decentralised systems such as solar home systems and pico-PV devices (Nygaard et al., 2016; Tinta et al., 2023). These systems have been piloted with some success, especially under pay-as-you-go (PAYG) models that enable flexible financing. However, multiple barriers continue to constrain their adoption. Foremost among these are economic barriers. High upfront costs, limited credit mechanisms, and uncertain returns on investment prevent many low-income households from transitioning to solar technologies (Chidembo et al., 2022). Even when systems are acquired, they often support only minimal energy services, typically lighting and mobile phone charging, leaving critical needs such as cooking and income-generating activities unmet (Chanda et al., 2025b; Hassan et al., 2020). This has led to concerns over “energy lock-in,” where households become confined to low-capacity systems that cannot scale with demand. Socio-cultural dynamics further complicate the transition. Charcoal remains culturally embedded in Zambian cooking practices, preferred for its familiarity and perceived utility (Chanda et al., 2025b). Gender dynamics also play a role, with women, who are most affected by indoor air pollution, often excluded from household energy decision-making (Johnson et al., 2019). These realities underscore the importance of designing solar energy policies that are not only technologically sound but also socially responsive.

1.3. Policy gaps and research contribution

While Zambia has adopted various energy and forestry policies aimed at promoting renewable energy and environmental conservation, many of these frameworks remain siloed, failing to reflect the complex interdependencies between rural livelihoods, charcoal trade, and solar energy adoption. Existing policies often treat renewable energy promotion and forest protection as parallel, rather than intersecting, objectives. This disconnect has contributed to fragmented interventions that do little to mitigate energy poverty or reduce biomass dependency in rural communities (Gumbo et al., 2013; Veen et al., 2021). Additionally, weak enforcement mechanisms, limited coordination across sectors, and insufficient decentralisation continue to undermine implementation. Despite efforts to promote improved carbonization and afforestation, informal charcoal production and unsustainable harvesting persist (USAID A2C, 2024). Similarly, renewable energy programmes have yet to achieve meaningful scale, constrained by market underdevelopment, affordability challenges, and inadequate engagement with rural populations (Chambalile et al., 2024; Mfuno and Boon, 2008).

This study addresses these gaps by examining the intersection of charcoal trade and solar PV adoption within the broader context of sustainable rural development in Zambia. Its objectives aim to:

- Analyse the socio-economic drivers of charcoal dependency and their implications for household energy security.
- Assess structural and behavioural barriers to solar PV adoption in low-income rural settings.
- Propose integrated policy recommendations that align energy access, forest governance, and climate mitigation with equity and local realities.

By situating energy transitions within localised contexts of poverty, informal markets, and policy incoherence, the research contributes to a

deeper understanding of how integrated, context-sensitive strategies can advance sustainability goals in Sub-Saharan Africa's rural energy landscape.

2. Literature review

2.1. Charcoal production in sub-Saharan Africa

Findings from prior research illustrate that charcoal remains a key energy source in Sub-Saharan Africa, with 195 million people relying on it as their primary fuel and an additional 200 million as a secondary source (Rose et al., 2022). However, its production drives environmental and health crises. Inefficient carbonization contributes to about 7 % of global deforestation, releasing 71.2 million tonnes of CO₂ and 1.3 million tonnes of CH₄ annually, exacerbating climate change (Sakala et al., 2023). In Ghana, Ethiopia, and Somalia, unsustainable harvesting has led to extensive forest loss, mirroring Zambia's worsening deforestation (Arko et al., 2024; Gebremeskel, 2023; Kullane et al., 2022). Additionally, charcoal combustion elevates indoor carbon monoxide levels, increasing risks of poisoning, cognitive decline, and respiratory diseases such as chronic obstructive pulmonary disease (COPD), asthma, and tuberculosis (Dillon, 2021; McCord et al., 2024; Senya et al., 2018). Despite these dangers, public awareness remains low, emphasizing the urgency for targeted policy interventions (Idowu et al., 2023). Charcoal's persistent reliance across SSA highlights a regional crisis that blends energy poverty with health burdens, underlining the need for cohesive policy responses that move beyond localised accounts to systemic solutions.

2.2. Deforestation and policy gaps in Zambia

Extant literature identifies charcoal production as a key driver of deforestation in Zambia, contributing to about 25 % of annual forest loss, which ranges between 180,000 and 250,000 ha (Nansikombi et al., 2020a; Tembo et al., 2015; USAID A2C, 2021). Unlike agricultural expansion, which can result in cropland use, charcoal-driven deforestation is often followed by long-term land degradation, with less than 25 % of cleared areas cultivated within seven years (Sedano et al., 2022). This process diminishes soil fertility, biodiversity, and carbon sequestration. Additionally, weak enforcement mechanisms allow illegal charcoal production to persist even in protected areas, further undermining conservation efforts (Sedano et al., 2022; Silva et al., 2019). Contrastingly, other literature postulates that agricultural expansion is a more significant contributor to deforestation, accounting for nearly 90 % of Zambia's forest cover loss (Kabisa et al., 2019; Mabeta et al., 2018). Between 2000 and 2018, cropland expanded by 25 %, leading to a 10 % decline in forest cover (Phiri et al., 2022). Smallholder farmers, responsible for 60 % of this loss, clear forests due to declining soil fertility, encroaching into an average of 0.10 ha per household annually (Ngoma et al., 2021). The Miombo ecoregion, covering 45 % of Zambia, experiences the highest deforestation rates from both agricultural expansion and charcoal production (Nansikombi et al., 2020a). Despite these competing perspectives, weak land governance and poor enforcement remain central to Zambia's deforestation crisis (Kabisa et al., 2019; Moombe et al., 2020). Given the Miombo woodlands' role in biodiversity conservation and carbon sequestration, sustainable interventions such as improved land-use regulations and soil restoration programmes are crucial (Handavu et al., 2019). The contrasting perspectives appear to stem from differing methodological focuses, as some studies isolate the localised impact of charcoal production, while others assess broader national trends dominated by agriculture. Both, however, reveal policy and enforcement weaknesses as core drivers. While this section centres Zambia, similar governance gaps affect forest management across SSA, demonstrating a need for comparative studies and harmonised policy approaches to address charcoal-induced degradation regionally.

2.3. Charcoal and solar energy dilemma

Empirical evidence indicates that despite the environmental and health risks associated with charcoal, Zambia's energy transition remains sluggish. Solar photovoltaic (PV) technology is a viable alternative, yet its widespread adoption is impeded by high initial costs, limited financing, and infrastructural deficiencies (Chambalile et al., 2024). While off-grid solar systems have been introduced, their impact on reducing charcoal dependency remains limited, as biomass continues to dominate household energy consumption for cooking (Nygaard et al., 2016; Tinta et al., 2023). Interestingly, other scholars postulate that income from charcoal production has facilitated solar PV adoption in some rural communities, as earnings are reinvested in solar home systems and pico-solar devices, mainly for lighting and phone charging (Chanda et al., 2025a; Nygaard et al., 2016). This presents a contradictory dynamic where charcoal both contributes to deforestation and enables renewable energy uptake (Chanda et al., 2025e; Tinta et al., 2023). However, without stronger financial incentives and policy interventions, solar adoption will remain constrained, reinforcing biomass reliance (Chambalile et al., 2024). Extant literature highlights that Zambia's high solar potential could significantly reduce biomass reliance and lower CO₂ emissions (Aboagye and Adjei Kwakwa, 2023; Byaro et al., 2024; Chanda et al., 2025b). Conversely, while some scholars argue that charcoal-generated income is actively financing small-scale solar adoption in SSA (Chanda et al., 2025a), others emphasise that the prohibitive cost of productive-use solar systems restricts broader adoption (Tinta et al., 2023). This stresses the need for targeted financial mechanisms to accelerate Zambia's energy transition (Chambalile et al., 2024). This connection of biomass dependency and renewable uptake reflects a wider SSA pattern, demanding integrated policy responses that recognise charcoal's economic utility while promoting scalable clean energy solutions.

2.4. Charcoal's economic role in Zambia

Existing research indicates that charcoal production remains a key economic activity in Zambia, providing income for rural households, particularly in regions with limited employment opportunities (Wang et al., 2022). Non-timber forest products (NTFPs), including charcoal, contribute up to 32 % of total rural income (Chanda et al., 2025a; Mulenga et al., 2014; Steel et al., 2022). While its economic significance is undeniable, unsustainable harvesting has resulted in extensive deforestation and land degradation, with miombo woodlands experiencing severe biomass depletion (Gumbo et al., 2013; Kutsch et al., 2011). Nationally, 68 % of NTFP-dependent households rely on charcoal and firewood sales, reinforcing the "charcoal trap," where the absence of viable energy alternatives perpetuates reliance on wood fuel (Kutsch et al., 2011). To mitigate these effects, policymakers have introduced forest regeneration programmes and promoted alternative NTFPs, such as wild honey and mushrooms, as sustainable income sources to reduce charcoal dependence while balancing rural livelihoods and conservation (Chanda et al., 2025a; Wang et al., 2022). Extant literature emphasises charcoal's dual function as both energy and income source, making it vital for policy design to balance environmental limits with rural livelihood imperatives across the SSA region.

2.5. Health impacts from charcoal use

Scholarly discourse emphasises the severe health risks associated with charcoal burning in Zambia, particularly chronic respiratory diseases such as COPD (Fullerton et al., 2011). Biomass fuel users experience lung function deterioration, with exposure levels exceeding World Health Organisation (WHO) thresholds (Dillon, 2021). Poorly ventilated homes intensify the dangers, as charcoal combustion releases high concentrations of particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs) (Iqbal and Kim, 2016; Mencarelli

et al., 2023). Women and children are disproportionately affected due to prolonged exposure (Balmes, 2015; Kirubi, 2004). Scholars propose clean cooking technologies, liquefied petroleum gas (LPG), and biogas as viable interventions (Makai and Molinas, 2013). While evidence on health impacts is robust, policy-focused literature remains limited; more emphasis is needed on translating these risks into enforceable and context-specific interventions across SSA households.

2.6. Policy and regulation in energy transitions

Prior Energy transitions in Sub-Saharan Africa are constrained by weak institutional coordination, fragmented policies, and limited engagement with informal energy practices (Dagnachew et al., 2020; Kovacic et al., 2021; Sedano et al., 2022). Despite policy emphasis on electrification and renewable energy, implementation often overlooks the lived realities of rural populations (Newell and Bulkeley, 2017). Zambia exemplifies this disjuncture, although endowed with renewable resources, only 25 % of the population has access to electricity and clean cooking (Lyambai, 2017; Energy Regulation Board, 2024). Rural communities rely predominantly on traditional biomass, perpetuating deforestation and respiratory illnesses (Kaoma and Gheewala, 2020). While projects like USAID's A2C and ZIFLP promote alternatives, adoption is hampered by high costs, weak enforcement, and poor public awareness (Serenje et al., 2022; USAID A2C, 2021). Even promising solar initiatives remain underutilised due to undeveloped markets and inadequate community engagement (Mfuno and Boon, 2008; Obeng-Darko, 2023). Although existing literature highlights barriers to energy access, few studies offer integrated policy recommendations addressing both charcoal governance and solar PV adoption in rural Zambia. This study addresses that gap by linking policy design to sustainability, enforcement, and inclusive stakeholder engagement. This section consolidates prior findings by highlighting the urgent need for cross-sectoral policy coherence, particularly where charcoal regulation and solar market stimulation intersect across rural Sub-Saharan contexts.

2.7. Charcoal's medicinal properties overview

Previous research has established charcoal's dual role as both an urban fuel and a medicinal agent, with historical records tracing its therapeutic applications to the Middle Stone Age (Chikumbirike and Bamford, 2021; Herlihy et al., 2013). Its adsorptive properties facilitate detoxification, treating poisonings, lowering cholesterol, and reducing intestinal gas (Lee et al., 2019; Zaini and Mohamad, 2015). In rural Zambia, it is traditionally applied to newborns' umbilical cords for drying and infection prevention (Herlihy et al., 2013; Kar, 2018). However, scholars argue that such practices may not align with modern medical guidelines, necessitating culturally sensitive health education (Hassen and Abdulkadir, 2022). This above writeup further illustrates charcoal's complex role in rural life, medical, economic, and energetic, highlighting the necessity of policies that account for both modern health standards and traditional practices.

3. Theoretical framework

This study applies the Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM) (Chanda et al., 2025a–e) to assess the interplay between charcoal trade, solar photovoltaic (PV) adoption, and sustainability in rural Zambia (see Fig. 1). The model offers a multi-theoretical lens to understand the complex socio-economic and environmental factors shaping rural energy transitions. Given the urgency of addressing deforestation, energy poverty, and policy gaps in Sub-Saharan Africa, RUDSHAM integrates multiple adoption theories to evaluate both individual decision-making and broader structural influences. At its core, RUDSHAM synthesises three established theories: the Technology Acceptance Model (TAM), Diffusion of Innovations Theory (DOI), and the Theory of Planned Behaviour (TPB). TAM (Davis,

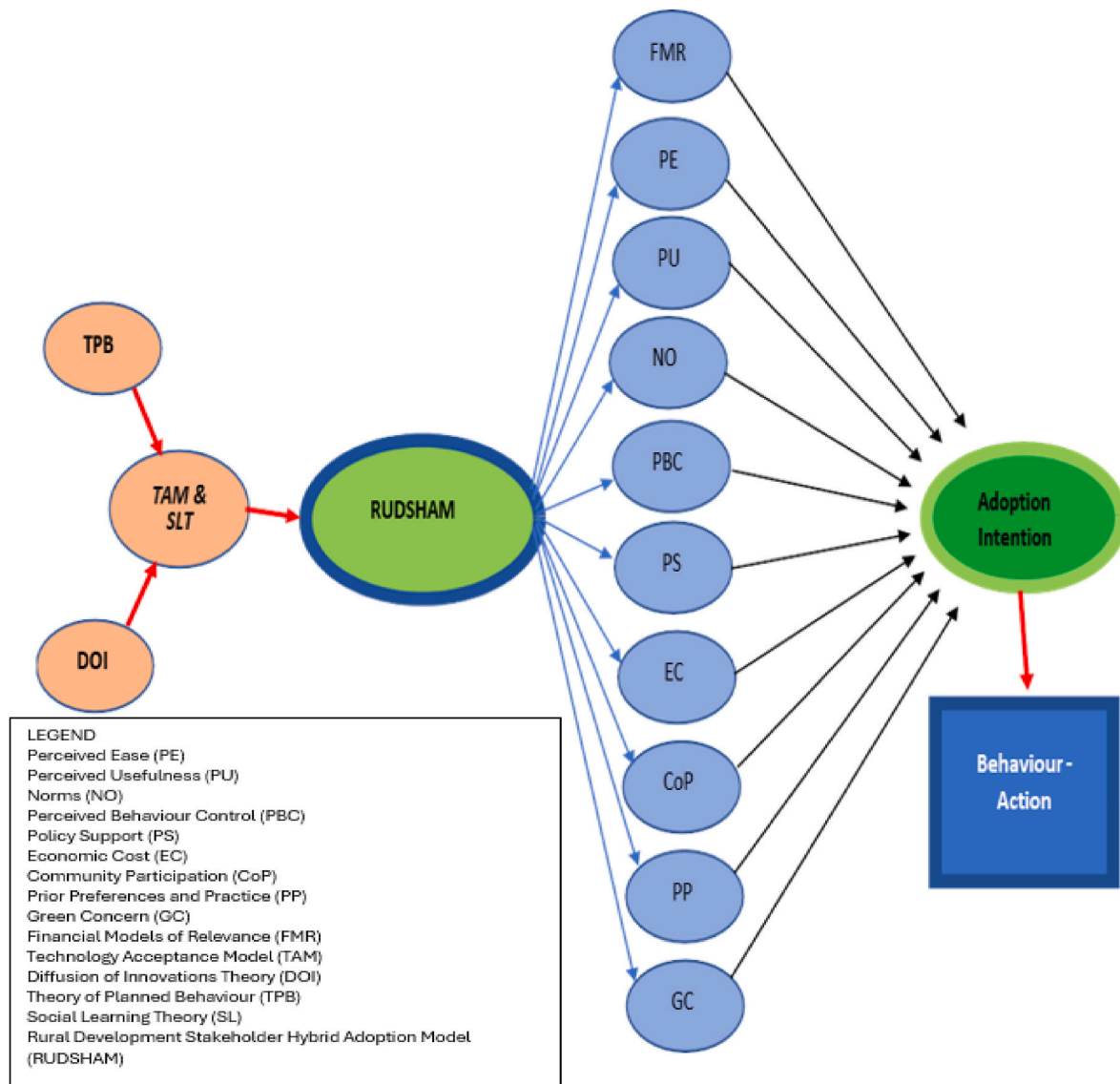


Fig. 1. RUDSHAM hybrid adoption model.

1989; Venkatesh and Davis, 2000) explains technology adoption through perceived usefulness, effort expectancy, social influence, and facilitating conditions. It is particularly relevant in rural Zambia, where solar PV systems are often viewed through a cost-benefit lens that prioritises immediate economic returns over long-term sustainability. DOI (Rogers, 2003) contextualises how renewable energy solutions spread within communities, emphasising the role of early adopters, social networks, and innovation diffusion dynamics. Meanwhile, TPB (Ajzen, 1991) accounts for behavioural intentions, linking attitudes, subjective norms, and perceived behavioural control to the slow yet essential transition away from traditional biomass fuels. Beyond these individual-level adoption drivers, RUDSHAM incorporates Social Learning Theory (SLT) (Bandura, 1977) to capture the broader social and cultural dimensions influencing solar PV adoption. Rural communities in Zambia operate within strong social networks, where knowledge-sharing, imitation, and peer influence shape energy choices. Households adopting basic solar PV systems for lighting and phone charging serve as reference points for others, yet the inability to afford higher-capacity systems for irrigation and income-generating activities limits the full transition to productive renewable energy use. In addition to behavioural and social dimensions, RUDSHAM integrates key policy, economic, and environmental variables, making it uniquely suited for

analysing energy policy implications.

The study employed a structured deductive approach in applying the RUDSHAM framework. Qualitative data from interviews and focus group discussions were systematically coded in NVivo 14 across the ten RUDSHAM domains. Responses were categorised based on relevance. e. g., user experiences with system maintenance were coded under Perceived Ease (PE), while affordability concerns were linked to Economic Cost (EC). An inductive layer allowed emergent sub-themes to be integrated within the existing framework. Coding matrices enabled the identification of patterns across respondent categories. This dual-layered analysis ensured both conceptual fidelity and analytical flexibility. By explicitly mapping empirical data to each RUDSHAM component, the study enhances methodological clarity and allows for replicability in similar energy transition research contexts.

By applying RUDSHAM to the Zambian energy landscape, this study provides an integrated framework for understanding rural energy transitions, balancing technological, cultural, socio-economic, and policy perspectives. The model's multi-dimensional approach aligns with the energy policy discourse, offering evidence-based insights for designing more effective interventions. This study utilises a mixed-methods approach, incorporating in-depth interviews, focus group discussions, carbon emission calculations and observational data to rigorously

analyse energy adoption behaviours. In doing so, this research contributes to a more nuanced understanding of rural energy transitions, equipping policymakers with actionable strategies to facilitate a just, sustainable, and economically viable energy transition in the Zambian and Sub-Saharan Africa contexts. For a detailed breakdown of RUD-SHAM's attributes and applications (refer to [Appendices A and B](#)).

4. Research methodology

4.1. Research strategy and data collection

This study was conducted over a 28-month period (October 2022–February 2025) across four rural districts in Zambia: Mkushi Rural (Central Province), Kapiri Rural (Central Province), Chongwe Rural (Lusaka Province), and Chingola Rural - Luano (Copperbelt Province) (see [Fig. 2](#)). These regions were purposively selected due to their relative isolation, lack of access to the national power grid, and active charcoal production activities. A multi-stage sampling approach was employed. In the first stage, the four regions were purposively selected based on, and charcoal production characteristics.

These sites were strategically selected based on:

- Geographical location and high rates of off-grid solar PV penetration.
- Informal energy market prevalence, particularly in solar and charcoal trade.
- Absence of formal e-waste management infrastructure.
- Socio-economic vulnerabilities and low literacy levels.
- Cultural and ecological diversity relevant to wild food harvesting and sustainable livelihoods.
- Mkushi was further selected for its high concentration of white commercial farmers, enabling investigation of their role in shaping rural solar transitions.

In the second stage, participants for focus group discussions (FGDs) and interviews (refer to [Appendices C and D](#)) were selected using non-probability sampling techniques. Specifically, convenience sampling was applied for FGDs, which included three FGDs exclusively for full-time charcoal burners, each comprising seven members. Meanwhile, purposive sampling was used to select key informants and stakeholders from the energy and policy sectors. To enhance validity and reliability, a four-week pilot study was conducted with five participants in Luano village (Chingola Rural, Copperbelt Province). This pre-testing phase refined the research instruments, ensuring methodological robustness. Data collection was facilitated by a research assistant fluent in English and multiple local languages (Bemba, Tonga, Soli, Lamba, and Nyanja), alongside the primary investigator, who is proficient in English and has working knowledge of Bemba, Nyanja, and Lamba. Ethics approval for this data collection was granted by the Ethics Committee at the University of Reading.

The primary data collection methods included in-depth interviews and focus group discussions. A total of 21 full-time charcoal burners, 40 rural farmers, 16 commercial farmers, and 3 key stakeholders from solar energy companies and government policymaking institutions were interviewed, with interview durations ranging from 30 to 60 min. Ten FGDs were conducted across the four selected areas: three in Kapiri, three in Mkushi, one in Luano, and three in Chongwe. Each FGD consisted of 7–12 participants, ensuring diverse perspectives. Of the ten total FGDs, three were exclusively dedicated to full-time charcoal burners in Mkushi, Luano, and Chongwe, with seven members per group. Gender-sensitive research practices were incorporated by organising both mixed-gender and separate FGDs for men and women, facilitated by village headmen or councillors to encourage trust and mitigate dominance bias. Participants received refreshments and tokens of appreciation for their time and insights. Topics discussed in these interviews included economic dependence on charcoal, perceived



Fig. 2. Map of Zambia (UN 2022)- (Data collection areas – yellow circles).

demand and impacts of the charcoal trade, profitability of charcoal, solar PV adoption and its barriers, charcoal use and its gender, socio-economic, and cultural dynamics, as well as policy approaches to charcoal regulation.

To ensure data security and ethical compliance, all recorded interviews, photographs, and video clips - captured with full informed consent - were securely stored on Reading University's OneDrive cloud account with restricted access. Data analysis was conducted using NVIVO 14, ensuring methodological rigour and systematic thematic analysis guided by the RUDSHAM framework. Interview transcripts and FGD recordings were coded into themes, employing colour-coding techniques and NVIVO's advanced analytical tools to identify patterns, relationships, and insights. NVIVO facilitated the organisation of data linked to key RUDSHAM attributes, including Perceived Usefulness (PU), Policy Support (PS), and Community Participation (CoP). This thematic analysis approach enhanced the credibility, reliability, and depth of the study's findings.

4.2. Methodology for carbon stock loss

Building on the socio-economic and policy-oriented fieldwork outlined in Section 4.1, this section introduces the ecological dimension of the study by quantifying carbon stock loss associated with charcoal and fuelwood production. Integrating this assessment is critical to situating rural energy transitions within the broader RUDSHAM framework, as it links community energy practices (Perceived Usefulness, Community Participation) with their environmental consequences and policy relevance (Policy Support). By examining both human dynamics and ecological impacts, the methodology provides a holistic foundation for analysing the sustainability of charcoal dependence and the potential of solar PV adoption in rural Zambia.

This study assessed the loss of carbon stocks and future carbon sequestration potential resulting from forest degradation attributable to charcoal and fuelwood production in Zambia and the four selected districts (Chingola - Luano, Kapiri Mposhi, Mkushi, and Chongwe) during the periods 2008–2015 and 2016–2023. These two consecutive 8-year periods were selected to enable a temporal comparison of forest loss trends over time. The study assumed that all forest loss occurred in natural forests, leading to immediate carbon emissions without considering subsequent land-use changes. Additionally, carbon storage in harvested wood products was not considered, and all harvested biomass was assumed to be immediately emitted. Forest loss data was obtained from Hansen et al.'s dataset (Hansen et al., 2013), using the 2000 tree cover dataset along with the loss year dataset for 2001–2023, which were processed in Quantum Geographic Information System (QGIS 3.34). The dataset has a 30-m (900m²/pixel) spatial resolution, which enables precise measurement of forest loss in the four regions. A 10 % canopy threshold was applied to classify forest cover, aligning with standard global forest definitions (FAO-FRA, 2025). To estimate forest loss area (ha), the 2000 tree cover percentage was combined with the binary loss year dataset, so that the calculation accounts for the proportional canopy cover lost in each affected pixel, rather than assuming a uniform loss across all pixels classified as forest loss.

Charcoal and fuelwood production is estimated to account for approximately 90 % of forest loss in Zambia (Forest Trends, 2021; LCMS, 2022; USAID A2C, 2021; ZNCAF, 2023), and this proportion was applied to both national and district-level loss data for the carbon stock calculations. Carbon stock loss was calculated based on the carbon stock of aboveground biomass (AGB), as belowground biomass is typically not removed or combusted in charcoal production processes. The values for AGB (69.6 t/ha) and Carbon Fraction (0.47) were derived from the IPCC 2006 Guidelines and 2019 Refinement (IPCC, 2019, 2006). The AGB value was based on the Tropical Dry Forest (≥ 20 years) category in IPCC guidelines, while the carbon fraction was applied as the default IPCC value. An emission factor of 1.00 was applied, assuming all harvested biomass is immediately combusted and released to the atmosphere. The

following equations were used for calculation (refer to equations (1)–(4)):

$$\text{Carbon Stock Loss (tC)} = \text{Forest Loss (ha)} \times \text{AGB} \times \text{Emission Factor} \times \text{Carbon Fraction} \quad (1)$$

$$\text{Carbon Stock Loss (tCO}_2\text{)} = \text{Carbon Stock Loss (tC)} \times 3.67 \quad (2)$$

Additionally, the annual carbon sequestration potential that would have occurred if the forests had remained intact was estimated. This estimation was based on the AGB Growth Rate for Tropical Dry Forests (1.6 t/ha/yr) from IPCC (2019). The future sequestration potential was determined using the equations:

$$\text{Future Carbon Sequestration Calculation (tC/yr)} = \text{Forest Loss (ha)} \times \text{AGB Growth Rate (t/ha/yr)} \times \text{Carbon Fraction} \quad (3)$$

$$\text{Future Carbon Sequestration (tCO}_2\text{/yr)} = \text{Future Carbon Sequestration (tC/yr)} \times 3.67 \quad (4)$$

This methodological approach enables a comprehensive assessment of forest loss-related carbon emissions and the foregone sequestration potential, contributing to the broader discourse on climate change mitigation and energy transitions in Sub-Saharan Africa.

5. Findings

This section synthesises empirical data gathered from charcoal producers, commercial farmers, and rural residents in four rural areas in four districts. Findings are organised around thematic domains grounded in the RUDSHAM framework, illuminating the dynamic interplay between energy practices, economic realities, environmental degradation, and policy responses. The evidence presented draws from in-depth interviews and focus group discussions.

5.1. Economic dependence on charcoal trade

These findings are grounded in the discussion of economic marginalisation, informal livelihood strategies, and solar uptake trade-offs as observed during the fieldwork. The results in Table 1 indicate that charcoal burning persists in the studied communities due to economic hardship, seasonal farm incomes, and unemployment. Social networks sustain the trade, while charcoal income paradoxically enables limited solar PV adoption and agricultural investments, despite its environmental consequences and the continued demand-driven deforestation. These findings intersect with the Economic Cost (EC) and Perceived Usefulness (PU) domains of RUDSHAM, suggesting that while charcoal offers short-term income, its role in enabling solar PV uptake remains contextually limited. These insights underline how economic imperatives simultaneously reinforce environmentally detrimental behaviours and enable limited transitions to clean energy, highlighting a tension central to rural energy transitions in Zambia.

5.2. Deforestation and charcoal trade findings

This theme emerged from interviewees' observations on biodiversity loss, land-use pressures, and declining forest quality, corroborated by ecological field assessments. Empirical evidence in Table 2 highlights that shrinking forests force charcoal producers to cut smaller and fruit trees, threatening biodiversity and food security. While charcoal burning accelerates deforestation, agriculture and timber harvesting also contribute. Weak environmental awareness and poor policy enforcement further endanger Zambia's remaining forests. This finding engages with Green Concern (GC) and Policy Support (PS), revealing limited environmental awareness and enforcement. However, the extent of charcoal's contribution to deforestation must be interpreted alongside other land-use drivers. These findings reflect the complexity of attributing forest loss to a single activity and reinforce the importance of

Table 1
Economic and livelihood dependence on charcoal trade.

Participant	Direct Quotation	Source
(a)	"Life has become very expensive. There are no jobs, and farming inputs are costly, leading to poor harvests and less disposable income. Hence, we are left with no option but to look for extra income sources through charcoal burning."	Charcoal Burner FGD 1
(b)	"Farm jobs are seasonal in nature, just like income from agriculture. Hence, we use other means to bridge the financial gap through the use of charcoal, which is always in high demand."	Charcoal Burner FGD 1
(c)	"The charcoal business is not abnormally high in profit, and I know the negative consequences of charcoal burning, but I have no option. It's better to engage in charcoal burning than to steal or go around begging for food from people."	Charcoal Burner Interview 21
(d)	"It's not by choice that I entered the charcoal business. I have literally tried everything, and it has not worked. The only thing that has worked for me is charcoal burning. To me, it's a source of livelihoods, a matter of life and death."	Charcoal Burner Interview 6
(e)	"The relatively easy money and constantly increasing demand have pulled many into the charcoal business, in addition to those who were pushed into the charcoal business out of poverty and unemployment."	Charcoal Burner Interview 9
(f)	"The income from charcoal burning has helped us in buying solar home systems and paying back the SHS loans, including chargers, torches, and solar home systems. The income also supplements buying fertiliser to help with agriculture."	Charcoal Burner FGD 2
(g)	"Some of us never really planned to be charcoal burners, but we were introduced to it and got addicted after we cleared a farm, produced the charcoal, and sold. The money was sweet! laughs!"	Charcoal Burner FGD 2
(h)	"The knowledge about charcoal burning was handed down to me by my parents, and through observation and early exposure to it, I learned and started my own business. Now, I am proudly self-employed and even hire some people to help on some big projects. I am a boss ... laughs ... charcoal burner boss ... laughs."	Charcoal Burner Interview 14
(i)	"I got attracted to charcoal burning because I was exposed to it through my relatives and forefathers, who were also in the trade. It's a family business."	Charcoal Burner Interview 6
(j)	"I have managed to buy a TV and have lighting in my house through income from charcoal burning."	Charcoal Burner Interview 7
(k)	"I am very grateful to God for the charcoal business, which has really been helpful to me. The farm that you see, including the bicycle that I am riding, are all products of income from charcoal burning."	Charcoal Burner Interview 1
(l)	"To ask a rural person who depends on charcoal burning to stop, you are basically asking him to give up his income, and it's a challenge just as many of us would resist if we were told to stop doing what brings us income, such as farming or our jobs. Alternatives will need to be found, but as long as there is demand for charcoal, no matter what laws are put in place, the problem of charcoal burning is likely to continue for a long time until all the trees run out."	Commercial Farmer Interview 5

multifaceted, cross-sectoral responses to ecological degradation.

5.3. Charcoal profitability and seasonality

This segment draws from seasonal patterns in price and labour allocation that emerged during interviews and correlates with the Economic Cost (EC) and Prior Preferences (PP) constructs. The results in Table 3 show that charcoal profitability fluctuates seasonally, peaking

Table 2
Deforestation and charcoal trade findings.

Participant	Direct Quotations	Source
(a)	"In the past, only mature, good trees that produced the best charcoal were used for charcoal production. But with the shrinkage of forests, we are now forced to use even small trees and sometimes fruit trees."	Charcoal Burner FGD 2
(b)	"Times are hard, and there is so much demand for charcoal with fewer right trees. Hence, we have been forced to start cutting even fruit trees and trees with medicinal qualities."	Charcoal Burner FGD 1
(c)	"Some of us are involved in both mopane worm collection and charcoal burning. The bad thing I have noticed is that some of the best trees used for charcoal burning are also host trees for mopane worms, such as Mpsa [Julbernardia globiflora], Mutondo [Cordyla africana], and Miombo [Brachystegia boehmii]. Their loss has a double impact, affecting both charcoal burning and the mopane worm trade, which borders on food security in rural areas."	Charcoal Burner FGD 1
(d)	"I own some planes, and I have been flying between Lusaka and Mkushi, and gosh, when you look at how the number of trees has reduced since 1986 to now. It's a sad state of affairs. I mean, it used to be green all over, and now it's just patches everywhere."	Commercial Farmer Interview 9
(e)	"The trees that we mostly use for charcoal burning include Umutondo [Cordyla africana], Umubanga [Pericopsis angolensis], Mpsa [Julbernardia globiflora], Kaputu [Brachystegia spiciformis], Umuombo [Brachystegia stipulate], Umusamba [Brachystegia longifolia], Imitobo [Anisophyllea boehmii], and Umulombwa [Pterocarpus angolensis]."	Charcoal Burner FGD 2
(f)	"The people blame us for the lack of rain, but we are not the only ones cutting down trees. Those doing farming are sometimes even worse. And a lot of people cut trees for timber and other purposes, so they cannot heap the entire blame on us. It's not fair."	Charcoal Burner FGD 1
(g)	"When you look at the villages and the areas where rural people live, all the trees are gone compared to the area on the side of the commercial farmers, which is well preserved. It's so sad."	Commercial Farmer Interview 2
(h)	"We have planted about 3 ha of gum trees and eucalyptus, which we allow our workers to use for firewood. In addition, we give our workers trees that fall naturally, but deliberate cutting of trees is strictly prohibited and punishable through disciplinary action."	Commercial Farmer Interview 11
(i)	"There are trees that can be planted and harvested for making charcoal. The government needs to take this seriously."	Commercial Farmer Interview 5
(j)	"Both charcoal and agriculture contribute to deforestation, but charcoal is worse."	Commercial Farmer Interview 5
(k)	"Environmental understanding in Zambia is low despite the country being among the top five or ten countries with the highest deforestation. At this rate, there will be no forests left by the time the population hits 100 million."	Commercial Farmer Interview 9

during cold months and the rainy season due to increased demand and limited supply. However, rural producers earn minimal profits compared to urban retailers, exacerbating income disparity and reinforcing dependency on charcoal burning as a livelihood. Linking to Prior Preferences and Practice (PP) and Economic Cost (EC), seasonal profitability appears to reinforce dependence, though this dynamic could shift under alternative livelihood options and market restructuring. Thus, charcoal's seasonal profitability masks its structural inefficiency for rural livelihoods and reveals a cycle of subsistence exacerbated by unequal value chain participation.

Table 3
Charcoal profitability and seasonality.

Participant	Direct Quotation	Source
(a)	"Profitable months for charcoal, even if it is available throughout the year, are June to July when it's cold. Hence, more people need warmth and use charcoal for heating, bathing water, and poultry farming to warm the chickens."	Charcoal Burner Interview 3
(b)	"Around harvest time, there is more disposable income as people sell some of the farming produce from the previous year."	Charcoal Burner FGD 2
(c)	"The other profitable months are during the rainy season because not everyone is willing to do charcoal burning during this period, as it is more difficult. The kiln could be soaked, or the charcoal harvest process can be compromised when the charcoal is buried under sand and exposed to rain."	Charcoal Burner FGD 2
(d)	"In the dry season and at the beginning of the rainy season, people are busy with farming, preparing for food for the next year, and also trying to plant cash crops that are profitable. During the rainy season, there are more jobs available on different farms where people can do some piecework and raise some income instead of engaging in charcoal burning."	Charcoal Burner FGD 1
(e)	"The profit from charcoal mainly goes to the retailers who sell in town and along the road. The profit for a 25m ² kiln on average is around K800 (\$32 US) for the producer whilst the retailer gets net profit of around K2,000 (\$80 US)."	Charcoal Burner Interview 5
(f)	"We make very little profit; that's why we have stayed in this business and have failed to diversify. Tubombelafye ubuchushi (we are only in this because of poverty and have no other alternative). It's so painful to be taken advantage of, but there is nothing much we can do. We are not united, so we are taken advantage of as we set charcoal prices individually and many times at giveaway prices."	Charcoal Burner FGD 1
(g)	"The only way to make more money is to make more charcoal. Hence, sometimes we combine forces to make big kilns so that we get more charcoal and increase our profits."	Charcoal Burner FGD 1

5.4. Solar adoption and livelihood diversification

This subsection draws on thematic evidence relating to technology uptake, aspirations, and access to productive-use solar tools facilitated by NGOs. Empirical evidence in Table 4 highlights a growing shift toward solar energy adoption, driven by safety concerns and aspirations for modern living. Access to solar irrigation enables small-scale farmers to transition from charcoal burning to profitable gardening, facilitated by NGO-supported credit schemes for solar-powered water pumps. Findings map onto Perceived Usefulness (PU) and Community Participation (CoP), as solar technology uptake appears aspirational. However, adoption remains uneven and may reflect early-stage transitions rather than a widespread behavioural shift. These observations suggest that solar PV holds transformative potential, yet its scaling remains constrained by economic access, initial capital, and uneven institutional support.

5.5. Economic barriers and charcoal dependency

Grounded in household level financial data and affordability metrics, this section engages with structural economic limitations on renewable energy adoption. The findings in Table 5 reveal that high solar PV costs limit productive use, sustaining charcoal dependence. Land clearing drives opportunistic charcoal burning, while costly fertilisers encourage unsustainable farming. Charcoal income funds household solar PV systems, highlighting economic trade-offs in rural energy transitions. This aligns with Financial Models of Relevance (FMR) and Economic Cost (EC). While charcoal income supports solar investment, such trade-offs

Table 4
Solar adoption and livelihood diversification.

Participant	Direct Quotation	Source
(a)	"The world is changing, and everyone is turning to solar lighting and abandoning candles and traditional lamps. So, we have also joined the bandwagon, as we don't want to be left behind. The house looks better when lit with solar bulbs kwati nikumayadi (like in urban high-cost areas), and you don't have to worry about fires compared to using lamps and candles, which have caused many fires. Some people have actually been killed, or houses have been completely burned down."	Charcoal Burner FGD 1
(b)	"Our friends who have solar-powered water pumps can engage in gardening and raise a lot of money even in the dry season. They don't engage in charcoal burning because it's much easier to have a garden than to burn charcoal."	Charcoal Burner FGD 2
(c)	"Our NGO provides support with solar irrigation systems for small-scale farmers (SSFs) on a credit basis through providing funds for boreholes and a solar irrigation system that can irrigate up to a lima (50m ²). They start with small loans and, over the years, graduate to bigger loans of K20,000 (\$800 US), which include solar irrigation systems that they pay back over a period of about four years. One farmer actually made a profit of K20,000 in one farming season from gardening alone."	Commercial Farmer Interview 8

Table 5
Economic barriers and charcoal dependency.

Participant	Direct Quotation	Source
(a)	"The problem is that people just talk, and there is very little action. If someone could provide us with a credit pay-slow system or affordable loans for solar irrigation systems, all of us would want to get that system. But the problem is that, apart from lighting systems, which are affordable, solar systems for productive purposes have proved to be very expensive and almost outside of our ability to pay. You need to burn the whole forest to afford such a system ... laughs!"	Charcoal Burner FGD 1
(b)	"The beginning of the farming season sees a lot of opportunistic charcoal burners who join because they must cut trees to prepare agricultural land for farming. New farming areas offer more fertility. But this supply is not enough to satisfy the demand for charcoal when other players are involved, like those whose main business is charcoal burning."	Charcoal Burner FGD 2
(c)	"Fertiliser is expensive, and the government subsidies that we used to get for fertiliser have been drastically reduced, to impress the whites so that we can be allowed to borrow money from the West ... laughs!"	Charcoal Burner Interview 7
(d)	"Fertiliser has destroyed the soil to such an extent that it's almost impossible to get yield without fertiliser and treated seeds. So, we are forced to look for means to raise money to buy these inputs so that we can afford these."	Charcoal Burner Interview 19
(e)	"Apart from heating up our homes and helping us cook, charcoal also provides 'lighting' for us by providing income, which we use to make payments for the solar home systems provided by companies like Ready Pay, My Sol, Fenix, and Sun King."	Charcoal Burner FGD 2
(f)	"The available solar home system prices and loans depend on the size that you want and can afford, ranging from two-bulb solar home systems costing around K1,300 (\$52 US) cash and K1,700 (\$68 US) in instalments payable in 18 months. Also, those with four bulbs cost around K3,600 (\$144 US) cash."	Charcoal Burner Interview 17

raise concerns about the scalability and equity of clean energy transitions. The persistence of charcoal reliance reflects not just market failures but systemic affordability challenges that constrain energy diversification.

5.6. Safety risks from charcoal burning

Building on the earlier discussion of economic and ecological drivers, this segment turns attention to the environmental hazards and health implications tied to charcoal production practices. The findings in Table 6 highlight the environmental and health risks of charcoal production, including forest fires, respiratory illnesses, and snakebites. Competition for dwindling trees fuels land disputes, while some men misuse earnings, exacerbating social issues. Women, however, invest more responsibly in household needs. Findings relate to Green Concern

Table 6
Safety risks from charcoal burning.

Participant	Direct Quotation	Source
(a)	"Ifibili (kilns) during the initial lighting process, if not done properly, especially by novices, have led to forest fires. That is a danger, and we ensure that we try to be as careful as possible during the process. But I guess in life, you can't be too careful, especially since the charcoal business is not regulated ... it's a free-for-all business."	Charcoal Burner Interview 4
(b)	"Times are hard, and there is so much demand for charcoal with fewer right trees. Hence, we have been forced to start cutting even fruit trees and trees with medicinal qualities."	Charcoal Burner FGD 1
(c)	"The nearby trees close to the villages and roads have been depleted. Hence, for someone to find good trees, they have to travel long distances, which adds to transport costs. There is serious competition for the few remaining trees, even those on private lands."	Charcoal Burner FGD 2
(d)	"Someone tried to cut trees for charcoal burning in an area that was mine, so we got into a serious argument, which the chief had to sort out. It's not the first time this is happening, especially since trees have become rare. People are claiming land that is not theirs ... It's survival of the fittest, and you have to be tough ... laughs."	Charcoal Burner Interview 10
(e)	"We face a lot of dangers and encounter poisonous snakes, especially when we venture into the deep forests far from the villages."	Charcoal Burner Interview 13
(f)	"There are several people that have been bitten by poisonous snakes, and some have even died in the recent past."	Charcoal Burner FGD 2
(g)	"I sometimes get chest pains that last for weeks from burning charcoal. The smoke and heat do me harm. I take some munkoyo [Rhynchosia venulose] shrub drink to help, or milk if available."	Charcoal Burner Interview 14
(h)	"We suffer several negative health effects in the charcoal burning process, including chest pains, headaches, colds, coughs, and TB. But we have no option; otherwise, we die of hunger, what's better?.. laughs."	Charcoal Burner FGD 1
(i)	"We play down the dangers, but the truth of the matter is that we have seen some of the people who have been involved in charcoal burning for a long-time suffering from chronic coughs like TB."	Charcoal Burner FGD 1
(j)	"Women usually use the proceeds from charcoal burning properly, but some men and youths indulge in dangerous behaviour, which exposes them to life-threatening diseases."	Charcoal Burner Interview 21
(k)	"Some charcoal burners become excited with the money that they make and end up drinking too much or womanizing, eventually contracting STIs, which not only endanger them but also their spouses. But mostly, women charcoal burners use their money more responsibly to buy household items, pay for SHS, or help educate their children."	Charcoal Burner FGD 2

(GC) and Perceived Behaviour Control (PBC). While health and environmental harms are evident, the uneven awareness and behavioural agency limit systemic change without stronger interventions. Understanding these risks contributes vital insights into the human cost of energy poverty and underscores the necessity of designing energy transition pathways that safeguard health and safety in marginalised settings.

5.7. Gender challenges in charcoal trade

Following the previous analysis of health and safety concerns, this examination highlights the distinct gender-based constraints and vulnerabilities faced by women in the charcoal value chain. The results in Table 7 reveal significant gender disparities in the charcoal trade, where women face exploitation, financial dependency, and societal stigma. Limited physical capacity, lack of maternity support, and male dominance further disadvantage women, often forcing them into exploitative relationships to sustain their businesses. These results touch on Community Participation (CoP) and Norms (NO), highlighting gendered disadvantages. Yet, further inquiry is needed into how agency and institutional support shape women's pathways within the trade. Incorporating gender-responsive strategies is critical to achieving equitable energy transitions and fostering inclusive rural development across Sub-Saharan Africa.

5.8. Policy and legal trade issues

Expanding from the gender dimension, this section interrogates the disconnect between formal charcoal regulation and the lived realities of enforcement and compliance. Empirical evidence in Table 8 highlights widespread non-compliance due to high permit costs, corruption, and weak enforcement. Bribery sustains the illegal charcoal trade, while officials exploit confiscations. Policies exist but lack enforcement, and

Table 7
Gender challenges in charcoal trade.

Participant	Direct Quotation	Source
(a)	"As a woman, being in the charcoal business is not very easy because you must hire men to do everything for you, and at the end of the day, your profits are reduced. Some naughty men with bad manners even demand your body as a woman in exchange for free help. Sadly, some women who love money end up giving in ... the love of money ... laughs."	Charcoal Burner FGD 2
(b)	"Women usually use the proceeds from charcoal burning properly, but some men and youths indulge in dangerous behaviour, which exposes them to life-threatening diseases."	Charcoal Burner Interview 3
(c)	"It's an uphill struggle to be a woman and a charcoal burner because, traditionally, it's a male-dominated trade."	Charcoal Burner Interview 10
(d)	"Many people discourage us and tell us that charcoal burning is for men. As women in the village, we are regarded as second-class citizens without rights ... only good for having babies and looking after children ... laughs."	Charcoal Burner Interview 18
(e)	"It's naturally more difficult for a woman to be a charcoal burner, especially when she is pregnant or breastfeeding, because there is no maternity leave. It means either the business has to stop until she gets back on her feet or she has to comprise childcare leading to health problems in children. In the process of delegating tasks, many women have experienced losses or even gone under."	Charcoal Burner FGD 1
(f)	"Some single women involved in charcoal burning are sometimes forced to find a 'special' male partner ... laughs ... to help out in the business. But not everyone resorts to such desperate measures to stay in business."	Charcoal Burner FGD 1

Table 8
Policy and legal trade issues.

Participant	Direct Quotations	Source
(a)	"It's expensive to get permits/licences for charcoal burning. I have never obtained a licence, so I ensure I keep something aside to bribe the forest officers or the police. The police are easier to deal with, but the forest rangers sometimes confiscate the bags, and you lose out."	Charcoal Burner Interview 4
(b)	"We are all aware that we need permits to make charcoal, but honestly, no one follows it. I mean, I have never seen anyone within my village and beyond who has gone to get a permit to make charcoal. I mean, we all understand no one planted these trees, so why should someone come up with restrictions on how to make use of God-given resources?"	Charcoal Burner Interview 6
(c)	"I feel for the forest officers because they have bad manners and bad hearts and like confiscating hard-earned charcoal. They can be a nightmare because the cost of retrieving the charcoal once confiscated is as high as K500 (\$20 US) to K700 (\$28 US), which is almost equivalent to the entire profit, you see."	Charcoal Burner Interview 5
(d)	"Sometimes we suspect that these officers just set deliberate ambushes to confiscate our charcoal on purpose so that they can, in turn, go and sell the charcoal. Open their own small shops over our sweat ... very evil people."	Charcoal Burner FGD 1
(e)	"Once confiscated, we rarely pay the penalty because usually, it is even higher than the value of the charcoal. So, the best thing is to negotiate with the arresting officer so that you give him something before it goes to the offices, and you can go and sell the charcoal and make some money ... laughs ... you have to be sharp."	Charcoal Burner FGD 2
(f)	"Look, I don't understand how they calculate these permit issues for charcoal burning. Once I was clearing my farm and, as a law-abiding citizen and a Christian, I went to the council to inquire how much I would have to pay to get a licence for making charcoal. The quotation amount that I was given was so huge that I ended up just burning the trees. Maybe it's because I am a 'Muzungu' (White)."	Commercial Farmer Interview 6
(g)	"Policies and laws against charcoal burning are there, but every day you see truckloads of charcoal going into the cities, and you wonder how this is possible. The government is not doing much. The policies are just on paper."	Commercial Farmer Interview 7
(h)	"To some extent, the government tries to discourage people from deforestation, but they don't offer any serious alternatives; hence, it fails to implement. With the availability of alternatives, almost all of us are willing to stop and do something better."	Charcoal Burner FGD 1
(i)	"They have tried to stop us, but it's just on paper, and it's not real. Whoever would try to ban the production of charcoal would dig his own grave and the graves of many charcoal burners and their families. If it's a political party, no doubt, it would definitely lose elections because the votes come from here."	Charcoal Burner FGD 2
(j)	"Some chiefs and headmen are corrupt and are actually at the forefront of charcoal burning since they have huge traditional portions of land by virtue of their positions, which they use to make charcoal and cut trees."	Charcoal Burner FGD 1

without viable alternatives, charcoal production remains essential for livelihoods, exacerbating deforestation and environmental degradation. Findings speak to Policy Support (PS) and Perceived Behaviour Control (PBC). Though policies exist, limited compliance and enforcement show that legal frameworks alone are insufficient without community-responsive governance structures. This analysis reveals that charcoal

governance reform must be reinforced by local participatory mechanisms and socioeconomic incentives if regulatory strategies are to succeed.

5.9. Urban demand and market drivers

Transitioning from governance issues, this focus area examines the market-side dynamics that perpetuate charcoal production, particularly the role of urban consumption patterns. The findings in Table 9 indicate that urban demand, worsened by economic hardship and load-shedding, sustains charcoal production. Rural communities use firewood, while charcoal is exported to cities. Stagnant prices and rising competition reduce profits, emphasising the need for urban-focused policies to curb

Table 9
Urban demand and market drivers.

Participant	Direct Quotations	Source
(a)	"The introduction of fertiliser and total dependence on it has seen many portions of land quickly lose fertility due to chemical use, meaning that new farms need to be opened."	Charcoal Burner FGD 1
(b)	"In the rainy season, it's difficult to do charcoal business, as it sometimes gets compromised due to rain and might be difficult to store for a long time while retaining quality."	Charcoal Burner Interview 6
(c)	"Our biggest customers have been in urban areas, especially in peri-urban areas where you find the lower class who do not earn much. But in the last few years, since load-shedding shifted gear, even people from high-cost areas are buying charcoal."	Charcoal Burner FGD 2
(d)	"The recent worsening of economic conditions in the country has worked to our advantage. Without load-shedding and increased ZESCO electricity tariffs, we wouldn't have seen this surge in demand for charcoal."	Charcoal Burner FGD 1
(e)	"Apart from charcoal, there are very viable income-generating ventures that don't require much capital. If we had alternative sources of income and jobs, we would have long shifted and stopped this charcoal business."	Charcoal Burner Interview 7
(f)	"Prices of charcoal have been almost stagnant for a while, whilst the cost of living has been increasing, and the number of charcoal burners has increased due to increased demand."	Charcoal Burner Interview 16
(g)	"So many people have joined the charcoal trade, and in the process, the prices have been affected, which has caused them to come down, especially in places where there are many in one place."	Charcoal Burner FGD 1
(h)	"Firewood is used in rural areas, and charcoal is exported to urban areas because many people in urban areas cannot afford electricity, especially when it comes to heating and cooking. People in rural areas depend on firewood and do not need charcoal except mainly for export to urban areas to earn an income."	Commercial Farmer Interview 2
(i)	"The solution to charcoal burning does not lie in the rural areas; it lies squarely in the urban places."	Commercial Farmer Interview 2
(j)	"If charcoal was used just in the rural areas, it would be sustainable, and there wouldn't be all these problems. The issue about charcoal burning is not so much to do with the local community but the commercialization aspect, which has been brought about by the demand from urban areas. I believe the solution regarding charcoal lies in the urban areas."	Commercial Farmer Interview 7
(k)	"This charcoal problem is a complex thing and has many facets. As much as the charcoal business drives the rural economy, you see, people in urban areas, where the unemployment rate is actually higher than in the rural areas, due to economic reasons, cannot afford to pay for power. Since there is no firewood, they resort to charcoal, which they can afford."	Commercial Farmer Interview 5

deforestation and promote energy alternatives. This reflects Perceived Usefulness (PU) and Financial Models of Relevance (FMR). The results suggest that urban demand sustains rural supply chains, but without price incentives or market shifts, change may be marginal and localised. These findings suggest that interventions aimed at rural producers will fall short unless urban demand-side policies, including affordable electricity and clean cooking, are implemented in tandem.

5.10. Charcoal Trade's political complexity

The discussion now turns to the embedded political and cultural realities that inhibit reform, drawing from local governance and traditional authority structures. Empirical evidence in Table 10 highlights that charcoal burning persists due to survival needs and weak enforcement. Chiefs attempt sensitisation, but headmen remain passive. Heating for cooking and warmth drives deforestation, necessitating urgent policy interventions to promote alternative energy sources and sustainable income opportunities. Findings connect to Norms (NO) and Policy Support (PS). Though traditional leaders attempt regulation, fragmented authority and grassroots disengagement suggest limited traction for long-term change under current governance dynamics. The findings imply that efforts to shift from biomass must acknowledge charcoal's symbolic functions, ensuring that proposed alternatives resonate with local value systems. This highlights that charcoal is not only an environmental and economic issue but also a politically entangled livelihood practice requiring nuanced and multi-scalar policy responses.

5.11. Charcoal's cultural and non-energy uses

Extending the inquiry into socio-cultural terrain, this portion illuminates the deeper symbolic, medicinal, and spiritual meanings ascribed to charcoal in rural life. The results in Table 11 show that firewood and charcoal hold deep cultural significance beyond cooking, serving as social focal points and integral elements of traditional rural African life. Additionally, charcoal has medicinal, spiritual, and functional uses, reinforcing its entrenched role in rural communities. These findings relate to Prior Preferences and Practice (PP) and Norms (NO). Charcoal's embedded social and symbolic meanings complicate substitution efforts, warranting culturally sensitive alternatives rather than purely technical interventions. The results imply that efforts to shift from biomass must acknowledge charcoal's symbolic functions, ensuring that proposed alternatives resonate with local value systems.

Table 10
Charcoal Trade's political complexity.

Participant	Direct Quotations	Source
(a)	"No one stops us because we rub shoulders with even headmen and fight over trees in the bush as we do business in charcoal because they also have to survive."	Charcoal Burner Interview 3
(b)	"Some chiefs, to some extent, try to sensitize subjects about the dangers of charcoal burning, but they can only go so far in the absence of alternative sources of income. Headmen, on the other hand, don't do anything much to discourage charcoal burning."	Charcoal Burner FGD 1
(c)	"Telling people to stop charcoal burning is like asking them to commit suicide, and I am sure no normal human being would want to do that."	Commercial Farmer Interview 4
(d)	"Lighting is good, but heating seems to be the main problem, which must be sorted out soon; otherwise, in a few years, we will have no trees remaining. Truth be told, people can do without lighting because it comes naturally, but heating for cooking and warmth is a necessity."	Commercial Farmer Interview 5

Table 11
Charcoal's cultural and non-energy uses.

Participant	Direct Quotation	Source
(a)	"Firewood and charcoal brazier culture is not just about cooking food and eating. It comes with its own social benefits that villages appreciate and have grown up living with. There is a lot that happens around the fire in Africa. More like the bonfire in Europe, which is nice to look at as you excitedly interact, except in Africa, it's done on a daily basis and engraved in the culture."	Commercial Farmer Interview 6
(b)	"Community social life revolves around fire in the kitchen. Around the fire, that's where you cook, sit, talk, interact, and get entertained whilst resting and catching up. Without fire, people feel out of place and as if their life is gone, empty and meaningless."	Commercial Farmer Interview 7
(c)	"I have built my workers very good houses and even provided some stoves for them, but even with stoves inside, they still bring the charcoal braziers into their homes to sit around them ... laughs."	Commercial Farmer Interview 5
(d)	"It would be a long time before the culture from 'imbaula' (charcoal brazier) and wood would change because firewood is about culture."	Commercial Farmer Interview 6
(e)	"There are places like South Africa where I have lived before, and because there are no forests there, people use cow dung and maize cobs for heating, and they are used to it. This can also work in Zambia except the use of firewood and charcoal is a cultural thing, and it's deeply entrenched in people."	Commercial Farmer Interview 4
(f)	"Firewood and charcoal brazier culture is not just about cooking food and eating. It comes with its own social benefits that villages appreciate and have grown up living with. There is a lot that happens around the fire in Africa."	Commercial Farmer Interview 7
(g)	"Apart from selling charcoal and using it for heating and cooking, we also use it for various other purposes. In its crushed form, charcoal is used to neutralize snake poison, particularly in emergencies when medical help is far. It is also taken for stomach aches and used as chalk for writing. Additionally, some people use it for painting houses and facial decorations during traditional entertainment. In certain cultural beliefs, a piece of charcoal is placed in a bag of mealie meal to prevent its magical theft."	Charcoal Burner FGD 2
(h)	"Charcoal is commonly used for treating poison ingestion and stomach aches, as well as for neutralizing snake venom. It is also believed to ward off evil spirits and witches and is sometimes placed under a pillow to prevent bad dreams. Historically, charcoal was buried with individuals who died tragically or were barren, as it was thought to prevent such misfortunes from recurring in future generations, which were perceived as curses."	Charcoal Burner FGD 1
(i)	"When I was a young boy, charcoal saved my life. I mistakenly drank kerosene, and I was given crushed charcoal mixed with water to drink. Within an hour, I vomited, and the dizziness I had been feeling disappeared soon afterward."	Charcoal Burner Interview 3

5.12. Challenges in energy-efficient cooking adoption

Following cultural perceptions, this part considers the barriers to adopting energy-efficient cooking technologies, especially improved cookstoves and braziers. The findings in Table 12 highlight significant resistance to energy-efficient braziers due to their perceived inefficiency in generating adequate heat for traditional cooking methods. Cultural norms, household dynamics, and slow cooking times discourage adoption, though alternatives like maize cob charcoal show promise when they meet user expectations. Linking to Perceived Ease (PE) and Norms (NO), resistance to efficient braziers reflects not only technical

Table 12
Challenges in energy-efficient cooking adoption.

Participant	Direct Quotation	Source
(a)	"I tried to distribute some free energy-efficient braziers (EEBs) to my farm workers, but the women were the first to complain that it was a bit too high and didn't provide as much heat as firewood or the charcoal brazier. Hence, within a short time, the EEBs were abandoned."	Commercial Farmer Interview 3
(b)	"We were given some free charcoal braziers that used small sticks, but it was just the same, and food took too long to cook, especially 'nshima' (maize meal mash), so we went back to firewood and charcoal, which we have grown up with."	Charcoal Burner FGD 1
(c)	"Sometimes, it's not that we are stubborn and refuse to adopt some of the stoves given to us by our bosses, NGOs, etc (I mean, sometimes it's dangerous to go into the bush because you might encounter snakes, wild animals, or even criminals, especially for girls). The problem is that these stoves don't do as good a job. For example, we have moved away from candles to solar lighting because it's a better option. Similarly, if a better cooking stove were provided, I'm sure many of us would switch."	Charcoal Burner FGD 2
(d)	"These braziers take so long to cook food. Some of us have husbands with huge appetites and short tempers when food takes too long ... laughs ... so to maintain peace in the home, we ensure we cook using tried and tested methods like firewood and charcoal ... laughs."	Charcoal Burner FGD 1
(e)	"Certainly, we don't enjoy the smoke from firewood, which is sometimes choking and makes the pots black on the outside. Hence, we wouldn't hesitate to switch to a cleaner system if it provided the same heat at the same rate as charcoal, firewood, or a modern stove ... laughs."	Charcoal Burner FGD 2
(f)	"Searching for firewood is hard work and not always easy, especially these days when the forest is dwindling. But it has its own advantages, as it allows people to socialize, take walks, and even gives young girls in love an opportunity to meet their loved ones under the pretext of collecting firewood ... laughs."	Charcoal Burner Interview 4
(g)	"Because of the so-called efficient braziers, I once ended up cooking ubwali ubwabishika (grossly undercooked maize mash due to insufficient heat). It was so embarrassing for my husband and family because I am a well-taught African woman in every aspect. From that day, I swore never to use them again."	Charcoal Burner Interview 5
(h)	"Through the North Swaka Project, we are promoting an energy-efficient wood stove, discouraging charcoal burning, teaching efficient agricultural methods that use less space and minimal fertiliser, promoting beekeeping and finding a market for honey. We also teach people how to make charcoal from maize cobs, and this charcoal doesn't smoke and is hot enough to cook 'nshima' (mashed maize meal) properly."	Commercial Farmer Interview 3

shortcomings but also deep-rooted culinary practices and intergenerational household norms that influence acceptability. This suggests that technological innovation alone is insufficient, behavioural, cultural, and contextual factors must be embedded into the design and dissemination of energy-efficient alternatives.

5.13. Environmental and economic charcoal impacts

Returning to the environmental domain, this discussion evaluates the ecological degradation and production dynamics within charcoal systems. The results in Table 13 indicate that charcoal production is labour-intensive, requiring skill and constant monitoring to ensure quality. Despite high tree consumption, reforestation efforts are

Table 13
Environmental and economic charcoal impacts.

Participant	Direct Quotations	Source
(a)	"The beginning of the farming season sees a lot of opportunistic charcoal burners who join because they must cut trees to prepare agricultural land for farming. New farming areas offer more fertility. But this supply is not enough to satisfy the demand for charcoal when other players are involved, like those whose main business is charcoal burning."	Charcoal Burner FGD 1
(b)	"If someone is serious, they can finish a whole kiln in a period of three weeks and start another cycle depending on the size of the kiln. Typically, the kiln sizes are around 5m long, 2m wide, and 2.5m high, giving a total volume of 25m ³ ."	Charcoal Burner FGD 2
(c)	"Charcoal burning is very difficult and requires a lot of hard work and skill, failure to which you can produce half-baked or overbaked charcoal. It requires constant monitoring. Sometimes you must camp and sleep by the kiln. It's difficult from the tree-cutting to the burning process, which, if not monitored, sometimes switches off."	Charcoal Burner FGD 2
(d)	"To be honest, almost none of us, if not all, have planted any trees except for maybe a few people who have planted fruit trees at their places. This is mainly because we believe that forests can rejuvenate as the trees grow naturally."	Charcoal Burner FGD 1
(e)	"For a 25m ³ kiln, we use a minimum of about 10 trees ranging from around 7 m in height and above. For very big trees, it might take just a few to make a kiln, but they tend to be more expensive if you are buying them."	Charcoal Burner FGD 3
(f)	"The cost of buying about 10 trees for one kiln of 25m ³ is around K500 (\$20 US), and the cost of a single tree averages around K100 (\$4 US), which is used for various purposes, including traditional timber processing."	Charcoal Burner FGD 3

minimal, as many believe forests regenerate naturally. Economic constraints also drive continued deforestation due to affordable tree acquisition costs. These findings engage with Green Concern (GC) and Community Participation (CoP). While producers recognise environmental degradation, limited institutional support and economic alternatives undermine collective reforestation or ecosystem restoration efforts. The findings offer empirical weight to arguments that environmental degradation must be addressed not only through enforcement but by transforming the economic rationalities that drive unsustainable resource extraction.

5.14. Carbon stock loss results

Concluding the empirical findings, this segment quantifies the climate impact of charcoal production through carbon stock loss and sequestration potential. The findings from Tables 14 and 15 reveal a sharp increase in carbon stock loss and future carbon sequestration potential due to forest degradation driven predominantly by charcoal and fuelwood extraction across Zambia and its selected rural districts. From 2008 to 2023, Zambia lost over 49 million tonnes of carbon (tC), equivalent to more than 183 million tonnes of CO₂, with significant emissions concentrated in districts like Mkushi and Kapiri Mposhi (Chanda et al., 2025e). Projections indicate continued loss of future carbon sequestration, with over 2.6 million tonnes of CO₂ lost annually since 2016 in Zambia. This section maps onto Green Concern (GC) and Policy Support (PS), illustrating systemic environmental loss. However, attributing causality solely to charcoal overlooks structural energy poverty and enforcement limitations in land-use policy. The data strengthens the case for urgent climate-smart interventions and place Zambia's charcoal dilemma within the broader discourse on global carbon responsibility and rural energy justice.

Table 14

Carbon stock loss.

Carbon Stock Loss Due to Charcoal and Fuelwood										
	Zambia		Chingola		Kapiri Mposhi		Mkushi		Chongwe	
	2008–2015	2016–2023	2008–2015	2016–2023	2008–2015	2016–2023	2008–2015	2016–2023	2008–2015	2016–2023
Forest area loss (ha)	620,733	1,074,226	2502	5611	18,985	38,765	20,226	40,804	3377	6431
% of Forest Loss:	90 %	90 %	90 %	90 %	90 %	90 %	90 %	90 %	90 %	90 %
Charcoal/Fuelwood										
Forest Loss: Charcoal/ Fuelwood (ha)	558,660	966,803	2252	5050	17,087	34,889	18,203	36,724	3039	5788
AGB (t/ha)(1*)	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6
Emission Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Carbon Fraction of Aboveground Biomass (2*)	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Carbon stock loss (tC)	18,274,876	31,626,073	73,661	165,192	558,934	1,141,273	595,470	1,201,302	99,422	189,334
Carbon stock loss (tCO ₂)	67,068,795	116,067,687	270,335	606,256	2,051,286	4,188,470	2,185,374	4,408,780	364,877	694,855

1* 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

4.7>Tropical dry forest > Africa > Secondary more than 20 years (IPCC, 2019).

2*2006 IPCC Guidelines for National Greenhouse Gas Inventories.

TABLE 4.3 >Default value (IPCC, 2006).

Table 15

Future carbon sequestration potential.

Future Carbon Sequestration Loss Due to Charcoal and Fuelwood										
	Zambia		Chingola		Kapiri Mposhi		Mkushi		Chongwe	
	2008–2015	2016–2023	2008–2015	2016–2023	2008–2015	2016–2023	2008–2015	2016–2023	2008–2015	2016–2023
Forest Loss: Charcoal/ Fuelwood	558,660	966,803	2252	5050	17,087	34,889	18,203	36,724	3039	5788
AGB Growth Rate(t/ha/ yr) (1*)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Carbon Fraction	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Future Carbon Sequestration Loss (tC/ yr)	420,112	727,036	1693	3797	12,849	26,236	13,688	27,616	2285	4352
Future Carbon Sequestration Loss (tCO ₂ /yr)	1,541,811	2,668,223	6215	13,937	47,156	96,287	50,238	101,351	8388	15,974

1*2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories 4.9>Tropical > Tropical dry forest > Africa (≥ 20 y) (IPCC, 2019).

6. Discussion section

This section synthesises the findings of the study in relation to existing literature and policy contexts. The discussion is structured thematically, highlighting the complexities of charcoal dependence, solar PV adoption, and their intersection with rural livelihoods and environmental sustainability.

6.1. Economic dependence and transition paradox

Understanding the entrenched economic dependence on charcoal production is essential for contextualising the slow uptake of renewable energy technologies in rural Zambia. The findings of this study seem to highlight the deep-rooted economic dependence on charcoal production in rural Zambia, shaped by poverty, seasonal agricultural income, and limited employment opportunities (see Table 1). Many charcoal producers view the trade as a survival mechanism rather than a choice, with some describing it as their only viable means of livelihood (Charcoal Burner Interview (d); Charcoal Burner FGD 1 (a)). This aligns with broader regional studies that emphasise how charcoal serves as a financial fallback for rural populations facing economic instability (Rose et al., 2022; Steel et al., 2022). The steady urban demand for charcoal seems to further entrench the trade, ensuring its continued profitability despite low returns (Charcoal Burner Interview (e); Nyarko et al., 2021).

The findings indicate that social networks and generational knowledge play a critical role in sustaining the charcoal trade (Chanda et al.,

2025b). Several participants reported being introduced to charcoal burning by family members, indicating an inherited practice passed down through generations (Charcoal Burner Interview (h, i)). Studies in SSA confirm that cultural transmission of charcoal-making skills perpetuates its role in rural economies, often limiting exposure to alternative livelihoods (Gumbo et al., 2013; Kutsch et al., 2011). Moreover, the “charcoal trap” persists due to the ease of entry into the business and the absence of accessible, sustainable alternatives (Commercial Farmer Interview (l)). Despite its environmental drawbacks, income from charcoal burning has facilitated access to solar home systems (SHS), televisions, and agricultural investments (Charcoal Burner Interview (j, k); Charcoal Burner FGD 2 (f)). This paradox mirrors findings from Nygaard et al. (2016) and Tinta et al. (2023), which suggest that unsustainable charcoal-generated income paradoxically enables limited renewable energy adoption. However, weak policy enforcement, high upfront costs for solar PV, and socio-cultural inertia continue to hinder a large-scale energy transition (Chambalile et al., 2024; USAID A2C, 2021). Addressing this issue requires integrated policies that balance economic security with sustainable energy promotion. Hence, navigating the paradox of charcoal income supporting limited renewable energy adoption requires policies that holistically address socio-economic needs while enabling long-term sustainability transitions.

6.2. Deforestation from charcoal production

Charcoal production's environmental externalities, particularly deforestation, represent a growing threat to Zambia's forest ecosystems and rural sustainability. The study stresses the possible role of charcoal trade in driving deforestation in rural Zambia, revealing an accelerating environmental crisis (see Table 2). With increasing economic hardship and rising demand for charcoal, tree felling seems to have become indiscriminate, possibly leading to the depletion of key species, including those essential for biodiversity and ecosystem stability (Charcoal Burner FGD 2 (a, e)). The shift from selective harvesting of mature trees to cutting younger and fruit-bearing trees illustrates the unsustainable nature of the trade, further exacerbating the depletion of forest resources (Charcoal Burner FGD 1 (b)). These findings align with existing literature, which shows that SSA loses approximately 0.7 % of its total forest cover annually due to charcoal production (FAO-FRA, 2025; Nyarko et al., 2021; Sakala et al., 2023).

The impact of deforestation extends beyond energy supply and affects food security. As reported, key host trees for mopane worms - an important protein source - are being destroyed, jeopardising both ecological balance and rural livelihoods (Charcoal Burner FGD 1 (c)). Similar studies highlight that miombo woodlands, which cover nearly 45 % of Zambia's landmass, are at high risk due to unsustainable charcoal production and agricultural expansion (Nansikombi et al., 2020b). Additionally, commercial farmers observe stark differences in forest depletion, with communal lands being severely degraded compared to private commercial farmland, where tree preservation efforts are more structured (Commercial Farmer Interview (g)). Despite these alarming trends, policy interventions remain insufficient. While some commercial farmers are adopting tree planting initiatives, the absence of government incentives and weak enforcement mechanisms hinder large-scale reforestation efforts (Commercial Farmer Interview (h, i); Moombe et al., 2020). Given that Zambia is among the top ten countries with the highest deforestation rates (Green Climate Fund (GCF), 2020; Nansikombi et al., 2020a; Ministry of Green Economy and Environment, 2025; USAID A2C, 2021), urgent policy action is needed to regulate charcoal production, promote sustainable alternatives, and strengthen afforestation efforts (Commercial Farmer Interview (k); USAID A2C, 2021). These revelations highlight the urgent need for comprehensive regulatory frameworks and reforestation initiatives that address both environmental degradation and livelihood preservation.

6.3. Charcoal profitability and seasonality

The economic viability of charcoal production in Zambia is not uniform but fluctuates with seasonal, market, and climatic dynamics. The data in Table 3 reveals that charcoal trade in rural Zambia is highly seasonal, with profitability fluctuating due to climatic and economic cycles. Peak sales occur between June and July when cold temperatures drive higher demand for charcoal used in heating, bathing water, and poultry farming (Charcoal Burner Interview (a)). Similarly, in rural areas, disposable income rises during post-harvest months, leading to a temporary surge in charcoal purchases (Charcoal Burner FGD 2 (b)). However, profitability remains uneven across the value chain, with rural producers earning significantly less than urban retailers. This disparity is consistent with findings across SSA, where charcoal markets are structured in ways that disproportionately benefit intermediaries while keeping rural producers trapped in economic vulnerability (Rose et al., 2022).

During the rainy season, charcoal production declines due to logistical challenges such as wet kilns and increased risks of spoilage (Charcoal Burner FGD 2 (c)). This seasonal variation forces many rural producers to seek alternative income sources, including agricultural wage labour (Charcoal Burner FGD 1 (d)). However, these jobs are often temporary and insufficient to provide long-term financial stability. The limited diversification opportunities for rural charcoal producers

highlight the urgent need for economic interventions that support alternative livelihoods (Chambalile et al., 2024; Steel et al., 2022). Market inefficiencies further disadvantage rural producers. On average, a 25 m³ kiln generates a profit of approximately K800 (\$32 US) per sale for the producer, while urban retailers make net profits of around K2,000 (\$80 US) per sale (Charcoal Burner Interview (e)). This disparity perpetuates economic hardship, with many producers unable to escape the cycle of low earnings and dependency on charcoal burning (Charcoal Burner FGD 1 (f)). The lack of market regulation and inability to collectively bargain among producers due to the underground trade has led to exploitative pricing, reinforcing the economic constraints faced by rural households. These findings reinforce the need for policy interventions aimed at ensuring fair pricing mechanisms and strengthening producer cooperatives to enhance market competitiveness (Charcoal Burner FGD 1 (g); USAID A2C, 2021). These insights reinforce the importance of policy mechanisms that stabilise rural incomes and provide viable alternatives during off-peak charcoal production periods.

6.4. Solar adoption and income diversification

Despite structural challenges, a gradual shift toward solar energy adoption suggests emerging opportunities for livelihood diversification in rural Zambia. The findings highlight an increasing shift towards solar energy adoption in rural Zambia, primarily driven by safety concerns, economic incentives, and the availability of financing mechanisms (see Table 4). Many rural households are transitioning from traditional lighting sources such as candles and kerosene lamps to solar-powered lighting due to its reliability and reduced fire hazards (Charcoal Burner FGD 1 (a)). This mirrors broader trends in SSA, where the affordability and accessibility of SHS have led to the widespread adoption of off-grid solar solutions, by extending study hours for school-aged children and reducing reliance on hazardous lighting alternatives, with more than 28 million systems installed across the region (Tinta et al., 2023).

Beyond lighting, solar-powered irrigation systems have emerged as an alternative livelihood strategy, allowing small-scale farmers to transition from charcoal burning to gardening and other agricultural activities (Charcoal Burner FGD 2 (b)). This aligns with studies indicating that access to solar irrigation can increase agricultural productivity by up to 300 %, enhancing food security and income stability (Byaro et al., 2024). In Zambia, NGO-led initiatives are supporting smallholder farmers through credit-based solar irrigation schemes, enabling investments in boreholes and irrigation systems that can generate significant profits within a single farming season (Commercial Farmer Interview (c)). Despite these positive trends, financial barriers remain a significant impediment to the widespread adoption of solar technology. While basic lighting solutions are affordable, the high upfront costs of solar-powered irrigation and mechanisation limit broader adoption. Expanding microfinance schemes and subsidised credit facilities for productive solar systems is essential to accelerating rural energy transitions while reducing dependence on biomass fuels (Chambalile et al., 2024). Overall, the integration of solar PV into rural development must be supported by accessible financing and complementary agricultural interventions to scale its impact sustainably.

6.5. Financial barriers and charcoal dependency

Financial exclusion remains a significant impediment to transitioning away from charcoal-based livelihoods towards renewable energy solutions. The testimonies demonstrate that economic constraints remain the primary barrier to a sustainable energy transition in rural Zambia (see Table 5). Charcoal production continues to serve as the dominant livelihood strategy for many households, driven by financial hardship, declining agricultural productivity, and limited employment opportunities (Charcoal Burner FGD 2 (b)). While awareness of deforestation and sustainability concerns exists, immediate economic needs

take precedence over long-term environmental considerations (Charcoal Burner Interview (d)). This reflects broader trends in SSA, where 32 % of rural households rely on charcoal as their primary income source (Chanda et al., 2025a; Steel et al., 2022).

The affordability of solar energy, particularly for productive applications such as irrigation and mechanisation, remains a significant challenge. While basic solar lighting systems are within financial reach for many households, larger systems for agricultural use require substantial investment, often exceeding local income levels (Charcoal Burner FGD 1 (a)). The high cost of solar technology has been identified as a key barrier to renewable energy adoption in SSA, with studies indicating that financing mechanisms, such as pay-as-you-go schemes and microloans, can significantly enhance affordability (Sadik-Zada et al., 2023). The findings suggest that a paradoxical relationship between charcoal income and solar adoption is evident, as many rural households reported that they use some earnings from charcoal sales to finance solar home system payments (Charcoal Burner FGD 2 (e)). Additionally, agricultural challenges further exacerbate financial constraints. The rising cost of fertiliser and declining government subsidies have increased production expenses, forcing farmers to supplement their income through charcoal burning (Charcoal Burner Interview (c, d)). This aligns with research indicating that declining soil fertility and the high cost of synthetic fertilisers have contributed to deforestation as farmers expand their cropland (Ngoma et al., 2021).

The poverty-environmental degradation nexus is a complex and debated issue in developing countries. Studies suggest a bidirectional relationship, where poverty can lead to environmental degradation and vice versa (Awad and Warsame, 2022; Duraiappah, 1999; Kassa et al., 2018). This cyclical relationship is particularly evident in Sub-Saharan Africa, where increased poverty correlates with deforestation and particulate matter (PM) 2.5 emissions (Ssekibaala and Kasule, 2023). Addressing these issues requires a multifaceted approach that enhances access to affordable fertilisers, promotes sustainable farming practices, and improves access to financing for renewable energy solutions (USAID A2C, 2021). Expanding financial support for solar photovoltaic (PV) adoption, particularly for productive uses, is essential to reducing dependence on charcoal in Zambia. Current solar financing models vary widely, with small lighting kits (two bulbs) costing K1,300 (\$52 US) upfront or K1,700 in instalments over 54 weeks. Larger systems with lights, a radio, and a 32-inch TV are priced at K11,300 (\$452 US) upfront or K16,000 in instalments over 78 weeks. Vendors such as My Sol, Fenix, Sun King, and Ready Pay collaborate with mobile network providers to offer these solutions (Charcoal Burner FGD 2 (e); Charcoal Burner Interview (f)). However, affordability remains a significant barrier, especially for productive solar systems. A 900 W system costs K39,000 (\$1560 US) upfront or K48,200 in instalments over 26 weeks, while a 1, 800 W system, suitable for irrigation, costs K49,600 (\$1984 US) upfront or K74,000 (\$2960 US) in instalments over 78 weeks, placing them beyond the reach of most rural households (Charcoal Burner Interview (f)). Tackling these intertwined challenges will require multi-sectoral strategies that address both energy access and broader rural economic vulnerabilities.

6.6. Health risks from charcoal usage

Beyond environmental and economic dimensions, the charcoal trade poses serious public health and safety risks to rural communities. The data highlight the substantial safety risks and negative consequences associated with charcoal production in rural Zambia (see Table 6). While charcoal burning remains a key economic activity, it exposes individuals to environmental, health, and social hazards. Unregulated kilns frequently lead to forest fires, particularly when handled by inexperienced burners (Charcoal Burner Interview (a)), exacerbating deforestation and loss of biodiversity. As demand for charcoal increases, tree depletion seems to have forced burners to cut fruit and medicinal trees, possibly impacting food security and traditional medicine availability

(Charcoal Burner FGD 1 (b)). This aligns with broader research showing that over 250,000 ha of forest are lost annually in Zambia, with charcoal production contributing significantly to this trend (USAID A2C, 2021).

Competition for limited forest resources has escalated conflicts over land ownership, leading to disputes among individuals and communities (Charcoal Burner FGD 2 (c); Charcoal Burner Interview (d)). This aligns with findings by Ngoma et al. (2021) who indicated that in resource-scarce environments, competition for natural assets can result in increased land-related conflicts and legal uncertainties. Additionally, charcoal burners are often forced to venture deeper into forests to evade rangers, due to declining availability of appropriate trees, increasing exposure to occupational hazards such as venomous snake bites, which have resulted in fatalities (Charcoal Burner Interview (e); Charcoal Burner FGD 2 (f)). Health complications are also a major concern, with prolonged exposure to charcoal smoke causing chronic respiratory illnesses, including tuberculosis-like symptoms and persistent coughs (Charcoal Burner Interview (g); Charcoal Burner FGD 1 (h, i)). This mirrors global studies linking biomass fuel smoke inhalation to increased incidences of chronic obstructive pulmonary disease (COPD), asthma, and lung infections (Fullerton et al., 2011). Moreover, the charcoal trade has social consequences, with some men engaging in excessive alcohol consumption and unsafe sexual behaviour, increasing the risk of sexually transmitted infections (STIs) (Charcoal Burner Interview (j); Charcoal Burner FGD 2 (k)). Women, by contrast, are more likely to invest their earnings into household needs, education, and solar energy systems, suggesting gendered disparities in economic decision-making (Charcoal Burner Interview (j)). Addressing these health and safety challenges necessitates cross-cutting interventions that include healthcare access, occupational safety, and transition support to cleaner energy alternatives.

6.7. Gender roles in charcoal production

Gendered experiences within the charcoal value chain reveal deep inequalities that shape participation, benefits, and exposure to exploitation. The findings reveal significant gender disparities within Zambia's charcoal trade, where women face systemic barriers, socio-economic exclusion, and exploitative practices (see Table 7). While some women actively participate in charcoal production, their involvement is constrained by cultural norms, limited decision-making power, and economic vulnerabilities (Charcoal Burner Interview (c)). These findings align with broader research indicating that women in energy-related trades across Sub-Saharan Africa face structural gender biases that limit their access to resources, market opportunities, and financial independence (Bitzer et al., 2024; Ihalaenen et al., 2020; Siakachoma, 2019; Tornel-Vázquez et al., 2024; Zulu et al., 2021). One of the key challenges women face in the charcoal business is financial dependency on male counterparts for labour, which significantly reduces their profit margins (Charcoal Burner FGD 2 (a)). Some women are subjected to transactional exploitation, where they are pressured into providing sexual favours in exchange for assistance with physically demanding tasks. Gendered economic disparities in the charcoal sector are further exacerbated by societal perceptions that consider charcoal burning a male-dominated trade, reinforcing discriminatory attitudes (Charcoal Burner Interview (d)).

Additionally, women in the charcoal business face unique biological challenges, particularly during pregnancy and breastfeeding, when physical labour becomes impossible. The absence of maternity leave or social support structures often forces women to temporarily either exit the trade, resulting in financial instability, or compromise childcare, endangering the health of children (Charcoal Burner FGD 1 (e)). Some single women resort to forming economic partnerships with men for survival, though not all adopt this strategy (Charcoal Burner FGD 1 (f)). Despite these barriers, women generally demonstrate more responsible financial management compared to their male counterparts, prioritising household needs, education, and renewable energy investments

(Charcoal Burner Interview (b)). As such, gender-sensitive policy responses are crucial for ensuring equitable access to energy opportunities and for protecting vulnerable groups from exploitation within informal energy economies.

6.8. Policy, legal and regulatory gaps

Weak governance structures and regulatory enforcement have enabled the persistence of illegal and unsustainable charcoal production. Participant narratives suggest that systemic weaknesses in the regulation and governance of the charcoal trade in Zambia (see Table 8). While laws require permits for charcoal production, widespread non-compliance persists due to the high cost of permits, corruption, and ineffective enforcement mechanisms. Many charcoal burners avoid the formal licensing process and instead rely on informal arrangements, including bribery, to continue operations (Charcoal Burner Interview (a)). Corruption among law enforcement officers and forestry officials exacerbates the issue, with reports of arbitrary confiscation of charcoal, followed by resale for personal gain (Charcoal Burner FGD 1 (d)). These governance failures mirror trends observed in other Sub-Saharan African countries, where weak regulatory frameworks and informal economies contribute to unsustainable charcoal production and environmental degradation (Kabisa et al., 2019; Moombe et al., 2020; Zulu et al., 2021).

The high cost of permits discourages legal compliance, with some producers viewing restrictions as an unfair imposition on their livelihoods (Charcoal Burner Interview (b)). As a result, regulatory efforts to control deforestation remain largely ineffective, as truckloads of charcoal continue to reach urban centres without significant governmental intervention (Commercial Farmer Interview (g)). Furthermore, political considerations hinder stricter enforcement, as charcoal production is a significant livelihood source for rural populations, making stringent regulations politically risky (Charcoal Burner FGD 2 (i), Branch et al., 2023; Cerutti et al., 2018). Chiefs and traditional leaders, who control large portions of communal land, also play a role in perpetuating illegal charcoal production for personal economic gain (Charcoal Burner FGD 1 (j)). The findings emphasise that regulatory efforts alone are insufficient without viable alternative energy sources and economic incentives to transition rural communities away from charcoal production. Without these, charcoal will remain an essential economic activity, regardless of legal restrictions (Charcoal Burner FGD 1 (h)). Thus, improving legal compliance will require not only stronger enforcement but also inclusive policies that provide viable and legal livelihood alternatives.

6.9. Urban demand and market drivers

Urban energy poverty and consumer demand exert significant influence on rural charcoal production, forming an interdependent supply-demand dynamic. The responses suggest an intricate possible link between urban energy demand, economic drivers, and the sustainability of the charcoal trade in Zambia (see Table 9). Rural deforestation is partly driven by declining soil fertility, leading to agricultural expansion and an increased reliance on charcoal as a financial safety net (Charcoal Burner FGD 1 (a)). Additionally, seasonal variations, particularly during the rainy season, make charcoal production more challenging due to moisture exposure and compromised storage conditions, affecting supply consistency and market prices (Charcoal Burner Interview (b)). Urban demand remains a key factor sustaining the charcoal industry (Kabisa et al., 2019; Ngoma et al., 2019; Nyarko et al., 2021; Rose et al., 2022). While traditionally, charcoal was predominantly used by low-income peri-urban communities, worsening economic conditions and persistent load-shedding have led to increased reliance on charcoal across all geographies and socio-economic groups (Charcoal Burner FGD 2 (c), Rose et al., 2022). Recent hikes in the cost of living (Zambia Statistics Agency, 2025) and electricity tariffs (Chanda et al., 2025a; ZESCO, 2024) have further expanded the charcoal consumer base,

making it a preferred alternative for both lower-income and middle-class urban households (Charcoal Burner FGD 1 (d)). These findings align with broader studies indicating that energy poverty in urban areas exacerbates deforestation in rural regions, as charcoal remains a cheaper and more accessible cooking fuel (Baltrusiewicz et al., 2021; Ngoma et al., 2021; Tembo et al., 2015).

Despite growing demand, the profitability of charcoal production remains volatile due to increased market participation. More individuals have entered the trade, leading to price fluctuations and reduced earnings for rural producers (Charcoal Burner Interview (f); Charcoal Burner FGD 1 (g)). This trend has intensified competition among charcoal burners, further accelerating deforestation. Commercial farmers argue that the root cause of Zambia's charcoal problem lies not in rural areas but in urban energy policies, which fail to provide affordable and reliable electricity access (Commercial Farmer Interview (i, j)). Ultimately, the findings suggest that addressing Zambia's charcoal dependency requires urban-focused interventions. Expanding access to renewable energy in cities, subsidising electricity for low-income households, and implementing incentives for clean cooking technologies could reduce charcoal consumption at scale. Without such measures, rural deforestation is likely to persist as long as urban demand remains high (Commercial Farmer Interview (k)). Hence, interventions aimed solely at rural producers will be insufficient unless complemented by urban energy reforms that reduce reliance on biomass fuels.

6.10. Socio-political dynamics of charcoal

The role of socio-political actors, including traditional leaders and state institutions, adds a complex layer to the governance of charcoal production. The findings demonstrate the entrenched socioeconomic and political dynamics that sustain the charcoal trade in rural Zambia (see Tables 8 and 10). Despite regulatory efforts aimed at mitigating deforestation and promoting alternative energy sources, charcoal remains a vital economic pillar for many rural households. Chiefs and traditional leaders play a dual role in this trade, with some actively discouraging deforestation while others either participate or turn a blind eye due to economic hardships in their communities (Charcoal Burner Interview (a); Charcoal Burner FGD 1 (b), Cerutti et al., 2018; Gumbo et al., 2013). These realities align with broader research indicating that traditional leadership structures often mediate access to natural resources, either facilitating sustainable management or enabling exploitation for economic survival (Zulu et al., 2021, 2022).

In April 2024, in alignment with the environmental sustainability goals outlined in Zambia's Eighth National Development Plan (8NDP), the Ministry of Green Economy and Environment (MGEE) announced a ban on charcoal burning in three districts with high production levels. Additionally, the ministry suspended the issuance of cordwood licences and permits, with plans to extend the ban nationwide (National Green Growth Strategy, 2024). However, empirical evidence from this study suggests that outright bans on charcoal production are neither practical nor enforceable without viable economic alternatives. Charcoal producers view such restrictions as a direct threat to their survival, equating these policies to an attack on their livelihoods (Commercial Farmer Interview (c), Charcoal Burner FGD 2 (8i)). Furthermore, charcoal's role extends beyond lighting to heating, which is an essential household necessity for cooking and warmth (Commercial Farmer Interview (d)). This aligns with prior studies showing that energy transitions in Sub-Saharan Africa often fail due to a mismatch between policy prescriptions and local economic realities (Chanda et al., 2025b; Kapole et al., 2023; Szabó et al., 2021). Addressing these challenges requires a holistic approach that integrates community-led initiatives, economic incentives, and sustainable energy solutions. Without alternative income-generating opportunities, efforts to phase out charcoal production will likely face resistance, reinforcing continued environmental degradation. Effective transition strategies must therefore engage these actors through participatory governance and incentive based

community programmes.

6.11. Charcoal's traditional and cultural importance

Charcoal's embeddedness in Zambia's cultural and traditional practices poses significant behavioural barriers to energy transition. The study highlights that firewood and charcoal are not merely sources of energy but integral components of Zambia's cultural and social fabric (see Table 11). Beyond cooking and heating, they serve as focal points for community interactions, family gatherings, and traditional customs. This deep-rooted cultural association presents a major challenge for energy transitions, as any shift to alternative energy sources must account for long-standing social practices (Commercial Farmer Interview (a); (b)., Ibraimo et al., 2017). Research across Sub-Saharan Africa confirms that energy choices are not solely determined by economic or technological factors but are strongly influenced by cultural norms and daily routines (Moombe et al., 2020; Wang et al., 2022). Despite the availability of modern stoves and electrification in some rural areas, many households continue to prefer charcoal braziers due to their perceived social benefits (Commercial Farmer Interview (c)). The "imbaula" (charcoal brazier) culture is deeply embedded, making it difficult for households to abandon traditional fuels in favour of electricity or gas (Commercial Farmer Interview (d)). Comparative studies in regions like South Africa, where alternative biomass sources such as cow dung and maize cobs are used for heating, suggest that fuel substitution is possible but requires significant behavioural shifts (Commercial Farmer Interview (e)).

Beyond its role as a household fuel, charcoal serves significant medicinal and cultural functions in rural Zambia. It is widely used as a traditional remedy for poison ingestion, stomach ailments, and snake venom neutralisation (Charcoal Burner FGD 2 (g); Charcoal Burner Interview (i)), which aligns with studies highlighting its adsorption properties in detoxification (Lee et al., 2019; Zaini and Mohamad, 2015). Additionally, charcoal holds deep cultural significance, as it is used in rituals to ward off evil spirits, prevent bad dreams, and protect ubunga (corn flour or mealie meal) from supernatural theft (Charcoal Burner FGD 1 (h)). This aligns with research by Chikumbirike and Bamford (2021), who document its symbolic use in African spiritual practices. Historically, charcoal was buried with individuals who suffered tragic deaths or were barren to prevent perceived curses from recurring in future generations (Charcoal Burner FGD 1 (h)). The persistence of these cultural practices highlights the need for energy transition policies that integrate social dimensions alongside technological and economic considerations. Simply introducing alternative fuels without addressing behavioural and cultural barriers is unlikely to yield sustainable adoption (Samboko et al., 2016; Zulu et al., 2021). Instead, community-driven energy education, culturally sensitive interventions, and hybrid energy solutions that align with traditional practices may facilitate smoother transitions. Subsequently, policies must move beyond technical solutions to include culturally attuned education and behavioural change campaigns.

6.12. Challenges to efficient cooking technology

Adoption of improved cooking technologies remains limited due to perceived inefficiencies, cultural preferences, and gender-based constraints. The findings reveal that despite efforts to promote energy-efficient cooking technologies, their adoption in rural Zambia remains low due to cultural preferences, gender roles, and technical inefficiencies (see Table 12). Many households continue to rely on firewood and charcoal because alternative stoves do not match the heating capacity required for staple foods like nshima (Charcoal Burner FGD 1 (b)). This aligns with the findings of Ibe and Kollur (2024) and Phillip et al. (2023), who argue that the perceived inefficiency of improved cooking stoves contributes to their rejection in many Sub-Saharan African communities. Some participants even abandoned free

energy-efficient braziers due to their inability to generate sufficient heat, highlighting the importance of functionality in energy transition efforts (Commercial Farmer Interview (a)).

Safety concerns also influence cooking technology choices. While some women acknowledge the risks associated with firewood collection, including security threats and encounters with wild animals (Charcoal Burner Interview (f)), they remain hesitant to transition to new cooking methods unless these alternatives meet their heating and cooking needs. This is similar to the findings of Phillip et al. (2023), Sesan (2012) and Tornel-Vázquez et al. (2024), who note that safety considerations alone are often insufficient to drive the adoption of alternative cooking technologies unless they align with users' practical needs. Furthermore, gender roles play a significant part in stove preferences, with women fearing domestic conflicts if food preparation takes longer (Charcoal Burner FGD 1 (d)). This reflects the conclusions of Phillip et al. (2023), Sovacool and Griffiths (2020) and Yunusa et al. (2023), who highlight that energy transitions must account for the social and cultural dimensions of household cooking habits. Nonetheless, initiatives such as the North Swaka Project, which promotes maize cob charcoal as a viable alternative, indicate that when new technologies align with cultural expectations and practical demands, adoption rates improve (Commercial Farmer Interview (h)., Adhikari et al., 2025). Sustainable energy transition strategies must prioritise culturally appropriate technologies that offer equal or superior performance compared to traditional fuels. Consequently, innovation in cooking technologies must be driven by local user needs and socio-cultural realities to ensure effective uptake.

6.13. Charcoal's environmental and Economic Costs

While charcoal offers short term economic relief, its long term environmental and economic consequences are becoming increasingly unsustainable. The findings highlight that charcoal production remains a crucial economic activity in rural Zambia, particularly during the agricultural off-season when alternative income opportunities are scarce (see Table 13). Many individuals engage in charcoal burning as a supplementary livelihood, especially at the start of the farming season when land is cleared for cultivation (Charcoal Burner FGD 1 (a)). This aligns with the findings of (USAID A2C, 2024; USAID A2C, 2021), which estimates that charcoal production contributes to 25 % of Zambia's annual deforestation, contributing to the 180,000–250,000 ha of forest loss per year. Despite this significant environmental impact, the high urban demand for charcoal seems to continue to drive production, outpacing the rate of natural forest regeneration (Charcoal Burner FGD 1 (d)., Kabisa et al., 2019; Mulenga et al., 2019; Rose et al., 2022). Charcoal production is a labour-intensive process requiring skill and close monitoring. Kilns can take up to three weeks to complete, and any lapse in attention can result in losses (Charcoal Burner FGD 2 (b); (c)). This is similar to the findings of (Gumbo et al., 2013; Njenga et al., 2023), who emphasise that inefficiencies in traditional charcoal-making techniques not only contribute to environmental degradation but also limit economic gains for producers. The reliance on large trees for production, with each 25 m³ kiln requiring around 10 trees, further accelerates deforestation (Charcoal Burner FGD (e)). Despite this, replanting efforts remain rare, as many charcoal burners believe forests regenerate naturally (Charcoal Burner FGD 1 (d)). This aligns with the conclusions of Zulu et al. (2021), who highlights that a lack of awareness and incentives for reforestation exacerbates unsustainable harvesting practices.

Financial constraints significantly influence charcoal production patterns in Zambia. Both trees and charcoal are undervalued, making unsustainable harvesting economically attractive. The cost of acquiring trees for a single kiln can be as low as K500 (\$20 US) for 10 trees, each approximately 7 m in height, with individual trees valued at around K100 (\$4 US) (Charcoal Burner FGD (f)). The undervaluation extends to renewable energy options, as it takes the equivalent of 20 trees (two kilns) worth of charcoal to afford a basic two-bulb solar lighting system. Despite the relatively low cost of raw materials, charcoal producers

often struggle to secure fair market prices due to increased competition and the dominance of middlemen in the supply chain. This aligns with the findings of Lyambai (2017) and Sumba et al. (2021), who highlight that economic vulnerabilities prevent producers from adopting sustainable practices (see Figs. 3 and 4). These dual costs necessitate a revaluation of both charcoal and renewable alternatives to shift economic incentives toward sustainability.

6.14. Actual and potential carbon loss

Charcoal related deforestation has resulted in substantial carbon stock loss, significantly impacting Zambia's climate mitigation capacity (Chanda et al., 2025e). The findings indicate a significant increase in charcoal attributed carbon stock loss in Zambia, with 67,068,795 tCO₂ lost between 2008 and 2015 and rising to 116,067,687 tCO₂ between 2016 and 2023 (see Table 14). Among the four study districts, Mkushi exhibited the highest carbon stock loss, increasing from 2,185,374 tCO₂ to 4,408,780 tCO₂ in the respective periods. Conversely, Chingola experienced the lowest loss, with 606,256 tCO₂ between 2016 and 2023. This trend aligns with findings in Ghana, where unsustainable charcoal production depletes half of standing tree stock per site annually (Arko et al., 2024), stressing the severe impact of charcoal-driven deforestation.

The study further estimated that Zambia's lost annual carbon sequestration potential, attributable to charcoal-related forest loss, increased from 1,541,811 tCO₂ per year (2008–2015) to 2,668,223 tCO₂ per year (2016–2023). Mkushi recorded the highest sequestration loss at 101,351 tCO₂ per year. Similar trends are observed in Ethiopia, where charcoal production contributes to the loss of over 71,000 trees annually, accelerating land degradation (Gebremeskel, 2023). These findings highlight the urgent need for enhanced forest conservation policies. The data reinforces the urgency of integrating forest conservation into national energy policy and climate commitments.

6.15. The charcoal - Solar Paradox (CSP) cycle

The Charcoal - Solar Paradox (CSP) Cycle illustrates the contradictory relationship between biomass-based livelihoods and renewable energy adoption (Chanda et al., 2025e). The CSP cycle highlights the paradox where charcoal earnings enable limited solar PV adoption while simultaneously fueling deforestation, economic vulnerability, and energy poverty (see Fig. 5).

6.15.1. Seven stages of the RUDSHAM Charcoal-Solar Paradox cycle

- 1) Resource Exploitation – Traditions, economic and energy poverty and urban charcoal demand drive rural communities to clear healthy forests for charcoal production, leading to deforestation and biodiversity loss.
- 2) Agricultural Expansion and Reinforcement – Land clearing for farming introduces new entrants to the charcoal trade, further entrenching deforestation and creating a self-reinforcing cycle.

- 3) Unregulated Charcoal Trade – The charcoal industry operates informally, contributing to greenhouse gas emissions, land degradation, and weak enforcement of sustainable practices.
- 4) Dependency on Charcoal Income – Many rural households rely on charcoal sales as their primary livelihood, making it difficult to shift to alternative economic activities which are mostly do not exist. Furthermore, cost of living challenges exacerbate demand as well as production.
- 5) Household-Level Solar Adoption – Some charcoal income is reinvested in basic solar lighting (e.g., phone charging and household illumination), but remains insufficient for productive energy use trapping them in perpetual cycles of poverty.
- 6) Solar PV Affordability Barrier – High upfront costs prevent widespread adoption of solar PV for irrigation, mechanisation, and other productive applications, limiting energy transition potential.
- 7) Missed Sustainable Transition – Without targeted interventions, reliance on charcoal persists, preventing a full shift to renewable energy and reinforcing continued environmental and economic vulnerabilities.

Addressing this paradox requires systemic interventions that integrate economic resilience, environmental protection, and energy access in a unified policy framework.

6.15.2. The RUDSHAM Charcoal-Solar Paradox in pictures

The RUDSHAM Charcoal-Solar Paradox in pictures (see Fig. 6) illustrate various stages of the charcoal trade: healthy forests (a–c), the charcoal production process (d–l), packaging and selling by producers (m–n), retail sales in urban areas (o), charcoal income contributing to solar PV adoption in rural areas (p–q), and environmental degradation (r), including deforestation (d–f), greenhouse gas emissions from burning wood (j–l), and carbon absorption loss (d–f).

7. Policy recommendations

The following policy recommendations are informed by the study's empirical findings and thematic discussion, which highlighted complex intersections between energy poverty, rural livelihoods, governance gaps, deforestation, and socio-cultural dynamics. Each recommendation is rooted in specific observations from the charcoal and solar adoption discourse presented earlier.

7.1. Support livelihoods to reduce charcoal

Grounded in the study's findings on economic dependence and seasonality (Section 6.1 & 6.3), this recommendation addresses the critical need to diversify rural income streams that currently hinge on unsustainable charcoal production. The Ministry of Green Economy and Environment and the Ministry of Small and Medium Enterprises Development should promote alternative income sources such as agro-processing, eco-tourism, and sustainable timber production. WWF Zambia and USAID A2C should expand microfinance initiatives to support small businesses, reducing reliance on charcoal. Addressing rural

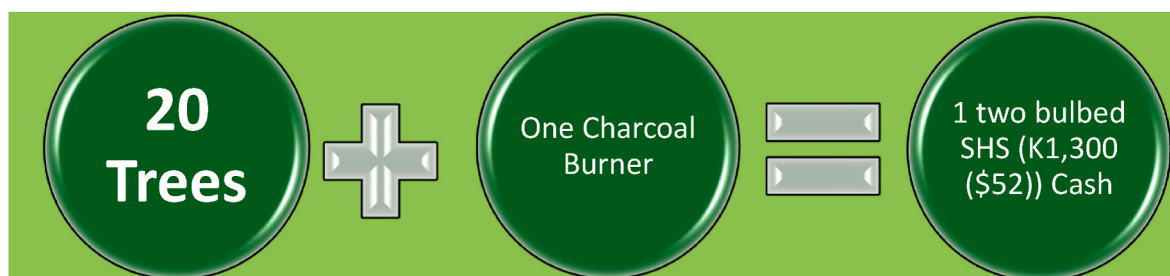


Fig. 3. Tree-to-solar economic trade-off ratio (Cash) (Author, 2025).

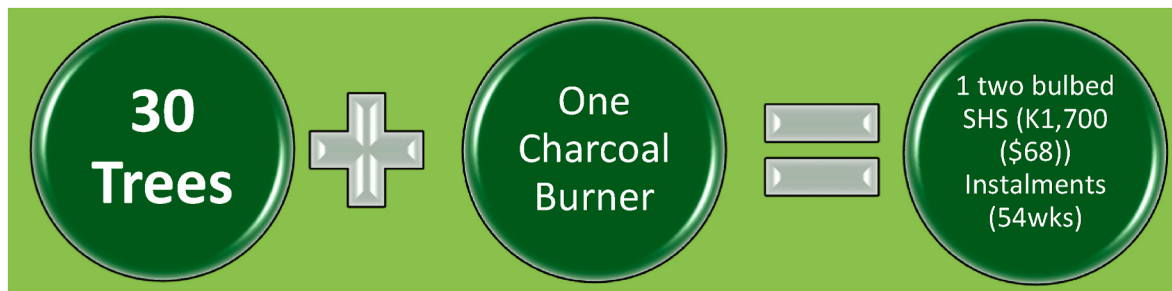


Fig. 4. Tree-to-solar economic trade-off ratio (Instalments) (Author, 2025).

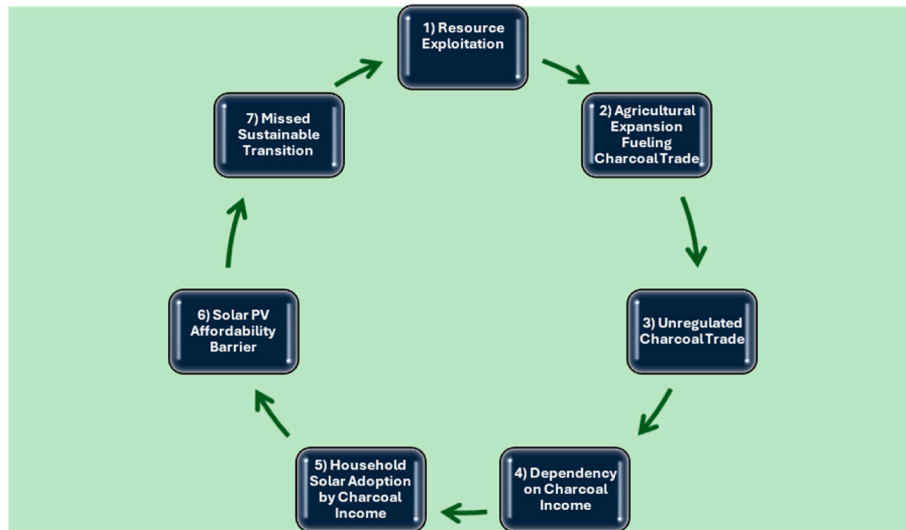


Fig. 5. Charcoal-Solar Paradox (CSP) cycle.

income insecurity remains politically sensitive but essential for shifting communities away from ecologically destructive charcoal economies.

7.2. Strengthen forestry governance and management

Drawing on the findings in Sections 6.2 and 6.8, which reveal the weakness of enforcement mechanisms and the depletion of forest cover due to illegal harvesting, this recommendation aims to enhance institutional oversight and incentivise reforestation. The Forestry Department must enforce reforestation mandates for charcoal producers and combat illegal deforestation through stricter regulations. Collaborations with ZEMA, UN-REDD, and FAO should promote carbon credit incentives and afforestation programmes. Community-led forestry management will ensure sustainability while allowing regulated charcoal production. Strengthening forestry governance should include support for community-managed woodlots using fast-growing species to meet charcoal demand sustainably. Political will is needed to decentralise forestry control, which often faces institutional resistance and contestation over land-use rights.

7.3. Expand solar and alternative fuel access

Based on Sections 6.4 and 6.5, which highlight the solar-charcoal paradox and financial constraints, this recommendation underscores the necessity of expanding affordable access to solar PV systems for productive and domestic use. The Ministry of Energy should prioritise financial support for solar PV adoption, particularly in rural areas. Expanding microfinance for solar-powered irrigation and productive-use technologies will enhance energy access. NGOs such as BGFA and SolarAid Zambia should facilitate affordable off-grid solar solutions and

improved biomass stoves. Policy coordination across ministries and donor agencies remains fragmented, limiting solar deployment and raising questions about long-term energy justice.

7.4. Improve market regulation and pricing

This recommendation responds to the structural market inequalities identified in Section 6.3, which documented profit disparities across the charcoal value chain, often to the detriment of rural producers. The Ministry of Commerce, Trade, and Industry should implement fair pricing regulations by strengthening producer cooperatives and reducing intermediary exploitation. ZAFFICO and IUCN should introduce sustainable charcoal certification programmes, incentivising eco-friendly production and discouraging unsustainable harvesting. Reforming charcoal markets entails confronting vested interests and informal networks that benefit from regulatory ambiguity and weak enforcement.

7.5. Address gender disparities in energy

Emerging from the gender-based analysis in Section 6.7, this recommendation reflects the need to redress gender inequities in energy production, access, and income distribution. The Ministry of Gender and Child Development, UN Women Zambia, and AWEFF should provide financial and vocational training programmes for women in clean energy enterprises. Micro-credit facilities and gender-focused policy frameworks should prevent economic exploitation and expand women's participation in renewable energy. Mainstreaming gender equity in energy policy requires overcoming systemic biases in planning, budgeting, and implementation across male-dominated institutions.



Fig. 6. Pictures a–r depicting the RUDSHAM Charcoal-Solar Paradox (by author).

7.6. Improve urban energy and reduce charcoal

This recommendation is informed by Section 6.9, which linked high urban demand for charcoal to unreliable and unaffordable electricity services in Zambia's towns and cities. The Ministry of Energy, in collaboration with ZESCO and ERB, should introduce subsidised electricity tariffs, prepaid metering, and increased investment in mini-grid solar solutions. The World Bank, USAID, and UNDP should support clean cooking initiatives, including subsidised LPG, to reduce urban charcoal dependency. Urban energy transitions demand balancing affordability, grid reliability, and political resistance to subsidy reforms within constrained fiscal contexts.

7.7. Promote energy-efficient cooking adoption

Stemming from Sections 6.12 and 6.6, which highlighted health risks and stove inefficiencies, this recommendation addresses both technical and behavioural obstacles to clean cooking transitions. The Ministry of Science and Technology, NISIR, and GIZ should support the development of culturally adaptable energy-efficient stoves. Awareness campaigns on the economic and health benefits of improved cookstoves should drive behavioural change, reducing reliance on biomass fuels. Policy inertia and lack of scale-up funding challenge widespread adoption, despite technical viability and strong evidence of health benefits.

7.8. Embed sustainability in education and awareness

Grounded in the sociocultural and behavioural insights from Sections 6.10 and 6.11, this recommendation advocates for a long-term educational strategy to reshape energy practices from a young age. The Ministry of Education should integrate sustainability studies from preschool onwards and conduct awareness campaigns via radio, TV, and social media. Donor partnerships should fund community-based environmental education programmes to highlight the consequences of deforestation and promote alternative energy solutions. Embedding sustainability in education requires navigating curricular rigidity and limited teacher training budgets, especially in under-resourced rural schools.

8. Conclusion

8.1. Key findings and knowledge contributions

This study introduces the RUDSHAM Charcoal - Solar Paradox (CSP), revealing how charcoal income paradoxically facilitates solar PV adoption in rural Zambia while simultaneously driving deforestation. This novel insight highlights the need for integrated energy and environmental policies that promote renewable energy financing while mitigating deforestation.

A major finding is that urban demand, rather than rural supply, seems to sustain the charcoal trade. Erratic electricity supply, economic constraints, and high tariffs force urban households to rely on charcoal for cooking and heating. Thus, urban-focused interventions, expanding electricity access and clean cooking solutions, are crucial for reducing rural deforestation.

Applying the RUDSHAM framework, this study is the first to holistically examine the behavioural, economic, and regulatory drivers of energy transitions in Zambia. It demonstrates that agricultural land clearing acts as a gateway to charcoal dependence, necessitating policies addressing both deforestation and farming expansion.

Gender disparities persist, with women earning significantly less and facing financial exclusion in the charcoal trade. Structural reforms are required to promote equitable economic participation. The study further reveals that the socio-economic and environmental impacts of charcoal production are inadequately recognised, as rural producers derive minimal benefits while intermediaries capture disproportionate gains - exacerbating poverty, social exclusion, and deforestation. Addressing these sustainability concerns requires fair pricing systems and inclusive producer cooperatives. Finally, findings highlight that 20 trees are required to produce charcoal equivalent to purchasing a basic solar lighting system, reinforcing the urgency for improved solar financing and alternative livelihoods to reduce charcoal dependency.

8.2. Future research directions

Future research should focus on longitudinal assessments of energy transition policies, particularly examining the long-term economic impacts of solar PV adoption on charcoal-dependent households. Additionally, gender dynamics in the charcoal trade warrant deeper investigation, particularly regarding the financial barriers women face in transitioning to alternative livelihoods. Another key area for further research is the effectiveness of urban energy policies in reducing charcoal demand.

CRediT authorship contribution statement

Hillary Chanda: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eugene Mohareb:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software,

Methodology, Funding acquisition, Conceptualization. **Michael Peters:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Conceptualization. **Chris Harty:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Martin Green:** Writing – review & editing, Methodology. **Edwin Bwanga Kasanda:** Writing – review & editing, Project administration, Investigation, Data curation. **Nao Shibata:** Writing – review & editing, Data curation, Investigation, Software.

Funding

This research was funded by the UK Commonwealth Scholarship Commission.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We express our gratitude to Stella Zulu Chisanga for the Commonwealth Scholarship funding acquisition. We are grateful to Pastor Maybin Mulofwa Kamfwa, Mr. Evans Chola, Mr. Golden Gilbert Maluma and Mr. Francis Kaunda for facilitating the data collection. We are thankful to all the participants who furnished the data required for the study. We are grateful to Reading University and the Copperbelt University for their support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enpol.2025.114936>.

Data availability

Data will be made available on request.

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