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Climate Change and the Energy Performance of Buildings in the Future – A case study for prefabricated buildings in the UK

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Abstract:

Climate change - partly driven by the increasing level of anthropogenic greenhouse gases - is affecting the energy consumption of buildings. This study assesses the impact of climate change on the energy performance of buildings. It focuses on the energy consumption associated with heating in a case study of prefabricated building in the UK.

The energy consumption associated with space heating is evaluated using the degree-days theory, and the actual energy consumption of the buildings is used to verify the outcome of the analytical degree-days approach for the estimated energy consumption. The verified degree-days model is then used to predict future energy demand of the case study building in 2030, 2050, and 2080 using two climate change scenarios with medium (A1B) and high (A1F1) emissions. In addition, the energy-related CO_2 emissions associated with the space heating are evaluated using carbon intensity projections. This study identified the true heating base temperature for the case study building and this allows for the estimation of the future energy consumption of the building with an average 6% margin of error. For the prefabricated case study building, the energy consumption associated with heating in 2030 and 2080 is expected to be up to 12% and 34% lower than in 2017 respectively. Moreover, the outcomes of this study showed that the standard base temperature of 15.5 ˚C for the degree-days method is significantly higher than the actual heating base temperature of the prefabricated building by 2.5 ˚C.

Keywords: climate change, energy consumption, degree-days theory, carbon dioxide emissions

1.0 Introduction

Climate change is one of the most pressing global issues of our time. IPCC (2014) stated that the main causes of climate change are the emissions of anthropogenic greenhouse gases (GHG), which include carbon dioxide (CO_2), methane, and nitrous oxide. The emissions not only impact the natural systems but also have an impact on buildings and the

built environment. Global warming (defined as the rise in the global temperature due to climate change) would lead to a reduction in the heating energy consumption of the buildings, but would also lead to an increase in the cooling energy consumption (Nik et al., 2017). Several studies identify the potential impacts of global warming on the local climate conditions in the UK (UKCP09-PROMETHEUS, 2009). The potential energy implications of climate change in the building sector have been studied previously (Zhai and Helman 2018, Nik et al., 2017). However, there are limited studies to address the impact of climate change on the energy and environmental performance of prefabricated buildings.

Prefabricated buildings are increasingly being used for new build constructions due to their capability to offer faster construction processes with lower environmental impacts. These benefits are associated with more efficient processes for developing the components of prefabricated buildings in a factory rather than those used on traditional construction sites (Li *et al.* 2011). This study focuses on quantifying the extent to which the energy consumption associated with heating systems in the prefabricated building is influenced by climate change.

A review of the literature identified that building simulation and degree-days methods are the main approaches used to assess the energy performance of buildings under climate change. The following subsections critically review the main outcomes of previous studies that adopted these two approaches.

1.1 Studies that adopted building simulations

Chan (2011) conducted a series of simulations using EnergyPlus to assess the impact of climate change on buildings by modelling a case study office building and a typical residential flat. The study involved producing a set of hourly weather data under two emission scenarios, SRA1B and SRB1 (Appendix A.1) to be used for building simulation. In the next stage, a set of simulations were conducted considering the future weather projection datasets. The outcomes of the research conducted by Chan (2011) showed that under the SRA1B scenario, the energy consumption associated with the cooling system for the case study office buildings is increased by 2.6%, 7.8%, and 14.3% respectively in 2030, 2065 and 2099 compared to the reference year 1989. Under the same emission scenario, the energy consumption associated with cooling for the residential flat increased by 3.9%, 13.4%, and 24% respectively in 2030, 2065, and 2099 compared to the reference year 1989.

Cellura *et al.* (2018) assessed the potential impact of climate change by investigating the trends of future energy consumption of a prototype office building in four Italian cities;

Venice, Messina, Palermo, and Genoa. In comparison with the reference period 1979 to 1989, the outcomes of simulations conducted using TRNSYS showed an increase in the average total energy consumption mainly due to the fact that the cooling demand continues to increase and overtakes the decrease in the heating demand. In 2035, it was expected that the average total energy consumption to be increased between 17.6 to 23% under different climate change scenarios compared to the energy consumption in the typical meteorological year between 1979 and 2000.

A different building simulation tool (TAS) was used in a study conducted by Berger et al. (2014) to analyse the impact of climate change on nine case study office buildings located in Vienna, Austria. The case study buildings were categorised in terms of their age into three groups; i) built before World War 1, ii) built after World War 2 and, iii) built from 2000 onwards. Regional climate model (RCM) data were used to generate future hourly weather projections for 2050 and the period between 1961 and 1980 was set as the baseline for comparisons with future energy consumptions. The results showed that in general, the buildings face an increase in their cooling demand and a decrease in their heating demand. However, the outcomes of the study conducted by Berger et al. (2014) revealed that old buildings are more impacted by climate change compared to those built more recently. The study also suggested that cooling devices will need to meet the increasing cooling demand as a result of climate change in the future.

In another study, Shibuya and Croxford (2016) investigated the energy consumption associated with heating and cooling under climate change to explore effective measures to meet the energy demands in the future. A multi-story office as a case study building was simulated for three different locations in Japan. In addition, three different periods were selected for the simulations: 1981 to 2000, 2031 to 2050, and 2081 to 2100. Data for these periods was generated by the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency (JMA). Comparing the results of simulations for three different zones revealed that the rate of change in energy consumption is different for each region. Naha and Tokyo regions experience a continuous increase in the total energy consumption as they are in the regions where cooling is dominant. Therefore, the increase in energy consumption to provide the required level of cooling overtakes the decrease in the energy consumption associated with heating. In contrast, Sapporo, which is located in the cold region does not experience an increase in the total energy consumption as

the increase in cooling demand is considered to be balanced with the decrease in the heating demand which results in a reasonably constant total energy consumption.

Based on the review of these previous studies that adopted the building simulation approach to evaluate the influence of climate change on the energy performance of buildings, it is found that the heating energy demand of buildings is expected to be reduced in the future.

1.2 Studies that adopted degree-days theory

Lee and Levermore (2010) assessed the impact of climate change on building energy consumption using the degree-days method. The study employed the Tyndall Centre data (TYN SC2.0) for South Korea which consists of monthly grid modelled climate data for the period between 2001 and 2100. The simulations generated 28 different daily weather parameters which include maximum, minimum, and average dry bulb temperature, wind speed, and solar radiation. Four emission scenarios were considered in the study; A1F1, A2, B1, and B2 (Appendix A.1). The Heating Degree-days (HDDs) and Cooling Degree-days (CDDs) were then evaluated considering the base temperature of 15.0°C and 18.0°C for the HDDs and CDDs respectively. The base temperature is the outdoor temperature above/below which the heating/cooling system would not be required to operate in order to achieve the desired indoor design temperature. The outcomes of the study conducted by Lee and Levermore (2010) showed that HDDs is decreased between 21% and 24% in the period between 1961 and 2005 in Seoul and Ulsan. During the same period, an increase between 12% and 16% was observed in the CDDs for both locations. Moreover, between 1980 and 2099, the HDD is expected to reach a maximum reduction of 63% and the CDD is expected to increase up to 160%. One of the main areas of uncertainty associated with this study was the lack of justification for the assumed base temperature which can potentially impact the reliability of the results.

The degree-days method was used by Christenson *et al.* (2006) to study the impact of climate change on buildings. The study was carried out in four major cities in Switzerland; Geneva, Zurich, Lugano, and Davos. They considered a set of base temperatures; 8, 10, and 12 °C for the HDD analysis. For cooling degree-days analysis, 18.3°C was considered as the base temperature. The outcomes showed a decrease in the HDDs between 11% and 18% through the period between 1901 and 2003. In addition, the study predicted that depending on the locations and magnitude of climate warming, the HDDs will be reduced by 13-17% in

2085 compared to 1975's level. In contrast, the study predicted a significant increase in the energy consumption associated with cooling, up to 2100% by 2085 compared to 1975. This figure is likely to indicate some level of uncertainty because the assumed base temperature of 18.3°C might only apply to buildings with higher internal heat gains. This highlights the fact that a more accurate base temperature is needed to improve the reliability of the predicted energy consumption associated with heating and cooling using degree days theory.

Although the impact of climate change on the energy performance of buildings has been studied (Chan, 2011; Cellura et al., 2018; Berger et al.; 2014; Shibuya and Croxford, 2016; Lee and Levermore, 2010; Berger et al.; 2016, Shen et al., 2020, Hosseini et al., 2018, and Christenson et al. 2006, Bhatnagar et al., 2018 and Yau and Hasbi (2017)), the majority of the previous studies focused on traditional buildings and there are very limited studies which focus on assessing the impact of climate change on the energy performance of prefabricated buildings.

1.3 Research aim

According to the literature, both building simulation and degree-days methods have been used to assess the impact of climate change on the energy performance of buildings. However, the main challenge found in the previous studies which adopted the approach of building simulation was the uncertainty associated with the results. This is mainly due to the fact that building simulation requires a big set of input data, some of which is hard to assume accurately. On the other hand, the degree-day theory needs fewer inputs, one of which is the base temperature. One of the main challenges in degree-days analysis is to find the true base temperature. By addressing these methodological challenges, this study aims to assess the impact of climate change on the energy performance of buildings with a focus on energy consumption associated with heating in a prefabricated case study building in the UK. To achieve this aim there are four main objectives for this study:

- To study the relationship between the energy consumptions of buildings and outdoor thermal conditions.
- To explore different methods available to estimate the energy consumptions of buildings.
- To compare the actual energy consumption associated with the space heating with the predicted energy consumption considering the historical weather conditions (meteorological data) and future energy consumptions under different climate change scenarios.

- To estimate the energy-related CO_2 emissions associated with space heating under different emission scenarios.

This study proposed a practical approach to predict the energy consumption of buildings considering climate change and verified the proposed approach in a case study prefabricated building. Both the proposed approach and findings of this study are of great significance in allowing more realistic modelling of the effect of climate change on the future energy performance of the prefabricated buildings and their contribution to reducing the UK energy demand.

2.0 Research design

This study adopts the approach proposed by degree-days theory to assess the energy performance of a case study non-residential prefabricated building (Chancellors Building at the University of Reading in the UK) under different climate change scenarios. This approach was chosen because of its capability to assess the energy performance of buildings using a limited set of inputs. This is in contrast to the large number of inputs required for numerical simulations. Gathering and entering a large amount of data into simulation tools increases the complexity of the process and the reliability of results heavily depends on the levels of accuracy and uncertainties associated with these inputs (Hui, 2003). In a recent study, Hong *et al.* (2018) identified the main challenges associated with the building simulation including, the limitation of building simulation on addressing performance gap, capturing the interaction between human and building services, modelling the actual operation and control mechanisms, and the faults in the operation of buildings environmental services. Considering these well-established constraints associated with building simulation, degree days theory can provide more reliable results if conducted rigorously, using fewer and more accurate inputs and taking into account the actual energy demand of buildings to establish the true base temperature.

The energy demand of the buildings depends on many factors most importantly the outdoor conditions such as the outdoor temperature (Perez-Andreu *et al.,* 2018). Degree-days theory explained the linear relationships between the weather-related energy consumptions of the buildings and outdoor dry bulb temperature (CIBSE 2006). Degree-days is referred to as the summation of temperature differences between a reference temperature (the base temperature) and an outdoor temperature over time (Carbon Trust, 2002). The heating system needs to operate only when the outdoor temperature falls below the base temperature. Similarly, cooling is needed only when the outdoor temperature rises above the base

temperature. The base temperature is the outdoor temperature above/below which the heating/cooling system would not be required to operate in order to achieve the desired indoor design temperature. Therefore, HDDs measure the summation of the temperature differences between base temperature and outdoor temperatures that fall below the base temperature; and vice versa for CDDs which measures summation of the temperature differences between base temperature and outdoor temperatures that rise above the base temperature (CIBSE, 2006).

Although several published degree-days data are calculated considering a base temperature of 15.5˚C as a so-called "standard base temperature", degree-days analysis will be made more reliable by establishing the true base temperature of the building first rather than relying on this standard base temperature (Carbon Trust, 2002). In some cases, the true base temperature of a building is significantly different from the standard base temperature as it depends on many factors including the thermal characteristics and specifications of the environmental systems deployed in the building (CIBSE, 2006). To briefly demonstrate the impact of base temperature on heating degree-days and considering the weather data for London Gatwick station, the total heating degree-days for the period of October 2019 to October 2020 for the standard base temperature (15.5 °C) was 1802(-) compare to 1181(-) for the base temperature of 13 °C (Degreedays.net, 2020). This highlights the fact that a 2.5 °C difference between standard and a true base temperature can potentially result in the overestimation of heating degree days and consequently energy consumption associated with heating systems by up to 50% of the actual values. In this research, the performance line method is adopted to evaluate the true base temperature (CIBSE, 2006).

This study evaluates the impact of climate change on the energy performance of a prefabricated non-domestic building. The Chancellor's Building, a prefabricated building on the Whiteknights Campus of the University of Reading was built in 2016 and includes offices, meeting rooms, and classrooms with a total useful floor area of 3473 (m^2). The building is a two-story modular block and is typical of the type used for modern office accommodation. The heating systems of the building consists of electrical radiators for the offices and air-source heat pumps for classrooms. The detailed energy consumption of the building can be found on the University Sustainability website (UoR, 2020). As a first step, the actual energy consumption of the building, as well as local weather conditions collected over a period of 12 months, were used to determine the true base temperature using the performance line method. The true base temperature was then used to predict the energy

consumption associated with space heating in the next year, and this was compared with the actual energy consumption of the system to evaluate the robustness of the process for determination of the true base temperature. Using this true base temperature, the HDDs for the standard reference period of 1961 to 1990 and HDDs for 2030, 2050, and 2080 under two climate change scenarios, medium, and high emissions, were evaluated using the UKCP09 future predicted climate data (UKCP09, 2009). These HDDs were then used to estimate the energy consumption associated with the heating process in the case study building. Energy-related CO_2 emissions were assessed considering the prediction of carbon intensity level for electricity. The rate of carbon emissions (the carbon intensity) for 2017, 2030, 2050, and 2080 used in this research based on HM Government (2009) under different scenarios which are: 70% base, 70% RES, 80% base, 80% high bio-energy, 80% resilience (low-electricity), 80% RES, 90% base, and 90% RES (Appendix B.1 and B.2). It should be noted that in this study the heating degree-days are determined only for the working hours (08:00 to18:00) from January to March and from October to December when the space heating system was on according to the University's Space and Heating Policy (University of Reading, 2018). The structure of this research is provided in the research framework in Figure 1.

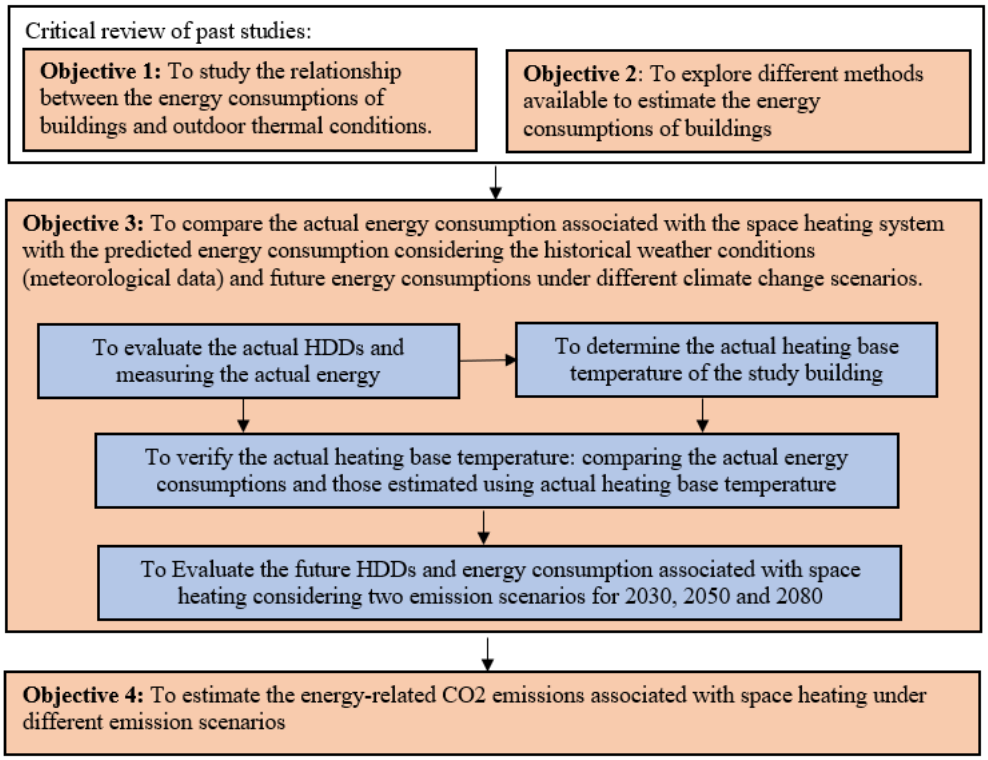

Figure 1: Research design framework

One of the limitations of the approach taken to estimate the true base temperature was the lack of information regarding the accuracy of the actual recorded energy consumption data in the case study building. As the energy meter was part of active building services, it was not possible to set a parallel meter to check the accuracy of the existing energy meter.

3.0 Results

3.1. Calculation of the true base temperature

In order to establish the true base temperature, the performance line method is adopted in this study (CIBSE, 2006). Figure 2 shows the outcome of performance line analysis which involved fitting a best-fit second-order polynomial according to the equation (1). In this analysis, a range of base temperatures is included from 12 to 20 ˚C, with 0.5˚C intervals.

$$Y = \alpha' x^2 + \alpha x + \beta \quad (1)$$

where Y represents the daily energy consumption (kWh), and x stands for the daily degree-days (-)

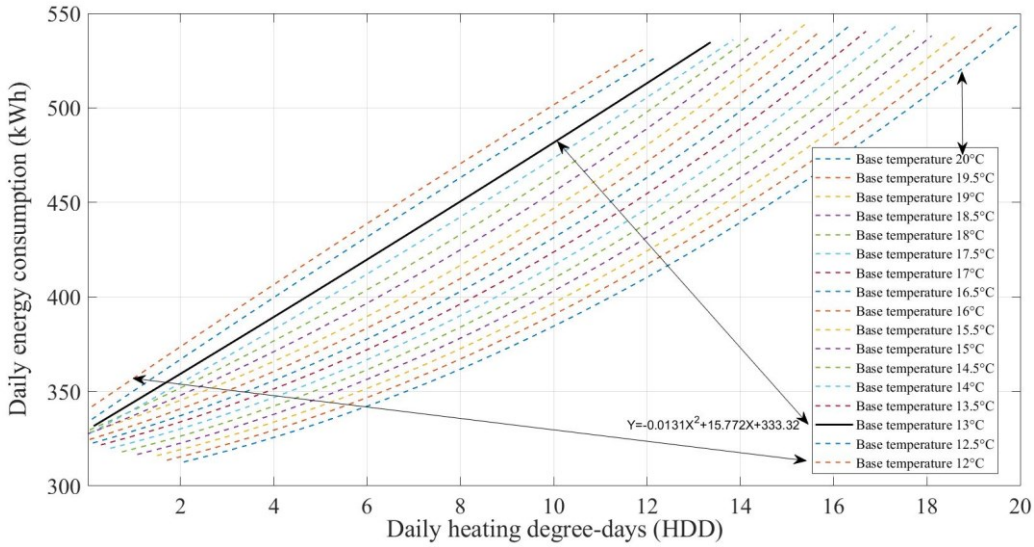

Figure 2: Results of polynomial performance lines for different base temperatures in 2017

Based on the degree-days theory, there should be a linear relationship between the HDDs developed based on the true base temperature and the weather-related energy consumption of the building. Therefore, the base temperature associated with the curve with the closest coefficient of the second-order (α') to zero (Figure 2 and Equation 1) should be

the true base temperature of the building. For further clarity, the results of polynomial performance lines presented in Figure 2 are provided in Table 1.

As shown in Table 1, the true base temperature is between 13.0˚C and 13.5 ˚C as there is a change in the sign of α' from negative to positive which implies that the line is associated with HDDs for the base temperature between 13-13.5 ˚C. Considering the resolution of the base temperatures used in this performance line (0.5 ˚C), this research established 13.0˚C as the actual heating base temperature for the case study building.

Table 1: Results of polynomial performance lines, based on Figure 2

Base Temperature/ ˚C	α'	R^2
12.0	-0.0651	0.54948
12.5	-0.0841	0.5526
13.0	-0.0131	0.56774
13.5	0.039	0.576
14.0	0.108	0.58604
14.5	0.2618	0.58312
15.0	0.3188	0.58303
15.5	0.4077	0.58126
16.0	0.3935	0.58815
16.5	0.4099	0.58861
17.0	0.4204	0.58893
17.5	0.4211	0.5849
18.0	0.4168	0.59012
18.5	0.4092	0.59081
19.0	0.4028	0.59134
19.5	0.3961	0.59183
20.0	0.3905	0.59223

3.2 Verification of the true base temperature

The percentage difference between the energy consumption estimated based on the determined true base temperature for the case study building and the actual energy consumption in 2018 are 6.2%, 3.4%, and 8.1% for October, November, and December respectively (Table 2). This indicates a total difference of 5.4% between the total calculated energy consumption and actual energy consumption for the three months. As the total difference between the calculated energy consumption and the actual energy consumption is below 6%, the true base temperature of 13.0˚C is established as a reliable base temperature of this case study building. In addition, the Wilcoxon rank-sum test (Gibbons and Chakraborti, 2014) was carried out to statistically compare the calculated and actual energy consumptions.

The outcomes of this test reveal the failure to reject the null hypothesis that data in these two datasets are samples from continuous distributions with equal medians with a high confidence interval (p=0.95).

Table 2: Comparisons between estimated energy consumption according to the true base temperature of 13.0˚C and actual energy consumption for October, November, and December in 2018

Month	Calculated energy consumption (kWh)	Actual energy consumption (kWh)	The error between actual and calculated energy consumption (%)
October	7,834.43	7,350.15	6.2
November	7,194.46	6,949.21	3.4
December	3,284.21	3,019.46	8.1
Total	**18,313.10**	**17,318.81**	**5.4**

3.3 Analysis of HDDs, energy consumption and CO_2 emissions

First, the daily HDD for the typical meteorological year between 1961 and 1990 was evaluated considering the true base temperature of the case study building. Along with the daily HDD, daily energy consumption was calculated using the best-fit second-order polynomial associated with the true base temperature. In this case, the equation is $Y = -0.0131x^2 + 15.772x + 333.32$ (Figure 2); where Y represents the daily energy consumption (kWh), and x stands for the daily degree-days (-). Secondly, the daily HDDs and daily energy consumption were summed to get the total HDDs and total energy consumption for the typical meteorological year between 1961 and 1990. The CO_2 emissions for the standard reference period were evaluated using the carbon intensity level which is assumed as 760gCO_2/kWh (Defra, 2012). The results are summarised in Table 3. The breakdown of the results on a monthly basis is presented in Appendix C.2.

Table 3: Summary of HDDs, energy consumption, and CO_2 emissions for the standard reference period

Year	HDDs	Energy consumption (kWh)	CO_2 emissions (kgCO_2)
The typical meteorological year between 1961 and 1990	585	47,175	35,853

The heating-related energy consumption of the case study building in 2017 was assessed using the actual daily HDDs. The values for the total HDDs and total energy consumption are the summations of the daily HDDs and daily energy consumption for 2017 for the period that the heating system was in operation (between January to March and October to December). The CO_2 emissions under different scenarios were then evaluated using the carbon intensity provided in Appendix B2. The results are summarised in Table 4 and the breakdown of the results on a monthly basis is available in Appendix C.1.

Table 4: Summary of actual HDD, energy consumption and CO_2 emissions

			CO_2 emissions/kgCO_2							
Year	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
2017	489	44,028	21,133	17,611	19,812	18,492	17,171	21,574	18,932	17,611

Future HDDs, energy consumption, and CO_2 emissions under two climate change scenarios: medium emission (A1B) and high emission (A1F1) were evaluated based on the true base temperature of 13.0˚C and UKCP09 weather projection for 2030, 2050, and 2080. Meanwhile, the CO_2 emissions under different scenarios for 2030, 2050, and 2080 were evaluated using the carbon intensity projections provided in Appendix B.2. The results are summarised in Table 5 and the monthly breakdown of the results for each year is available in Appendix C3 to C8. The summary of the heating degree- days, energy consumption for space heating, and the energy-related CO_2 emissions associated with the operation of heating systems under two climate change scenarios each with five probability percentiles are presented in Table 5. For example, the annual energy consumption associated with heating systems is estimated to be 36562 (kWh) in 2080 under the high emission climate change scenario with a 50% probability percentile compare to 42244 (kWh) in 2030 under the same scenario. In terms of annual energy-related CO_2 emissions under the above-mentioned climate change scenario, considering the 80% base carbon projection (Appendix B1), the energy-related CO_2 emission is estimated to be about 2957 and 914 ($kgCO_2$) in 2030 and 2050 respectively.

Table 5: Summary of future HDD, annual energy consumptions and CO_2 emissions

Year	Emission	Probability /%	HDD	Energy consumption /kWh	CO_2 emissions/kgCO_2							
					70% base	70% RES	80% base	80% high-bio energy	80% RES	80% resilient	90% base	90% RES
2030	Medium	10	536	43,735	7,872	6,997	3,061	4,373	3,498	9,621	1,093	1,093
		33	449	42,714	7,688	6,834	2,990	4,271	3,417	9,397	1,067	1,067
		50	432	42,447	7,640	6,791	2,971	4,244	3,395	9,338	1,061	1,061
		66	357	41,282	7,430	6,605	2,889	4,128	3,302	9,082	1,032	1,032
		90	276	38,675	6,961	6,188	2,707	3,867	3,094	8,508	966	966
2030	High	10	507	43,615	7,850	6,978	3,053	4,361	3,489	9,595	1,090	1,090
		33	431	42,770	7,698	6,843	2,993	4,277	3,421	9,409	1,069	1,069
		50	419	42,244	7,604	6,759	2,957	4,224	3,379	9,293	1,056	1,056
		66	428	42,046	7,568	6,727	2,943	4,204	3,363	9,250	1,051	1,051
		90	338	39,644	7,136	6,343	2,775	3,964	3,171	8,721	991	991
2050	Medium	10	488	43,316	2,165	1,949	1,082	1,299	866	693	736	779
		33	395	41,878	2,093	1,884	1,046	1,256	837	670	711	753
		50	379	39,957	1,997	1,798	998	1,198	799	639	679	719
		66	349	39,153	1,957	1,761	978	1,174	783	626	665	704
		90	233	35,998	1,799	1,619	899	1,079	719	575	611	647
2050	High	10	484	42,594	2,129	1,916	1,064	1,277	851	681	724	766
		33	406	41,380	2,069	1,862	1,034	1,241	827	662	703	744
		50	339	39,658	1,982	1,784	991	1,189	793	634	674	713
		66	307	38,160	1,908	1,717	954	1,144	763	610	648	686
		90	252	35,292	1,764	1,588	882	1,058	705	564	599	635
2080	Medium	10	470	42,708	2,135	1,921	1,067	1,281	854	683	726	768
		33	358	40,617	2,030	1,827	1,015	1,218	812	649	690	731
		50	321	37,049	1,852	1,667	926	1,111	740	592	629	666
		66	284	36,794	1,839	1,655	919	1,103	735	588	625	662
		90	192	32,355	1,617	1,455	808	970	647	517	550	582
2080	High	10	420	42,254	2,112	1,901	1,056	1,267	845	676	718	760
		33	334	39,577	1,978	1,780	989	1,187	791	633	672	712
		50	269	36,562	1,828	1,645	914	1,096	731	585	621	658
		66	234	35,351	1,767	1,590	883	1,060	707	565	600	636
		90	140	29,209	1,460	1,314	730	876	584	467	496	525

4.0 Discussion

The outcomes of this study (presented in Figure 3) shows that the actual HDDs in 2017 for the Chancellors building was 16.5% lower than those calculated based on the typical meteorological year between 1961 and 1990. There is a further reduction of HDDs between 11.6% to 44.9% for the period between 2030 and 2080 compared to the actual HDDs in 2017 under both emission scenarios (medium and high). Specifically, under the medium emission scenario, there is a reduction of 11.6% in 2030, 22.3% in 2050, and 34.2% in 2080 compared to the actual HDDs in 2017. In addition, there is a reduction of 14.3% in 2030, 30.6% in 2050, and 44.9% in 2080 under the high emission scenario compared to the actual HDDs in 2017. Between the two emission scenarios, the HDDs show a higher reduction under the high emission scenario compared to the medium emission scenario. A comparison of the outcome of this study with previous research revealed that there is a higher reduction in the HDDs associated with this case study compared to those presented by Christenson *et al.* (2006). The study conducted by Christenson et al. (2006) only reached a maximum decrease of 17% in HDDs by 2085, while this research predicted the maximum decrease in HDD reached 44.9% by 2080. This outlines that there will be a higher increase in the outdoor temperature for the location of this research (Reading, UK) as compared to the increase in the outdoor temperature in Switzerland, specifically in Geneva, Zurich, Lugano, and Davos. Both analyses showed a similar descending trend for HDDs when approaching 2080.

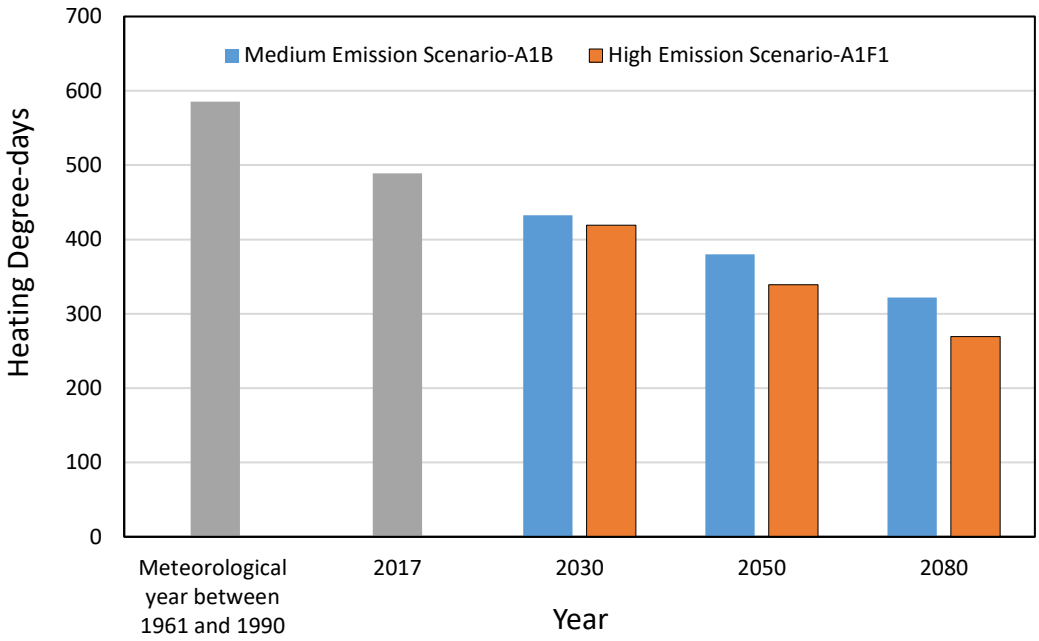

Figure 3: Comparisons between actual HDDs for 2017, HDDs for the typical meteorological year between 1961 and 1990 and predicted HDDs for 2030, 2050, and 2080 under different climate change scenarios (medium and high with the probability of 50 percentile)

The actual energy consumption associated with space heating in 2017 for the case study building is reduced by 6.7% compared to the energy consumption estimated based on the meteorological weather conditions, the period between 1961 and 1990 (Figure 4). In addition, the energy consumption associated with space heating is expected to reduce between 3.6% and 17.0% for the period between 2030 and 2080 compared to the actual energy consumptions in 2017 under both emission scenarios (medium and high). Under the medium emission scenario, the energy consumption of the building reduces by 3.6% in 2030, 9.3% in 2050, and 15.9% in 2080 compared to the actual energy consumption in 2017. On the other hand, energy consumption reduces by 4.1% in 2030, 9.9% in 2050, and 17.0% in 2080 under the high emission scenario compared to the actual energy consumptions in 2017.

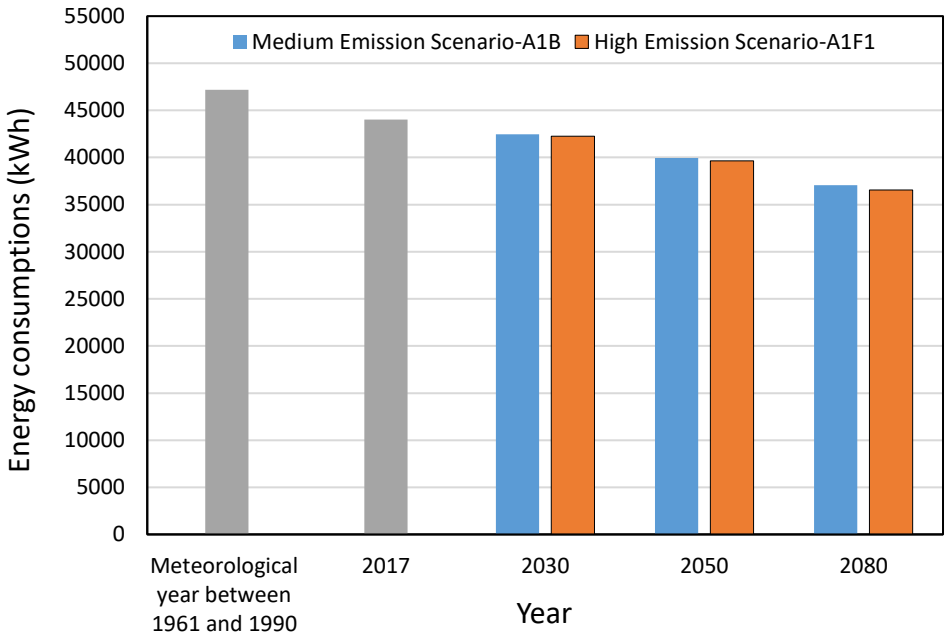

Figure 4: Comparisons between actual energy consumption associated with space heating for 2017, energy consumption for the typical meteorological year between 1961 and 1990, and the predicted energy consumption for 2030, 2050, and 2080 under different climate change scenarios (medium and high with the probability of 50 percentile).

Figure 5 shows that the actual CO_2 emissions associated with space heating in 2017 for the Chancellors building is reduced by 52.1% compared to the typical meteorological year between 1961 and 1990. Moreover, there is an 80.2% and 95.7% reduction in the CO_2 emissions associated with space heating respectively in 2030 and 2080 compared to the actual CO_2 emissions in 2017. Under the medium emission scenario, the reduction reaches 80.2% in 2030, 95.3% in 2050, and 95.7% in 2080 compared to the actual CO_2 emissions in 2017. Meanwhile, the CO2 emissions associated with the space heating in the case study building is expected to be reduced by 80.3% in 2030, 95.4% in 2050, and 95.7% in 2080 under the high emission scenario compared to the actual CO_2 emissions in 2017. It should be highlighted that the outcome of the CO_2 emissions analyses depends on the energy demand of the heating systems as well as the projection of carbon intensity for electricity. It should also be noted that the descending trend of the carbon intensity for electricity deriving by sustainable electricity production, plays a key role in the descending trend for CO2 emissions presented in this study.

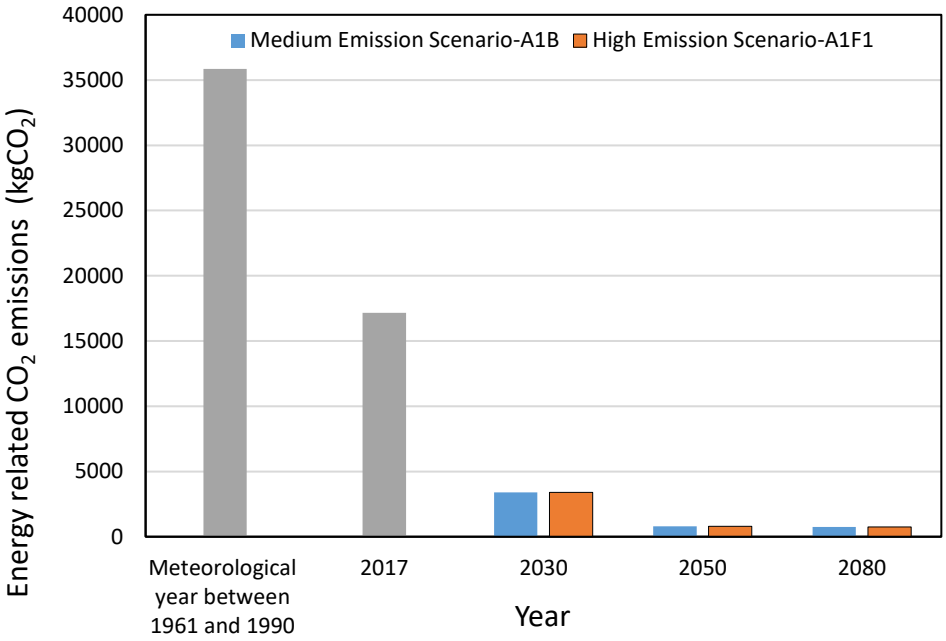

Figure 5: Comparisons between actual CO_2 emissions for 2017, CO_2 emissions for the typical meteorological year between 1961 and 1990, and predicted CO_2 emissions for 2030, 2050, and 2080 under 80% RES scenario for different climate change scenarios (medium and high with the probability of 50 percentile)

The outcomes of this study show that the actual HDDs for 2017 are reduced by 16.5% compared to HDDs of the typical meteorological year between 1961 and 1990. This leads to a lower energy consumption associated with space heating by 6.7% in 2017. Also, the energy consumption associated with space heating follows a descending trend with a reduction of 3.6/4.1% and 15.9/17.0% respectively in 2030 and 2080 under medium/high emission scenarios with the probability of 50 percentile compared to the actual energy consumption for 2017. In addition, this study found that the actual CO_2 emissions for 2017 are significantly reduced, by 108%, compared to the CO_2 emissions for the typical meteorological year between 1961 and 1990. The descending trend in the energy consumption associated with heating systems as it approaches 2080, leads to a sharp drop in the level of CO_2 emissions associated with space heating. Specifically, the case study building faces a CO_2 emission reduction of up to 80.2% and 95.7% respectively in 2030 and 2080, compared to the actual CO_2 emissions in 2017, under high emission scenarios with the probability of 50 percentile and considering a conservative projection of carbon intensity under 80% RES scenario.

5.0 Conclusions

This research robustly quantified the influence of climate change on the energy performance of a modular prefabricated building in the UK under different climate change scenarios. It was found that the increase in GHG emissions and consequently the ambient dry bulb temperature leads to a decrease in the heating demand of buildings. In contrast with most studies in the literature, this research found that the standard base temperature (15.5 ˚C) is unlikely to represent the thermal characteristics of very well insulated prefabricated buildings. Instead, 13.0˚C was shown to be the true heating base temperature for the case study prefabricated building. The robustness of this finding was tested using the actual energy consumption of the building. Using the true base temperature for the case study building this research was able to predict the actual energy consumption of the building with an average error of 6% in different months.

One of the challenges associated with the uptake of prefabricated buildings is the lack of reliable energy performance assessment of this type of construction, especially under weather projections for the UK. The outcome of this study revealed that the heating base temperature for the case study prefabricated building was significantly lower by 2.5˚C than the standard heating base temperature. This lower base temperature for prefabricated case study building indicates that the energy efficiency of the prefabricated buildings is likely to exceed that of the traditionally built buildings. An improved ability to model energy usage in modular, prefabricated buildings, together with the advantages of prefabricated construction in terms of increased material efficiency, speed of construction, and reduction in required skilled manpower would cement the important place that this type of construction has in designing the future built environment. Despite the advantages of prefabricated buildings, there are concerns over the level of thermal comfort that can be offered by this type of building. Therefore, more study is needed to assess the level of thermal comfort that can be offered by highly insulated prefabricated buildings with a special focus on the investigation of the overheating risks in the prefabricated building.

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Appendices

Appendix A: IPCC emission scenarios

Appendix A.1: Descriptions of different IPCC emission scenarios (IPCC, 2018a)

Emission Scenarios	Descriptions
A1	• Rapid economic growth. • Maximum population growth in the mid-century then declines afterwards. • Development of new and efficient technologies which is fossil intensive.
A1B	• A group under A1 emission scenario whose technology is energy-balance (balance between different sources).
A1F1	• A group under A1 emission scenario whose technology is fossil intensive.
A2	• Extreme heterogeneous world. • Self-reliance and preservation of local identities. • Fertility patterns converge slowly across regions, which increased population growth. • More fragmented and slow economic growth and technological change.
B1	• The convergent world with peaks population in the mid-century then declines afterwards. • Rapid economic growth towards a service and information century. • Material intensity reduced. • Introduction of clean and resource-efficient technology. • Improved equity without additional climate initiatives to improve economic social and environmental sustainability.
B2	• Focus on economic, social and environmental sustainability. • Continuous increase in population at a lower rate than A2. • Less rapid technological development, but more diverse than A1 and B1. • Oriented towards local and regional environmental protection and social equity. • Intermediate economic growth phase.
SRA1B	• Rapid economic growth. • The maximum global population in the mid-century and declines afterwards. • The rapid development of new and more efficient technologies, with balance across energy sources.
SRB1	• The same global population as A1 storyline. • Rapid changes in economic structures towards service and information economy. • Reductions in material intensity. • Introduction of clean and resource-efficient technologies.

Appendix B: CO_2 emission scenarios

Appendix B.1: Descriptions of different CO_2 emission scenarios based on HM Government (2009)

Scenario	Description
70% Base	CO_2 reduction targets commissioned by the Committee of Climate Change (CCC): 29% reduction by 2020 relative to the 1990 level, 70% reduction by 2050 relative to the 1990 level.
70% RES	CO_2 reduction targets commissioned by the Department of Energy and Climate Change (DECC): 29% reduction by 2020 relative to the 1990 level, 70% reduction by 2050 relative to the 1990 level.
80% Base	CO_2 reduction targets commissioned by CCC: 33% reduction by 2020 relative to the 1990 level, 80% reduction by 2050 relative to the 1990 level.
80% high bio-energy	CO_2 reduction targets commissioned by Department of the Environment, Fisheries and Rural Affairs (Defra): 31% reduction by 2020 relative to the 1990 level, 80% reduction by 2050 relative to the 1990 level.
80% Resilience (low-electricity)	CO_2 reduction targets commissioned by UK Energy Research Centre (UKREC): 26% reduction by 2020 relative to the 1990 level, 80% reduction by 2050 relative to the 1990 level.
80% RES	CO_2 reduction targets commissioned by DECC: 29% reduction by 2020 relative to the 1990 level, 80% reduction by 2050 relative to the 1990 level.
90% Base	CO_2 reduction targets commissioned by CCC: 38% reduction by 2020 relative to the 1990 level, 90% reduction by 2050 relative to the 1990 level.
90% RES	CO_2 reduction targets commissioned by DECC: 29% reduction by 2020 relative to the 1990 level, 90% reduction by 2050 relative to the 1990 level.

Appendix B.2: Rate of average carbon emission under different scenarios estimated by HM Government (2009)

	Average emission/gCO_2 per kWh							
Year	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
2017	480	400	450	420	390	490	430	400
2030	180	160	70	100	80	220	25	25
2050	50	45	25	30	20	16	17	18
2080	50	45	25	30	20	16	17	18

Appendix C: Breakdown of results

Appendix C.1: Breakdown of actual measured results for 2017

2017										
			CO_2 emissions/kgCO_2							
Month	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
January	178.41	10,449.14	5,015.58	4,179.65	4,702.11	4,388.64	4,075.16	5,120.08	4,493.13	4,179.65
February	76.11	6,696.65	3,214.39	2,678.66	3,013.49	2,812.59	2,611.69	3,281.36	2,879.56	2,678.66
March	42.70	6,163.78	2,958.61	2,465.51	2,773.70	2,588.79	2,403.87	3,020.25	2,650.42	2,465.51
October	13.34	7,285.66	3,497.12	2,914.26	3,278.55	3,059.98	2,841.41	3,569.97	3,132.83	2,914.26
November	94.52	8,744.91	4,197.56	3,497.96	3,935.21	3,672.86	3,410.51	4,285.01	3,760.31	3,497.96
December	84.03	4,688.72	2,250.59	1,875.49	2,109.93	1,969.26	1,828.60	2,297.47	2,016.15	1,875.49
Total	**489.11**	**44,028.85**	**21,133.85**	**17,611.54**	**19,812.98**	**18,492.12**	**17,171.25**	**21,574.14**	**18,932.41**	**17,611.54**

Appendix C.2: Breakdown of results for the standard reference period between 1961 and 1990

Standard reference period between 1961-1990			
Month	**HDD**	**Energy consumption /kWh**	**CO_2 emissions /kgCO_2**
January	148.25	8,986.91	6,830.05
February	147.61	8,976.84	6,822.40
March	114.11	9,122.99	6,933.47
October	32.50	7,844.35	5,961.70
November	105.09	8,648.86	6,573.13
December	37.98	3,595.73	2,732.75
Total	**585.54**	**47,175.67**	**35,853.51**

Appendix C.3: Breakdown of results for 2030 under medium emission scenario

2030 (medium emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
10	January	155.41	9,099.13	1,637.84	1,455.86	636.94	909.91	727.93	2,001.81	227.48	227.48
	February	130.23	8,706.75	1,567.21	1,393.08	609.47	870.67	696.54	1,915.48	217.67	217.67
	March	81.11	7,606.24	1,369.12	1,217.00	532.44	760.62	608.50	1,673.37	190.16	190.16
	October	21.02	6,330.72	1,139.53	1,012.92	443.15	633.07	506.46	1,392.76	158.27	158.27
	November	80.85	8,268.65	1,488.36	1,322.98	578.81	826.86	661.49	1,819.10	206.72	206.72
	December	67.55	3,724.09	670.34	595.86	260.69	372.41	297.93	819.30	93.10	93.10
	Total	**536.17**	**43,735.57**	**7,872.40**	**6,997.69**	**3,061.49**	**4,373.56**	**3,498.85**	**9,621.83**	**1,093.39**	**1,093.39**
33	January	139.77	9,188.63	1,653.95	1,470.18	643.20	918.86	735.09	2,021.50	229.72	229.72
	February	112.80	8,435.29	1,518.35	1,349.65	590.47	843.53	674.82	1,855.76	210.88	210.88
	March	71.64	8,124.96	1,462.49	1,299.99	568.75	812.50	650.00	1,787.49	203.12	203.12
	October	12.89	5,536.19	996.51	885.79	387.53	553.62	442.90	1,217.96	138.40	138.40
	November	60.66	7,285.92	1,311.47	1,165.75	510.01	728.59	582.87	1,602.90	182.15	182.15
	December	51.67	4,143.71	745.87	662.99	290.06	414.37	331.50	911.62	103.59	103.59
	Total	**449.43**	**42,714.70**	**7,688.65**	**6,834.35**	**2,990.03**	**4,271.47**	**3,417.18**	**9,397.23**	**1,067.87**	**1,067.87**
50	January	128.94	8,687.53	1,563.75	1,390.00	608.13	868.75	695.00	1,911.26	217.19	217.19
	February	108.62	8,369.58	1,506.52	1,339.13	585.87	836.96	669.57	1,841.31	209.24	209.24
	March	57.88	7,575.81	1,363.65	1,212.13	530.31	757.58	606.06	1,666.68	189.40	189.40
	October	14.53	5,895.22	1,061.14	943.23	412.67	589.52	471.62	1,296.95	147.38	147.38
	November	53.85	7,846.04	1,412.29	1,255.37	549.22	784.60	627.68	1,726.13	196.15	196.15
	December	68.59	4,073.15	733.17	651.70	285.12	407.32	325.85	896.09	101.83	101.83
	Total	**432.41**	**42,447.33**	**7,640.52**	**6,791.57**	**2,971.31**	**4,244.73**	**3,395.79**	**9,338.41**	**1,061.18**	**1,061.18**

2030 (medium emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
66	January	121.77	8,908.84	1,603.59	1,425.41	623.62	890.88	712.71	1,959.94	222.72	222.72
	February	96.81	8,185.47	1,473.38	1,309.68	572.98	818.55	654.84	1,800.80	204.64	204.64
	March	63.20	7,992.64	1,438.68	1,278.82	559.48	799.26	639.41	1,758.38	199.82	199.82
	October	10.27	4,828.29	869.09	772.53	337.98	482.83	386.26	1,062.22	120.71	120.71
	November	41.54	7,652.76	1,377.50	1,224.44	535.69	765.28	612.22	1,683.61	191.32	191.32
	December	24.21	3,714.02	668.52	594.24	259.98	371.40	297.12	817.08	92.85	92.85
	Total	**357.80**	**41,282.02**	**7,430.76**	**6,605.12**	**2,889.74**	**4,128.20**	**3,302.56**	**9,082.05**	**1,032.05**	**1,032.05**
90	January	86.98	8,364.03	1,505.53	1,338.25	585.48	836.40	669.12	1,840.09	209.10	209.10
	February	75.93	7,858.42	1,414.52	1,257.35	550.09	785.84	628.67	1,728.85	196.46	196.46
	March	56.37	7,552.41	1,359.43	1,208.39	528.67	755.24	604.19	1,661.53	188.81	188.81
	October	7.64	4,786.87	861.64	765.90	335.08	478.69	382.95	1,053.11	119.67	119.67
	November	29.37	6,795.14	1,223.13	1,087.22	475.66	679.51	543.61	1,494.93	169.88	169.88
	December	20.24	3,318.28	597.29	530.92	232.28	331.83	265.46	730.02	82.96	82.96
	Total	**276.53**	**38,675.15**	**6,961.53**	**6,188.02**	**2,707.26**	**3,867.51**	**3,094.01**	**8,508.53**	**966.88**	**966.88**

Appendix C.4: Breakdown of results for 2030 under high emission scenario

2030 (high emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
10	January	163.44	9,225.20	1,660.54	1,476.03	645.76	922.52	738.02	2,029.54	230.63	230.63
	February	119.22	8,202.31	1,476.42	1,312.37	574.16	820.23	656.18	1,804.51	205.06	205.06
	March	82.43	8,294.03	1,492.93	1,327.04	580.58	829.40	663.52	1,824.69	207.35	207.35
	October	22.49	6,686.89	1,203.64	1,069.90	468.08	668.69	534.95	1,471.12	167.17	167.17
	November	66.62	7,379.13	1,328.24	1,180.66	516.54	737.91	590.33	1,623.41	184.48	184.48
	December	52.82	3,828.24	689.08	612.52	267.98	382.82	306.26	842.21	95.71	95.71
	Total	**507.02**	**43,615.80**	**7,850.84**	**6,978.53**	**3,053.11**	**4,361.58**	**3,489.26**	**9,595.48**	**1,090.40**	**1,090.40**
33	January	131.53	8,726.73	1,570.81	1,396.28	610.87	872.67	698.14	1,919.88	218.17	218.17
	February	98.57	8,213.23	1,478.38	1,314.12	574.93	821.32	657.06	1,806.91	205.33	205.33
	March	75.45	7,851.21	1,413.22	1,256.19	549.58	785.12	628.10	1,727.27	196.28	196.28
	October	13.41	5,877.70	1,057.99	940.43	411.44	587.77	470.22	1,293.10	146.94	146.94
	November	60.37	7,948.40	1,430.71	1,271.74	556.39	794.84	635.87	1,748.65	198.71	198.71
	December	52.31	4,153.61	747.65	664.58	290.75	415.36	332.29	913.79	103.84	103.84
	Total	**431.64**	**42,770.88**	**7,698.76**	**6,843.34**	**2,993.96**	**4,277.09**	**3,421.67**	**9,409.59**	**1,069.27**	**1,069.27**
50	January	124.44	8,949.77	1,610.96	1,431.96	626.48	894.98	715.98	1,968.95	223.74	223.74
	February	98.12	8,205.28	1,476.95	1,312.85	574.37	820.53	656.42	1,805.16	205.13	205.13
	March	75.59	8,186.97	1,473.65	1,309.92	573.09	818.70	654.96	1,801.13	204.67	204.67
	October	11.43	5,513.20	992.38	882.11	385.92	551.32	441.06	1,212.90	137.83	137.83
	November	57.94	7,243.02	1,303.74	1,158.88	507.01	724.30	579.44	1,593.46	181.08	181.08
	December	51.85	4,146.68	746.40	663.47	290.27	414.67	331.73	912.27	103.67	103.67
	Total	**419.37**	**42,244.92**	**7,604.09**	**6,759.19**	**2,957.14**	**4,224.49**	**3,379.59**	**9,293.88**	**1,056.12**	**1,056.12**

2030 (high emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
66	January	127.52	8,331.44	1,499.66	1,333.03	583.20	833.14	666.52	1,832.92	208.29	208.29
	February	93.66	8,136.75	1,464.62	1,301.88	569.57	813.68	650.94	1,790.09	203.42	203.42
	March	67.23	8,056.40	1,450.15	1,289.02	563.95	805.64	644.51	1,772.41	201.41	201.41
	October	11.28	6,177.48	1,111.95	988.40	432.42	617.75	494.20	1,359.05	154.44	154.44
	November	55.99	6,879.40	1,238.29	1,100.70	481.56	687.94	550.35	1,513.47	171.98	171.98
	December	72.35	4,464.78	803.66	714.36	312.53	446.48	357.18	982.25	111.62	111.62
	Total	**428.03**	**42,046.26**	**7,568.33**	**6,727.40**	**2,943.24**	**4,204.63**	**3,363.70**	**9,250.18**	**1,051.16**	**1,051.16**
90	January	108.36	8,031.33	1,445.64	1,285.01	562.19	803.13	642.51	1,766.89	200.78	200.78
	February	79.69	7,584.24	1,365.16	1,213.48	530.90	758.42	606.74	1,668.53	189.61	189.61
	March	65.89	8,035.16	1,446.33	1,285.62	562.46	803.52	642.81	1,767.73	200.88	200.88
	October	9.40	4,814.52	866.61	770.32	337.02	481.45	385.16	1,059.19	120.36	120.36
	November	27.20	7,094.66	1,277.04	1,135.15	496.63	709.47	567.57	1,560.82	177.37	177.37
	December	47.86	4,084.60	735.23	653.54	285.92	408.46	326.77	898.61	102.12	102.12
	Total	**338.40**	**39,644.51**	**7,136.01**	**6,343.12**	**2,775.12**	**3,964.45**	**3,171.56**	**8,721.79**	**991.11**	**991.11**

Appendix D.5: Breakdown of results for 2050 under medium emission scenario

2050 (medium emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
10	January	146.82	8,964.29	448.21	403.39	224.11	268.93	179.29	143.43	152.39	161.36
	February	129.81	8,698.88	434.94	391.45	217.47	260.97	173.98	139.18	147.88	156.58
	March	88.94	9,062.51	453.13	407.81	226.56	271.88	181.25	145.00	154.06	163.13
	October	10.64	5,167.42	258.37	232.53	129.19	155.02	103.35	82.68	87.85	93.01
	November	76.58	8,536.02	426.80	384.12	213.40	256.08	170.72	136.58	145.11	153.65
	December	35.28	2,886.90	144.35	129.91	72.17	86.61	57.74	46.19	49.08	51.96
	Total	**488.07**	**43,316.02**	**2,165.80**	**1,949.22**	**1,082.90**	**1,299.48**	**866.32**	**693.06**	**736.37**	**779.69**
33	January	123.34	8,600.45	430.02	387.02	215.01	258.01	172.01	137.61	146.21	154.81
	February	113.38	8,443.40	422.17	379.95	211.08	253.30	168.87	135.09	143.54	151.98
	March	73.41	8,819.79	440.99	396.89	220.49	264.59	176.40	141.12	149.94	158.76
	October	11.07	5,507.50	275.37	247.84	137.69	165.22	110.15	88.12	93.63	99.13
	November	46.63	7,733.34	386.67	348.00	193.33	232.00	154.67	123.73	131.47	139.20
	December	28.07	2,773.79	138.69	124.82	69.34	83.21	55.48	44.38	47.15	49.93
	Total	**395.90**	**41,878.27**	**2,093.91**	**1,884.52**	**1,046.96**	**1,256.35**	**837.57**	**670.05**	**711.93**	**753.81**
50	January	120.01	8,545.58	427.28	384.55	213.64	256.37	170.91	136.73	145.27	153.82
	February	100.73	8,246.20	412.31	371.08	206.15	247.39	164.92	131.94	140.19	148.43
	March	71.57	8,790.57	439.53	395.58	219.76	263.72	175.81	140.65	149.44	158.23
	October	7.07	4,444.53	222.23	200.00	111.11	133.34	88.89	71.11	75.56	80.00
	November	52.75	7,162.10	358.11	322.29	179.05	214.86	143.24	114.59	121.76	128.92
	December	27.75	2,768.95	138.45	124.60	69.22	83.07	55.38	44.30	47.07	49.84
	Total	**379.88**	**39,957.93**	**1,997.90**	**1,798.11**	**998.95**	**1,198.74**	**799.16**	**639.33**	**679.28**	**719.24**

2050 (medium emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
66	January	102.15	7,934.95	396.75	357.07	198.37	238.05	158.70	126.96	134.89	142.83
	February	106.32	8,333.86	416.69	375.02	208.35	250.02	166.68	133.34	141.68	150.01
	March	70.24	8,436.43	421.82	379.64	210.91	253.09	168.73	134.98	143.42	151.86
	October	4.73	4,074.40	203.72	183.35	101.86	122.23	81.49	65.19	69.26	73.34
	November	34.73	7,546.25	377.31	339.58	188.66	226.39	150.92	120.74	128.29	135.83
	December	31.50	2,827.95	141.40	127.26	70.70	84.84	56.56	45.25	48.08	50.90
	Total	**349.67**	**39,153.84**	**1,957.69**	**1,761.92**	**978.85**	**1,174.62**	**783.08**	**626.46**	**665.62**	**704.77**
90	January	76.81	7,538.90	376.94	339.25	188.47	226.17	150.78	120.62	128.16	135.70
	February	61.70	7,635.87	381.79	343.61	190.90	229.08	152.72	122.17	129.81	137.45
	March	42.90	8,007.72	400.39	360.35	200.19	240.23	160.15	128.12	136.13	144.14
	October	4.75	4,408.02	220.40	198.36	110.20	132.24	88.16	70.53	74.94	79.34
	November	30.62	6,148.22	307.41	276.67	153.71	184.45	122.96	98.37	104.52	110.67
	December	16.52	2,259.48	112.97	101.68	56.49	67.78	45.19	36.15	38.41	40.67
	Total	**233.30**	**35,998.21**	**1,799.91**	**1,619.92**	**899.96**	**1,079.95**	**719.96**	**575.97**	**611.97**	**647.97**

Appendix D.6: Breakdown of results for 2050 under high emission scenario

2050 (high emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
10	January	143.65	8,916.56	445.83	401.25	222.91	267.50	178.33	142.67	151.58	160.50
	February	100.88	8,248.86	412.44	371.20	206.22	247.47	164.98	131.98	140.23	148.48
	March	97.30	8,860.07	443.00	398.70	221.50	265.80	177.20	141.76	150.62	159.48
	October	10.83	5,837.07	291.85	262.67	145.93	175.11	116.74	93.39	99.23	105.07
	November	67.25	7,389.02	369.45	332.51	184.73	221.67	147.78	118.22	125.61	133.00
	December	64.67	3,343.30	167.16	150.45	83.58	100.30	66.87	53.49	56.84	60.18
	Total	**484.58**	**42,594.88**	**2,129.74**	**1,916.77**	**1,064.87**	**1,277.85**	**851.90**	**681.52**	**724.11**	**766.71**
33	January	110.81	8,403.67	420.18	378.17	210.09	252.11	168.07	134.46	142.86	151.27
	February	111.68	8,418.12	420.91	378.82	210.45	252.54	168.36	134.69	143.11	151.53
	March	75.12	8,512.61	425.63	383.07	212.82	255.38	170.25	136.20	144.71	153.23
	October	10.87	5,837.64	291.88	262.69	145.94	175.13	116.75	93.40	99.24	105.08
	November	56.81	7,225.78	361.29	325.16	180.64	216.77	144.52	115.61	122.84	130.06
	December	41.38	2,982.55	149.13	134.21	74.56	89.48	59.65	47.72	50.70	53.69
	Total	**406.67**	**41,380.36**	**2,069.02**	**1,862.12**	**1,034.51**	**1,241.41**	**827.61**	**662.09**	**703.47**	**744.85**
50	January	101.24	7,920.99	396.05	356.44	198.02	237.63	158.42	126.74	134.66	142.58
	February	84.61	7,994.75	399.74	359.76	199.87	239.84	159.89	127.92	135.91	143.91
	March	48.59	8,430.84	421.54	379.39	210.77	252.93	168.62	134.89	143.32	151.76
	October	9.27	5,145.02	257.25	231.53	128.63	154.35	102.90	82.32	87.47	92.61
	November	45.58	7,049.85	352.49	317.24	176.25	211.50	141.00	112.80	119.85	126.90
	December	49.98	3,116.70	155.84	140.25	77.92	93.50	62.33	49.87	52.98	56.10
	Total	**339.27**	**39,658.15**	**1,982.91**	**1,784.62**	**991.45**	**1,189.74**	**793.16**	**634.53**	**674.19**	**713.85**

2050 (high emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
66	January	97.39	8,194.22	409.71	368.74	204.86	245.83	163.88	131.11	139.30	147.50
	February	89.26	7,733.25	386.66	348.00	193.33	232.00	154.67	123.73	131.47	139.20
	March	65.32	8,025.76	401.29	361.16	200.64	240.77	160.52	128.41	136.44	144.46
	October	5.95	4,760.21	238.01	214.21	119.01	142.81	95.20	76.16	80.92	85.68
	November	36.67	6,909.75	345.49	310.94	172.74	207.29	138.20	110.56	117.47	124.38
	December	12.97	2,537.24	126.86	114.18	63.43	76.12	50.74	40.60	43.13	45.67
	Total	**307.56**	**38,160.44**	**1,908.02**	**1,717.22**	**954.01**	**1,144.81**	**763.21**	**610.57**	**648.73**	**686.89**
90	January	79.39	6,910.59	345.53	310.98	172.76	207.32	138.21	110.57	117.48	124.39
	February	86.63	8,026.23	401.31	361.18	200.66	240.79	160.52	128.42	136.45	144.47
	March	46.78	7,735.23	386.76	348.09	193.38	232.06	154.70	123.76	131.50	139.23
	October	3.19	3,383.48	169.17	152.26	84.59	101.50	67.67	54.14	57.52	60.90
	November	20.28	6,652.47	332.62	299.36	166.31	199.57	133.05	106.44	113.09	119.74
	December	15.97	2,584.46	129.22	116.30	64.61	77.53	51.69	41.35	43.94	46.52
	Total	**252.24**	**35,292.45**	**1,764.62**	**1,588.16**	**882.31**	**1,058.77**	**705.85**	**564.68**	**599.97**	**635.26**

Appendix D.7: Breakdown of results for 2080 under medium emission scenario

2080 (medium emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
10	January	149.55	9,342.96	467.15	420.43	233.57	280.29	186.86	149.49	158.83	168.17
	February	118.56	8,526.09	426.30	383.67	213.15	255.78	170.52	136.42	144.94	153.47
	March	74.38	7,833.94	391.70	352.53	195.85	235.02	156.68	125.34	133.18	141.01
	October	17.05	5,934.79	296.74	267.07	148.37	178.04	118.70	94.96	100.89	106.83
	November	60.59	7,284.88	364.24	327.82	182.12	218.55	145.70	116.56	123.84	131.13
	December	50.08	3,785.41	189.27	170.34	94.64	113.56	75.71	60.57	64.35	68.14
	Total	**470.21**	**42,708.07**	**2,135.40**	**1,921.86**	**1,067.70**	**1,281.24**	**854.16**	**683.33**	**726.04**	**768.75**
33	January	130.46	8,710.52	435.53	391.97	217.76	261.32	174.21	139.37	148.08	156.79
	February	86.72	8,027.80	401.39	361.25	200.69	240.83	160.56	128.44	136.47	144.50
	March	71.04	7,782.21	389.11	350.20	194.56	233.47	155.64	124.52	132.30	140.08
	October	10.58	5,166.39	258.32	232.49	129.16	154.99	103.33	82.66	87.83	93.00
	November	49.10	7,771.44	388.57	349.71	194.29	233.14	155.43	124.34	132.11	139.89
	December	10.10	3,158.97	157.95	142.15	78.97	94.77	63.18	50.54	53.70	56.86
	Total	**358.00**	**40,617.33**	**2,030.87**	**1,827.78**	**1,015.43**	**1,218.52**	**812.35**	**649.88**	**690.49**	**731.11**
50	January	114.58	8,795.80	439.79	395.81	219.89	263.87	175.92	140.73	149.53	158.32
	February	85.42	8,006.18	400.31	360.28	200.15	240.19	160.12	128.10	136.10	144.11
	March	62.10	6,641.87	332.09	298.88	166.05	199.26	132.84	106.27	112.91	119.55
	October	5.64	4,088.74	204.44	183.99	102.22	122.66	81.77	65.42	69.51	73.60
	November	40.58	6,637.34	331.87	298.68	165.93	199.12	132.75	106.20	112.83	119.47
	December	13.53	2,879.46	143.97	129.58	71.99	86.38	57.59	46.07	48.95	51.83
	Total	**321.85**	**37,049.38**	**1,852.47**	**1,667.22**	**926.23**	**1,111.48**	**740.99**	**592.79**	**629.84**	**666.89**

2080 (medium emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
66	January	101.53	8,259.35	412.97	371.67	206.48	247.78	165.19	132.15	140.41	148.67
	February	69.40	7,756.87	387.84	349.06	193.92	232.71	155.14	124.11	131.87	139.62
	March	45.79	7,053.18	352.66	317.39	176.33	211.60	141.06	112.85	119.90	126.96
	October	3.80	3,393.10	169.66	152.69	84.83	101.79	67.86	54.29	57.68	61.08
	November	26.67	6,752.89	337.64	303.88	168.82	202.59	135.06	108.05	114.80	121.55
	December	36.87	3,578.83	178.94	161.05	89.47	107.36	71.58	57.26	60.84	64.42
	Total	**284.06**	**36,794.21**	**1,839.71**	**1,655.74**	**919.86**	**1,103.83**	**735.88**	**588.71**	**625.50**	**662.30**
90	January	73.45	7,486.30	374.31	336.88	187.16	224.59	149.73	119.78	127.27	134.75
	February	48.09	7,422.27	371.11	334.00	185.56	222.67	148.45	118.76	126.18	133.60
	March	30.36	7,144.21	357.21	321.49	178.61	214.33	142.88	114.31	121.45	128.60
	October	2.17	2,367.45	118.37	106.54	59.19	71.02	47.35	37.88	40.25	42.61
	November	14.89	4,567.55	228.38	205.54	114.19	137.03	91.35	73.08	77.65	82.22
	December	23.37	3,367.30	168.37	151.53	84.18	101.02	67.35	53.88	57.24	60.61
	Total	**192.33**	**32,355.08**	**1,617.75**	**1,455.98**	**808.88**	**970.65**	**647.10**	**517.68**	**550.04**	**582.39**

Appendix D.8: Breakdown of results for 2080 under high emission scenario

2080 (high emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
10	January	146.66	8,961.12	448.06	403.25	224.03	268.83	179.22	143.38	152.34	161.30
	February	106.55	8,337.21	416.86	375.17	208.43	250.12	166.74	133.40	141.73	150.07
	March	62.36	7,646.06	382.30	344.07	191.15	229.38	152.92	122.34	129.98	137.63
	October	7.25	5,780.72	289.04	260.13	144.52	173.42	115.61	92.49	98.27	104.05
	November	48.05	7,754.83	387.74	348.97	193.87	232.64	155.10	124.08	131.83	139.59
	December	49.37	3,774.34	188.72	169.85	94.36	113.23	75.49	60.39	64.16	67.94
	Total	**420.24**	**42,254.27**	**2,112.71**	**1,901.44**	**1,056.36**	**1,267.63**	**845.09**	**676.07**	**718.32**	**760.58**
33	January	105.79	7,991.78	399.59	359.63	199.79	239.75	159.84	127.87	135.86	143.85
	February	82.83	7,966.33	398.32	358.48	199.16	238.99	159.33	127.46	135.43	143.39
	March	57.57	7,571.12	378.56	340.70	189.28	227.13	151.42	121.14	128.71	136.28
	October	4.51	5,070.90	253.55	228.19	126.77	152.13	101.42	81.13	86.21	91.28
	November	40.21	7,298.93	364.95	328.45	182.47	218.97	145.98	116.78	124.08	131.38
	December	43.23	3,678.34	183.92	165.53	91.96	110.35	73.57	58.85	62.53	66.21
	Total	**334.14**	**39,577.41**	**1,978.87**	**1,780.98**	**989.44**	**1,187.32**	**791.55**	**633.24**	**672.82**	**712.39**
50	January	104.08	8,298.57	414.93	373.44	207.46	248.96	165.97	132.78	141.08	149.37
	February	60.16	7,611.22	380.56	342.50	190.28	228.34	152.22	121.78	129.39	137.00
	March	38.64	7,274.48	363.72	327.35	181.86	218.23	145.49	116.39	123.67	130.94
	October	3.82	3,060.09	153.00	137.70	76.50	91.80	61.20	48.96	52.02	55.08
	November	31.35	6,826.06	341.30	307.17	170.65	204.78	136.52	109.22	116.04	122.87
	December	31.35	3,492.31	174.62	157.15	87.31	104.77	69.85	55.88	59.37	62.86
	Total	**269.40**	**36,562.73**	**1,828.14**	**1,645.32**	**914.07**	**1,096.88**	**731.25**	**585.00**	**621.57**	**658.13**

2080 (high emission)											
				CO_2 emissions/kgCO_2							
Probability /%	**Month**	**HDD**	**Energy consumption /kWh**	**70% base**	**70% RES**	**80% base**	**80% high-bio energy**	**80% RES**	**80% resilient**	**90% base**	**90% RES**
66	January	85.49	8,007.80	400.39	360.35	200.19	240.23	160.16	128.12	136.13	144.14
	February	55.21	7,200.75	360.04	324.03	180.02	216.02	144.01	115.21	122.41	129.61
	March	37.21	6,918.32	345.92	311.32	172.96	207.55	138.37	110.69	117.61	124.53
	October	2.81	3,377.50	168.87	151.99	84.44	101.32	67.55	54.04	57.42	60.79
	November	23.59	6,370.89	318.54	286.69	159.27	191.13	127.42	101.93	108.31	114.68
	December	30.29	3,476.22	173.81	156.43	86.91	104.29	69.52	55.62	59.10	62.57
	Total	**234.60**	**35,351.47**	**1,767.57**	**1,590.82**	**883.79**	**1,060.54**	**707.03**	**565.62**	**600.98**	**636.33**
90	January	52.88	7,163.54	358.18	322.36	179.09	214.91	143.27	114.62	121.78	128.94
	February	41.73	6,988.52	349.43	314.48	174.71	209.66	139.77	111.82	118.80	125.79
	March	17.56	6,609.70	330.48	297.44	165.24	198.29	132.19	105.76	112.36	118.97
	October	0.83	1,013.05	50.65	45.59	25.33	30.39	20.26	16.21	17.22	18.23
	November	12.78	4,201.08	210.05	189.05	105.03	126.03	84.02	67.22	71.42	75.62
	December	14.87	3,233.79	161.69	145.52	80.84	97.01	64.68	51.74	54.97	58.21
	Total	**140.65**	**29,209.68**	**1,460.48**	**1,314.44**	**730.24**	**876.29**	**584.19**	**467.35**	**496.56**	**525.77**