Modelling Scenarios for Low Carbon Heating Technologies in the Domestic Sector Towards a Circular Economy

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This thesis is submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

September 2022

Declaration

I confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

The UK Government's Net Zero strategy requires strong commitments to avoid catastrophic impacts of climate change. The built environment puts major pressure on the natural environment, especially with space heating-related emissions; therefore, transitioning to a circular economy is vital. In this direction, the heat pump market in the UK has been growing gradually whereas the number is still low (43,000 units in 2021). The UK Government aims to reach 600,000 heat pump installations per year by 2028, and according to the Climate Change Committee (CCC), this number should reach 1 million by 2030. In order to accelerate the transition, the Boiler Upgrade Scheme (BUS) has been introduced to provide a £5,000 grant in the UK, and the Scottish Government granted Home Energy Scotland (HES) loan and cashback scheme providing a £7,500 grant and a £2,500 interest-free loan for heat pumps.

Islands are facing environmental, economic and social pressure due to the lack of connection to the mainland and dependency on fossil fuel imports. Exploring the benefits of renewable energy and low carbon heating technologies is crucial to overcome these issues. Orkney has a huge potential for renewable energy by producing electricity more than its needs. Therefore, this study chooses Orkney as a case study to explore potential heat pump uptake scenarios in line with government targets towards Circular Economy (CE). The study aims to create a comprehensive holistic approach to evaluate the environmental, energy and economic impacts of heat pump deployment scenarios. The consequences of replacing conventional heating technologies with heat pumps have been assessed through (i) comparative life cycle assessment (LCA) of heat pumps with gas boilers in UK houses, (ii) energy systems modelling (ESM) to optimise the performance of a heat pump coupled with thermal energy storage (TES) tank to reduce use phase related impacts in Orkney, (iii) building stock modelling (BSM) of Orkney's domestic sector to understand the housing condition, (iv) economic modelling to analyse life cycle cost of an air source heat pump and potential savings when existing conventional heating systems are replaced with heat pumps in Orkney, and (v) heat pump diffusion model to quantify hourly electric load curves of variable heat pump operation

optimised by the energy model. The integrated methodology creates a more holistic and life cycle-wide approach to both demand, supply and end-user side of the system; therefore, the results are illustrated in both individual house archetypes level to provide guidance to the end-users and at the Orkney level to calculate cumulative savings for the policymakers.

The results show that the use phase is the major contributor to the environmental impacts; therefore, increasing the renewable share in the UK's electricity mix could help to reduce negative impacts in most of the categories. However, the high deployment of wind farms also creates toxicity and metal depletion problems. The heat pump uptake scenarios in Orkney shows that 82% reductions in energy supply could be achieved when ambitious energy efficiency improvement measures are taken in the CE scenario. The use phase-related emissions could be reduced by 98% when the heat pump becomes the only heating technology in Orkney. However, the life cycle-wide approach suggests that strong commitments are required in the manufacturing stage of these technologies through implementing circular principles such as including the use of secondary materials, eco-design and reusability of all components. Moreover, a market introduction program should be provided before shifting from one technology to another so greener production lines could be achieved. Total heating costs paid by consumers in Orkney could be reduced by 84% in the CE scenario when heat pump uptake is coupled with energy efficiency improvement measures; however, it requires a £130 million investment to insulate the unrefurbished housing stock of Orkney. Therefore, subsidies and incentives are also required for efficiency improvements such as reductions in VAT on equipment and labour costs, grants similar to BUS/HES and interest-free loans for the remaining costs. Future scenarios indicate that decision-making has significant importance on overall results; therefore, CE standards for heat pump manufacturing and deployment are crucial to reduce the negative impacts of fuel poverty and reach the Net Zero target.

Impact Statement

Climate Change is a major problem, and limiting temperature increases to 1.5 °C is crucial. Countries are trying to decarbonise their systems and the UK is the first country to set legislation to achieve 'Net Zero' emissions by 2050. Nearly one-third of these emissions come from buildings and heating-related activities. Therefore, the decarbonisation of heating is a priority to reach the Net Zero target.

Small islands are isolated areas due to the lack of connection to the mainland; therefore, they are facing economic stress because of high energy imports and reliance on fossil fuels. The situation is more difficult for Scottish islands where the energy prices are rising. Nearly two-thirds of the household are facing fuel poverty in Orkney despite high renewable energy potential, specifically wind. The number of heat pumps per 1000 households is 117 in Orkney which is the second highest among the Scottish local authorities. Therefore, focusing on the decarbonisation of heating at the island level, specifically Orkney, could help to analyse the current trend of electrification of heating and potential future decarbonisation scenarios towards a circular economy.

This research has a novel proposed methodological approach to support the UK's Net Zero target in terms of decarbonising space heating. Environmental and economic implications of heat pump uptake scenarios are investigated through quantified methods consisting of (i) a comparative life cycle assessment (LCA) of heat pumps with gas boilers in UK houses, (ii) energy systems modelling (ESM) to optimise the performance of an air source heat pump with demand side management to reduce the impact of the highest contributor phase in LCA analysis, (iii) a building stock modelling (BSM) to understand the housing condition and efficiency improvement requirements in Orkney, (iv) economic modelling to analyse the life cycle cost analysis of an air source heat pump and potential savings of replacing existing conventional heating technologies in Orkney, and (v) a heat pump diffusion modelling to quantify hourly electric load curves of heat pumps for house archetypes and Orkney electricity system.

The integrated approach analyses the current situation in the UK and Orkney and conducts scenario analysis for 2050 in line with government targets to evaluate the pathways. Financing options for end-users assess the current support mechanisms and provide suggestions from successful examples. Hourly load curves provide a system perspective and possible reductions in peak loads. Building stock model of Orkney helps to calculate both individual results at the house archetype level and cumulative results at the Orkney level.

A multi-level assessment provides insights into not only the end-user side of the system but also the system thinking with a holistic approach. The comprehensive manner with a life cycle-wide approach is fundamental to being able to evaluate environmental and economic perspectives of heat pump uptake scenarios to reach UK's Net Zero target. This research can be extended to other heat pump typologies and heating technologies, and the model can be adjusted for other locations.

Publications

Preliminary findings of the life cycle assessment (LCA) study (Chapter 4) have been presented at the following international conferences:

- Sevindik, S. and Spataru, C. (2020) 'Life Cycle Assessment of Domestic Heat Pumps with Gas Boilers and Hybrid Scenario Analysis in the UK', in Akansu, S. O. and Unalan, S. (eds) *Proceedings of International Conference on Energy, Environment and Storage of Energy (ICEESEN2020), 19-21 November 2020, Faculty of Engineering, Erciyes University, Erciyes Energy Association, Kayseri-Turkey*. isbn: 978-625-409-147-6.

- Sevindik, S. et al. (2020) 'Comparative Environmental Impact Assessment of Heat Pumps with Gas Boilers and Scenario Analysis Towards a Circular Economy in the UK', in Ban, M. et al. (eds) *15th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), 1-5 September 2020. Cologne, Germany: Faculty of Mechanical Engineering and Naval Architecture, Zagreb*.

Part of the thesis findings (Chapter 4-5-6) have been published in the following journals:

- Sevindik, S. *et al.* (2021) 'A Comparative Environmental Assessment of Heat Pumps and Gas Boilers towards a Circular Economy in the UK', *Energies*, 14(11), p. 3027. doi: 10.3390/en14113027.

- Sevindik, S. and Spataru, C. (2023) 'An Integrated Methodology for Scenarios Analysis of Low Carbon Technologies Uptake towards a Circular Economy: The Case of Orkney', *Energies*, 16(1). doi: 10.3390/en16010419.

Acknowledgements

This research would not be possible without the support of many people. I would like to take this opportunity to express my sincere gratitude to all those.

First of all, I would like to thank the Republic of Turkey Ministry of National Education for providing sponsorship and financial support throughout my PhD.

I would also like to express my deepest gratitude to my supervisors, Prof Catalina Spataru and Prof Raimund Bleischwitz, for their valuable support, guidance and insights. Their vision and motivation have inspired me all the time. I am also grateful to Dr Teresa Domenech Aparisi for the discussions and her advice about life cycle assessment analysis.

A special thanks to my family and my parents for their continuous support, infinite love and prayers during my education.

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Abbreviations

ALO	Agricultural land occupation
ASHP	Air Source Heat Pump
BAU	Business as Usual
BEIS	Department for Business, Energy & Industrial Strategy
BUS	Boiler Upgrade Scheme
BSM	Building Stock Model
CC	Climate Change
CCC	Climate Change Committee
CDW	Construction and Demolition Waste
CE	Circular Economy
CF	Carbon Footprint
COMFY	Comfy Heat
COP	Coefficient of Performance
DHW	Domestic Hot Water
DSM	Demand Side Management
E12	Economy 12
E20	Economy 20
E7	Economy 7
EEE	Electrical and Electronic Equipment
EEI	Energy Efficiency Improvement
EPC	Energy Performance Certificate
ESM	Energy System Modelling
FD	Fossil Depletion
FE	Freshwater Ecotoxicity
FEU	Freshwater Eutrophication
GHG	Greenhouse Gases

GSHP	Ground-Source Heat Pump
HC	Heat Collector
HES	Home Energy Scotland
HP	Heat Pump
HT	Human Toxicity
IPCC	Intergovernmental Panel on Climate Change
IR	Ionising Radiation
IRP	International Resource Panel
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCIA	Life Cycle Impact Assessment
LG	Limited Growth
LPG	Liquid Petroleum Gas
MD	Metal Depletion
ME	Marine Ecotoxicity
MEU	Marine Eutrophication
MPC	Model Predictive Control
NGB	Natural Gas Boiler
NIC	National Infrastructure Commission
NLT	Natural land transformation
OD	Ozone Depletion
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Formation
PV	Photovoltaics
RBC	Rule-Based Controls
RE	Resource Efficiency
RHI	Renewable Heat Incentive
RIBA	The Royal Institute of British Architects
SAP	Standard Assessment Procedure
SDG	Sustainable Development Goals
SPF	Seasonal Performance Factor
STAN	Standard
TA	Terrestrial Acidification
TE	Terrestrial Ecotoxicity
TES	Thermal Energy Storage
UHS	Underfloor Heating System
ULO	Urban Land Occupation
WD	Water Depletion
WEEE	Waste Electrical and Electronic Equipment
WGBC	World Green Building Council

Chapter 1

Introduction

1.1. Research Motivation and Novelty

The Intergovernmental Panel on Climate Change (IPCC, 2022) declared that achieving Paris Climate Agreement and limiting temperature increases to 1.5 °C requires exceptional actions. The UK is the first country to set legislation to achieve 'Net Zero' greenhouse gas (GHG) emissions by 2050 (BEIS, 2021f). This requires strong commitments to avoid further delays in reducing emissions. Of all sectors, the built environment is responsible for 30% of the UK's greenhouse gas (GHGs) emissions in 2019 which accounts for 454.8 $MtCO_2e$ (BEIS, 2021b). Heating emissions account for 77% of these emissions and the remaining comes from embodied emissions. Building-related emissions have decreased by 13% since 2013 and are around 20% below 1990 levels in the UK (CCC, 2019a). Natural gas is the dominant fuel type used in domestic buildings with 86% of the housing stock (DLUHC, 2022), and the total share of renewables in heating is still only 7.5% in the UK (EUROSTAT, 2022); therefore, electrification of the heating scheme via low carbon technologies plays a key role in the decarbonisation plans. The built environment puts major pressure on the natural environment especially with energy-related emissions, therefore, transitioning to a circular economy is vital. As countries face increasing challenges due to the scarcity of resources and dependence on raw materials, while carbon emissions reduction targets need to be met, circular economy could help move from traditional linear take, make and waste economy to a circular model.

The heat pump market has been growing gradually and reached 10% of the global building heating demand in 2021 (IEA, 2022). Heat pump sales in Europe have reached 7 million units in 2021 with France leading with 537,000 units per year (EHPA, 2022a). However, in the UK, yearly heat pump uptake is very low (43,000 in 2021) when compared with European countries. The UK government aims to reach 600,000 heat pump installations per year by 2028 (BEIS, 2020a). Climate Change Committee suggest that this number should reach 1 million installations per year by 2030 to track UK's Net Zero pathway. The UK government introduced the Boiler Upgrade Scheme (BUS) in 2020 to accelerate this transition by providing a grant of £5000 for heat pump installations (BEIS, 2022a). The Scottish Government granted a slightly higher subsidy named the Home Energy Scotland (HES) loan providing cashback of up to £7500 and an interest-free loan for the rest of the costs of up to £2500 for heat pumps (HES, 2022).

Heat pumps are efficient heating technologies when compared with conventional heating systems. The deployment of heat pumps provides reductions in energy demand while increasing decarbonisation levels in the energy system. However, the investment cost is still higher than other heating systems. A typical air source heat pump (ASHP) costs around £9000-£13,000 depending on the size of the house whereas a typical gas boiler is only around £2000 (Nesta, 2022). On the other hand, operation costs vary based on heat pump efficiency and energy prices. A study conducted by Nesta & BIT (2022b) indicates that only 25% of the consumers are willing to pay the current heat pump prices (£10,000-£12,000). Reducing the upfront and running cots and providing financial options are crucial to make heat pumps attractive from consumers' perspectives.

The Paris Agreement declare that the reliance on fossil fuels and energy imports makes islands vulnerable to climate change. There are about 2400 islands in Europe which have 15 million inhabitants representing 2% of the European population (European Commission, 2018). Small islands are isolated areas due to the lack of connection or poor connection to the mainland. This creates economic pressure on the island due to the dependency on imports (Marczinkowski & Østergaard, 2019). The situation is more difficult for Scottish islands where the price of heating homes is rising and most of the houses rely on electricity and heating oil and don't have access to mains gas. Even though Orkney generates its electricity from local renewable sources electricity prices are assumed to be 2.5 pence higher than southern Scotland values. Orkney's Fuel Poverty Strategy report indicates that 63% of households are living in fuel poverty in Orkney due to higher heating costs, older housing stock conditions, lower average income and a long winter season with strong wind speeds (OIC, 2017).

Buildings are responsible for 35% of the energy use after transport (45%) in Orkney (OREF, 2015). The majority of building-related energy consumption occurs in the domestic sector. The main fuel types used for heating are electricity and oil with 52% and 43% respectively. Orkney has a huge potential for renewable energy sources. The amount of electricity generated from renewables was more than the island's need in 2016 (OREF, 2022); therefore, there is a transition for electrification in heating. The number of heat pumps deployed in 2021 was more than 1000 which accounts for 117 heat pumps per 1000 households (Nesta, 2021). This is the second-largest heat pump uptake among the Scottish local authorities.

This study aims to take an integrated approach to investigate the environmental impacts of replacing conventional heating systems with heat pumps by combining life cycle assessment with energy systems modelling. A multi-level assessment framework helps to identify energy, environmental and economic savings of individual heating technologies by house archetypes and cumulative savings for the island level in line with the UK's Net Zero target. Orkney was selected as a case study to analyse the existing electrification of heating trend and potential future decarbonisation scenarios towards a circular economy.

1.2. Research Aim and Objectives

Current policies have largely concentrated on increasing energy efficiency in the built environment because of its high impact on overall energy demands. However, this concentrates on building performance rather than the life cycle of the built environment and heating technologies. In contrast, Circular Economy (CE) is a promising and more holistic concept for the life cycle of the technologies and the values associated with them. However, CE is a relatively new topic for the industry and policies despite all upwards projections for material consumption, waste production and emissions. Therefore, this study introduces a comprehensive approach for low carbon heating technologies (in this case air source and ground-source heat pumps) that allows a multi-level analysis focusing on the individual impacts of house archetypes and cumulative results for the entire system in Orkney as a case study. The aim of this thesis is to develop an integrated approach by combining life cycle assessment, energy system modelling, economic modelling and building stock modelling to assess energy, environmental and economic savings of heat pump uptake to decarbonise heating in domestic buildings in Orkney.

The key research questions are defined as follows:

a. What are the current environmental impacts of heat pumps compared with natural gas boilers and what are the potential implications for future scenarios in line with the government targets?
b. What is the best control strategy to optimise the performance of an air source heat pump in terms of energy demand, supply and heating cost?

c. Does the hybrid application of heat pumps and gas boilers create benefits to avoid high electricity prices and environmental burdens associated with standalone systems?
d. What are the total savings in terms of energy, environmental impacts and costs when heat pump uptake scenarios are engaged?

The answers to these questions will be addressed through the following objectives.

a. Compare the environmental impacts of key technologies (in this case air source and ground-source heat pumps) with natural gas boilers.
b. Conduct a scenario analysis to investigate government targets for 2050 and hybrid applications of heating technologies.
c. Optimise the performance of an air source heat pump coupled with a thermal energy storage tank and backup heater.
d. Identify the best electricity tariff and heat pump setting to optimise energy input, output and heating costs.
e. Analyse the housing stock condition with building stock modelling and existing heating fuel types to evaluate the impact of heat pump uptake scenarios.
f. Investigate the individual results of heat pump uptake by house archetypes and cumulative savings for Orkney Island

1.3. Research Structure and Layout

The thesis is organised as follows (Figure 1.1):

Following this introductory chapter, Chapter 2 conducted a literature review on heat pump technology in terms of the heat pump types, operation, efficiency and hybrid applications. The current heat pump market, supply chain and policies are investigated and compared with the European studies. The importance of energy efficiency improvement and demand-side management strategies are explored. On the other hand, individual methods of life cycle assessment, energy systems modelling, and integrated applications are reviewed, and previous studies are listed and analysed.

Chapter 3 introduces the framework of the integrated approach methodology. Multi-level analysis of life cycle assessment (LCA), energy systems modelling (ESM), building stock modelling (BSM), economic modelling and heat pump diffusion modelling methods have been illustrated based on the links between the two approaches.

Chapter 4 describes the life cycle assessment methodology, goal and scope of the study, system boundary, inventory data and assumptions used in the study. The scenario analysis context has been described and the results are illustrated. Key conclusions are drawn at the end of this chapter.

Chapter 5 investigates the optimisation of heat pump operation with a thermal energy storage tank by energy systems modelling (ESM). Input data and model calculations are described to run a sensitivity analysis and scenario optimisation. The results are illustrated based on optimum heat pump operation under different tank sizes, electricity tariffs and backup heater settings. Key conclusions are drawn at the end of this chapter.

Chapter 6 introduces the integrated approach methodology. The housing stock condition of Orkney is analysed to create building stock modelling and the framework for archetype-based results. Environmental impacts and optimisation of heat pump operation results are expanded for different house archetypes in Orkney. Energy, environmental and cost-related savings are modelled for individual archetypes, and cumulative results for Orkney are calculated.

Chapter 7 concludes the study with the main results and key findings. Contribution to the knowledge is highlighted and the limitation of the study is explained.

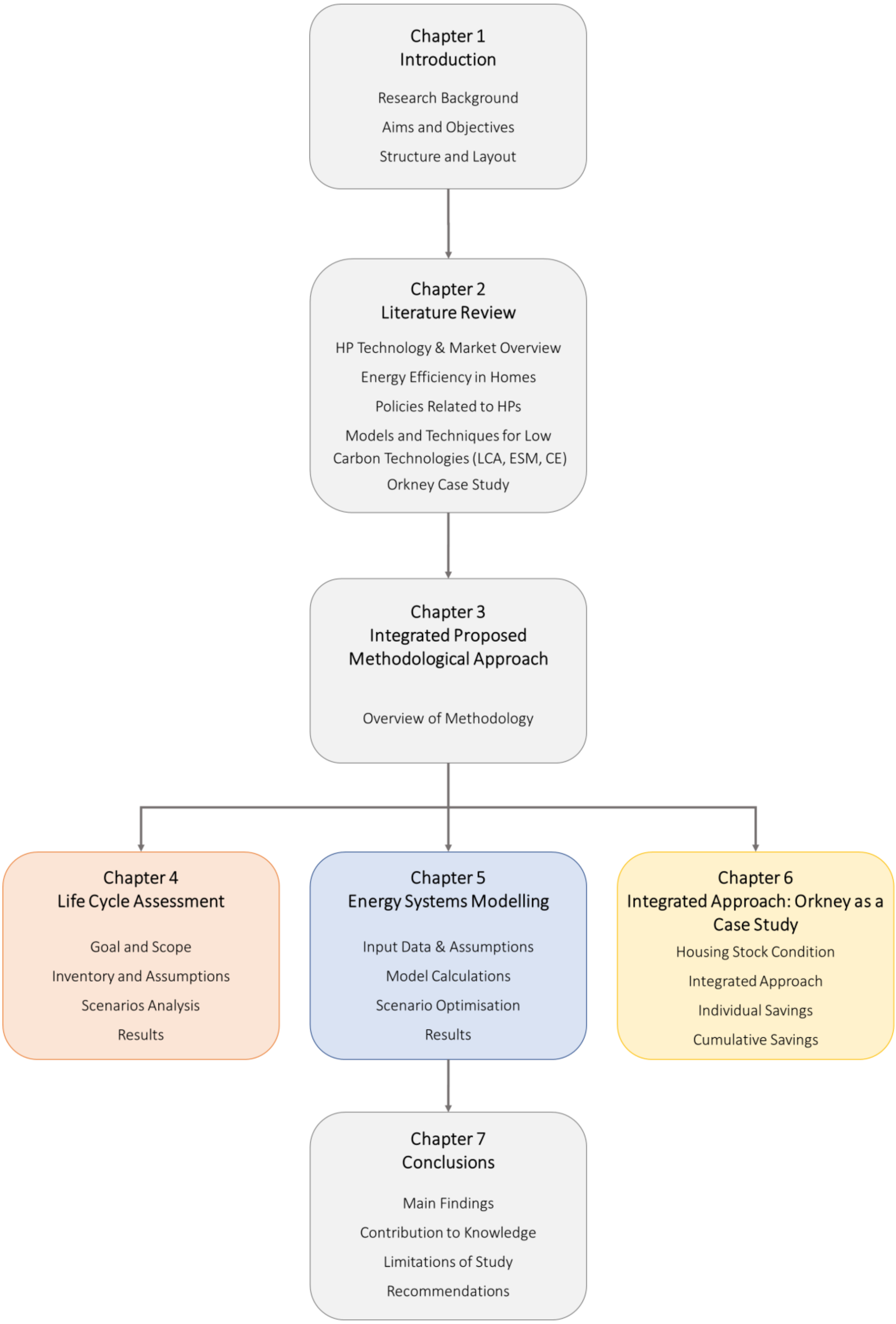

Figure 1.1 Thesis structure

Chapter 2

Literature Review

2.1. Heat Pump Technology

2.1.1. Overview

A heat pump extracts thermal energy or heat from an environment (air, ground, water) and delivers it to a heat distribution system. The second law of thermodynamics states that heat is transferred from a higher-temperature environment to the lower one. However, heat pumps reverse this cycle and transfer heat from a low-temperature environment to a higher one using some amount of energy (generally electricity but could be gas or waste heat) (Redko et al., 2020), (Marinchenko & Edelev, 2020). There are four main components in heat pumps (Figure 2.1):

- *Evaporator*: The energy taken from a low potential source is delivered to the evaporator with a pump, and the thermal energy is absorbed by the working fluid inside the evaporator. Low-pressure cooling agent refrigerant evaporates when it receives thermal energy.
- *Compressor*: The vaporised refrigerant is transferred to the compressor to increase its pressure. The compressor requires energy (generally electricity to run the motor) to increase the pressure of the refrigerant and consequently its temperature.
- *Condenser*: A condenser works similarly to an evaporator but in a reverse cycle. Hot and pressurised refrigerant is transferred to the condenser to release the heat energy to a colder heat carrier. As a result of the heat transfer, the refrigerant condenses while it is still pressurised.

- *Expansion* valve: The refrigerant is transferred to the expansion valve to reduce its high pressure and consequently the temperature. The temperature of the refrigerant should be lower than the heat source (air, ground, water) to continue the cycle.

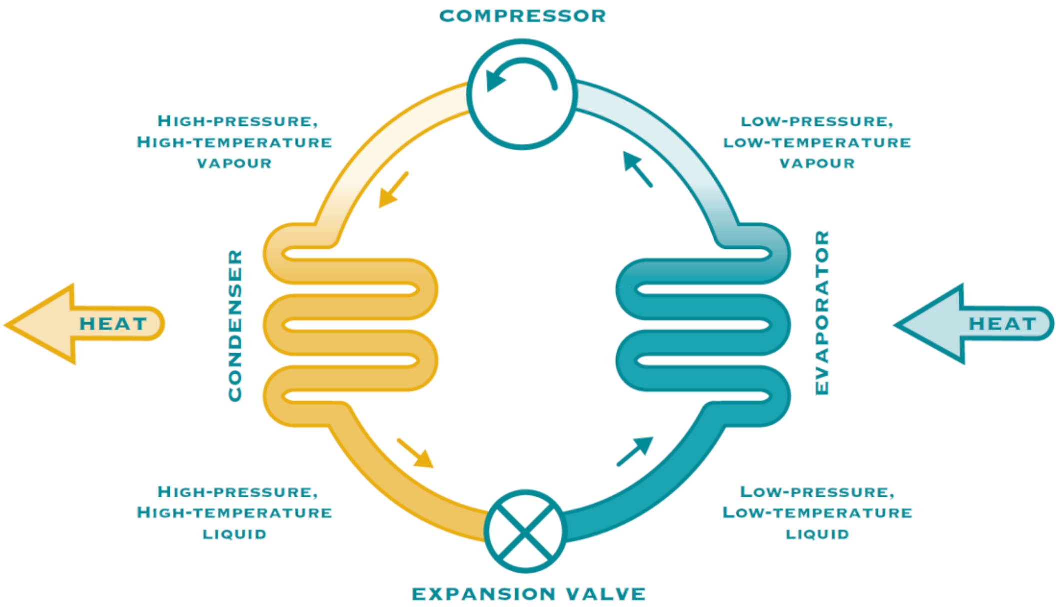

Figure 2.1 Simplified diagram of a heat pump system (Natural Resources Canada, 2002)

Heat pumps are specified based on where they get their heat source from (air, ground, water) and to which source they distribute the heat (air, water). Heat is extracted from the air in air source heat pumps (ASHP), from the ground in ground source heat pumps (GSHP) and from the water in water source heat pumps (WSHP) (Figure 2.2). The heat taken from air, ground and water could be distributed to air in air-to-air (ATA), ground-to-air (GTA) and water-to-air (WTA) systems or could be distributed to water in air-to-water (ATW), ground-to-water (GTW) and water-to-water (WTW) systems (BEIS, 2020c).

The efficiency of a heat pump is defined by the Coefficient of Performance (COP) by calculating the ratio of heating or cooling provided by the condenser to power supplied to the compressor. For instance, a COP of 3.0 means that when 1 unit of electricity is used the amount of transferred heating energy will be 3 units.

$$\mathrm{COP} = \frac{Q_{\mathrm{useful}}}{Q_{\mathrm{electric}}} \tag{2.1}$$

The COP measures efficiency in terms of power rather than energy consumption. Seasonal Coefficient of Performance (SCOP) provides the efficiency of a heat pump in terms of energy during a typical season. Climatic conditions and sink temperatures have an impact on SCOP values. Another metric defining heat pump efficiency is the Seasonal Performance Factor (SPF) which provides real data for heat pump efficiency. It is determined by a field trial in a specified building and climate and calculated by the ratio of annual heating output to electricity input (Etude, 2018).

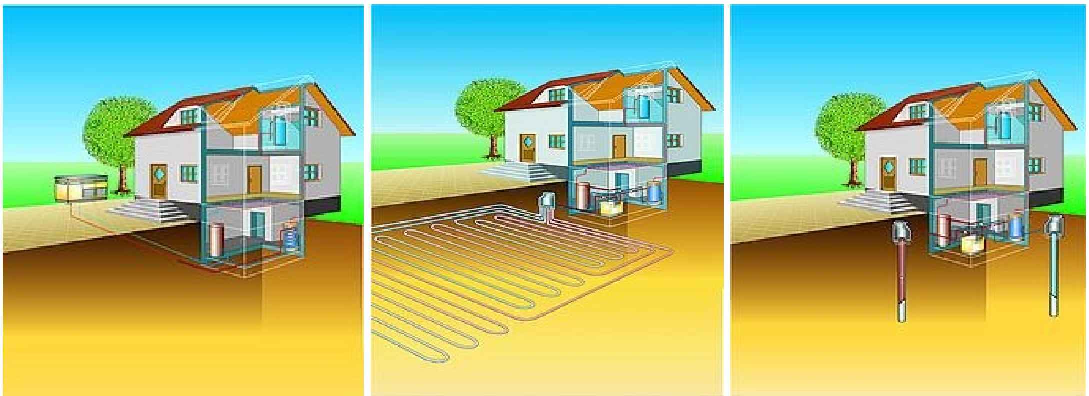

Figure 2.2 Simplified diagram of an air source heat pump (left), ground source heat pump (middle) and water source heat pump (right) (EHPA, 2021)

The efficiency of the heat pump depends on several factors such as refrigerant specifications, climate, heat distribution temperature and heat demand (Etude, 2018). Heat pumps perform better when the temperature difference between the heat source and heat distribution system does not exceed 35ºC (MCS, 2020). Underfloor heating systems become a suitable heat distribution system during low temperatures due to their larger surface area than other systems (radiators, etc.). It is also highly dependent on the heat pump capacity based on the variable heat demand. Heat pump units could either operate in a fixed speed schedule or variable speed controlling the speed of the compressor most of the time (Fischer & Madani, 2017). Variable-speed heat pumps could improve system efficiency by regulating electricity consumption and providing operational flexibility (Brunner et al., 2013). Therefore, the importance of optimising heat pump performance should be understood by designers, installers and end-users. This will create higher efficiencies in heat pump operation which will reduce energy consumption and heating costs.

Heat pumps could be installed as standalone or coupled with conventional heating systems (natural gas, LPG and oil). The hybrid application of heat pumps provides heat from the conventional system during low-temperature times in winter due to the lower efficiency of the heat pump and is controlled by a single controller. The heating schedule of hybrid heat pumps has a significant impact on demand. When a gas boiler is used twice a day during high demand times could reduce the annual emissions savings achieved by standalone heat pumps from 55% to 18%. However, this could also result in high peak demands because of the lower efficiency of the gas boiler. The ideal share of heating demand provided by the heat pump and gas boiler in a hybrid application would be between 70:30 and 85:15 (Element Energy, 2017).

2.1.2. Heat Pump Market Review

Buildings are responsible for 30% of the total emissions (454.8 $MtCO_2e$) in 2019 in the UK (BEIS, 2021b). The highest contributor to this emission in buildings is space heating which accounts for 23% of total emissions. The residential sector is dominating heating-related emissions with 17% of the total followed by the commercial (4%) and public (2%). Direct emissions from the domestic sector is reduced by 17% since 1990 according to Climate Change Committee figures in Sixth Carbon Budget (CCC, 2020). In order to achieve the Net Zero target by 2050 a 3.4% reduction rate per year is required.

The heat pump market has been growing gradually and accounted for 7% of the global building heating demand in 2020 (IEA, 2022). The European market has also seen a rapid increase with 1.8 million heat pumps sold in 2020. The total number of heat pumps reached 16.9 million in the EU which represents 14% of the heating market (EHPA, 2022b). The number of heat pumps sold in 2021 was around 537,000 in France, 380,000 in Italy and 178,000 in Germany (EHPA, 2022a). The numbers are relatively low in the UK with around 43,000 yearly sales in 2021 (Figure 2.3).

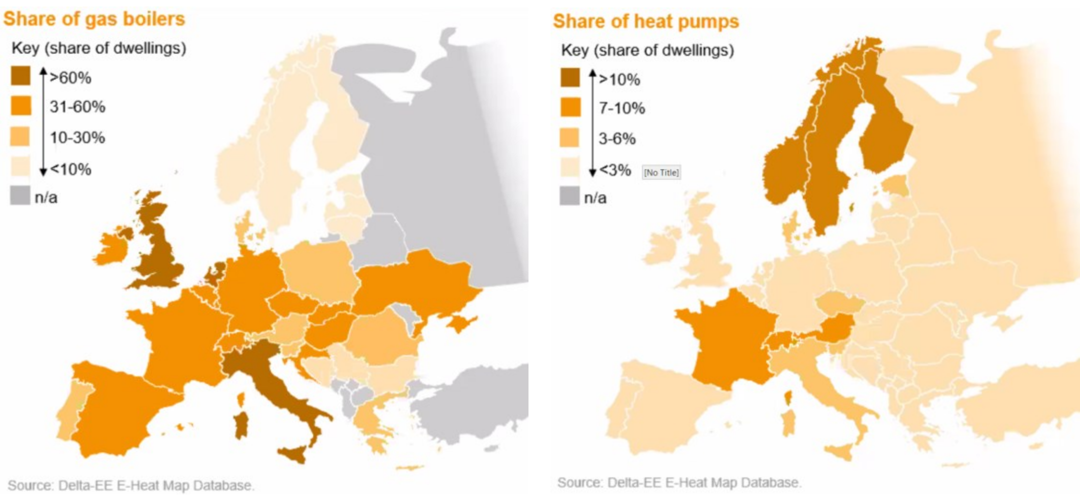

Figure 2.3 Share of gas boilers and heat pumps in dwellings in Europe (Delta-EE, 2022 as cited in EHPA, 2022c)

The total share of renewables in heating and cooling has been increasing during the last decade in the UK, however, it was still only 7.5% in 2019 and the UK is at the end of the list among the EU member states with the Netherlands (8.1%) and Ireland (6.3%) (EUROSTAT, 2022) (Figure 2.4). There are approximately 29 million homes in the UK, and around 85% of them are connected to the gas grid (CCC, 2019b). The remaining is using oil, liquid petroleum gas (LPG) or electricity as heating fuel. The UK government aims to phase out natural gas from new buildings by 2035. This is a step to reach 600,000 heat pump installations per year by 2028 to accelerate the decarbonisation of heating (BEIS, 2020a). According to CCC (2020), The number of heat pump sales should reach 1 million per year by 2030 to track the Net Zero pathway, and the total installations should reach 5.5 million of which 3.3 million are in existing buildings (Figure 2.5).

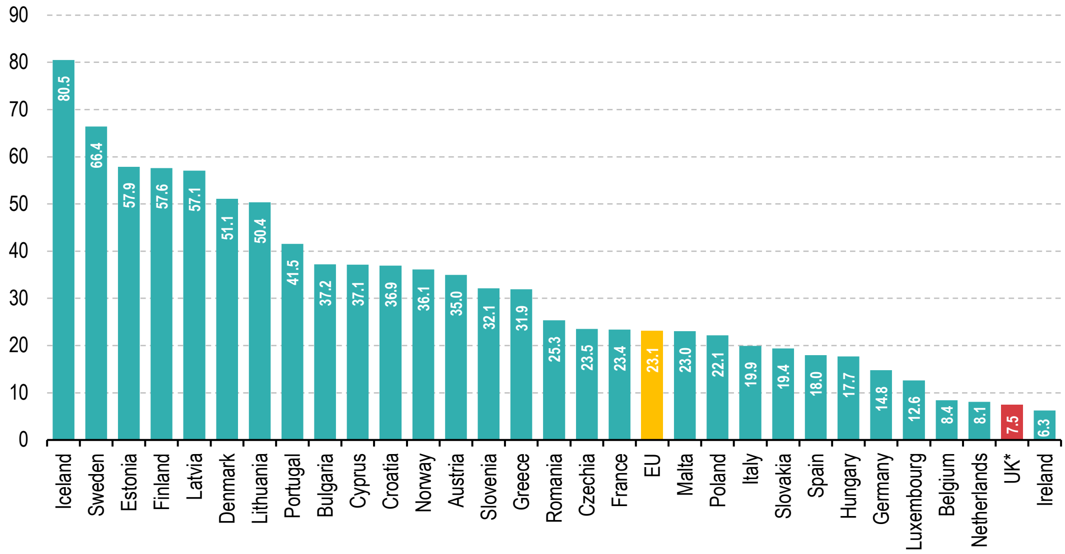

Figure 2.4 Share of renewables in heating and cooling activities in 2020 (Data source: EUROSTAT, 2022) * 2019 data is used for the UK.

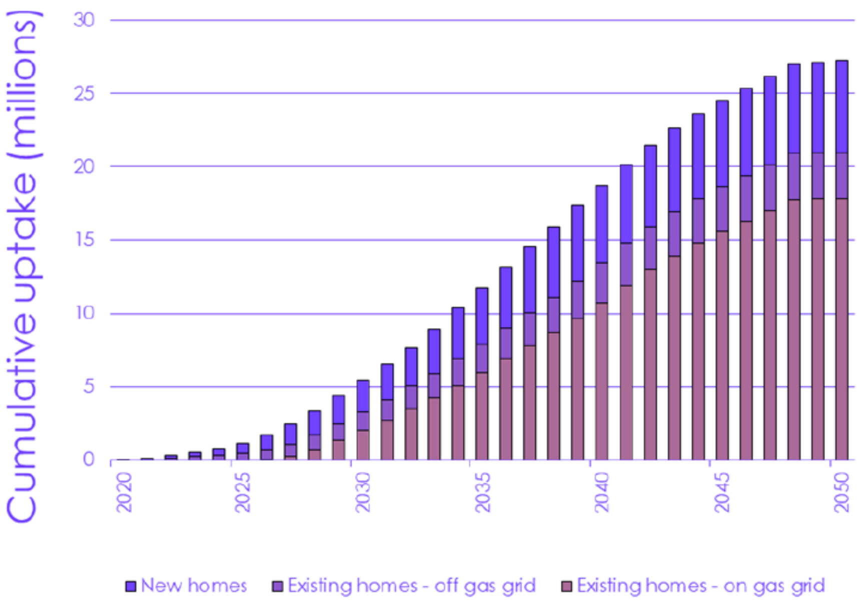

Figure 2.5 Heat pump uptake in residential buildings (CCC, 2020)

The dominant heat pump type sold in the UK is air source heat pumps (ASHP) with 87% of the total heat pump market. It is followed by ground source heat pumps (GSHP) and water source heat pumps (WSHP) with a total of 9% and hybrid systems (heat pump coupled with a fossil fuel boiler) with 4%. ASHP is preferred mainly in the retrofit market whereas GSHP is used in the new-build market. Nearly all heat pumps sold in the UK are hydronic heat pumps which distribute heat to water, so air-to-water (ATW) heat pumps dominate the UK market. ATW heat pumps could be classified as monobloc systems and split systems. Monobloc systems contain all the components in one single outdoor unit whereas split systems have both indoor and outdoor units. Therefore, the installation of split systems is more complex and requires professional expertise. On the other hand, split systems could also offer advantages such as lower noise problems. As split systems have two units, the condenser fan coils could be installed away from the building so the noise heard from the house could be reduced (BEIS, 2020c).

Low-temperature ATW monobloc heat pumps have 69% of the total market share in the UK in 2019. Even though the number of heat pump manufacturers is at least 33 in the UK, only three of them manufacture in the UK which accounts for 31% of the total UK sales. The remaining is imported mainly from Asia and Europe. In 2019, the highest number of air source heat pumps are imported from Sweden (344 units), South Korea (2754 units), Ireland (2600 units), China (2229 units), the Czech Republic (1904 units), Spain (1860 units) and Italy (1789 units) which accounts for 79% of the total imports (20981 units in total). A similar trend occurs in ground source heat pumps however only 1778 GSHP units are sold in the UK. 59% of these sales are imported from European countries and the remaining is manufactured in the UK. Moreover, manufacturers from Asia do not have any market share in GSHPs and only Japan has less than 1% market share in this heat pump type (BEIS, 2020c).

Heat pumps consist of several components as followed (Figure 2.6):

- Compressor: It accounts for 25% of the total heat pump value which is the largest value among other components. It is a specialised industry which has manufacturers in Europe, the USA and the UK.
- Controls: It is the other largest valued component among other units with 25% of the total value. The key manufacturers are located mainly in Italy and USA.
- Heat exchanger: It has a 15% share of the total heat pump cost. The key manufacturers are located in Sweden.
- Housing, valves, fan and pipework: They account for 30% of the total heat pump value. Manufacturing these components is less specialised so manufacturing locations are worldwide.
- Refrigerant: Manufacturing locations of refrigerant is worldwide, but several key players exist in the US and Asia.

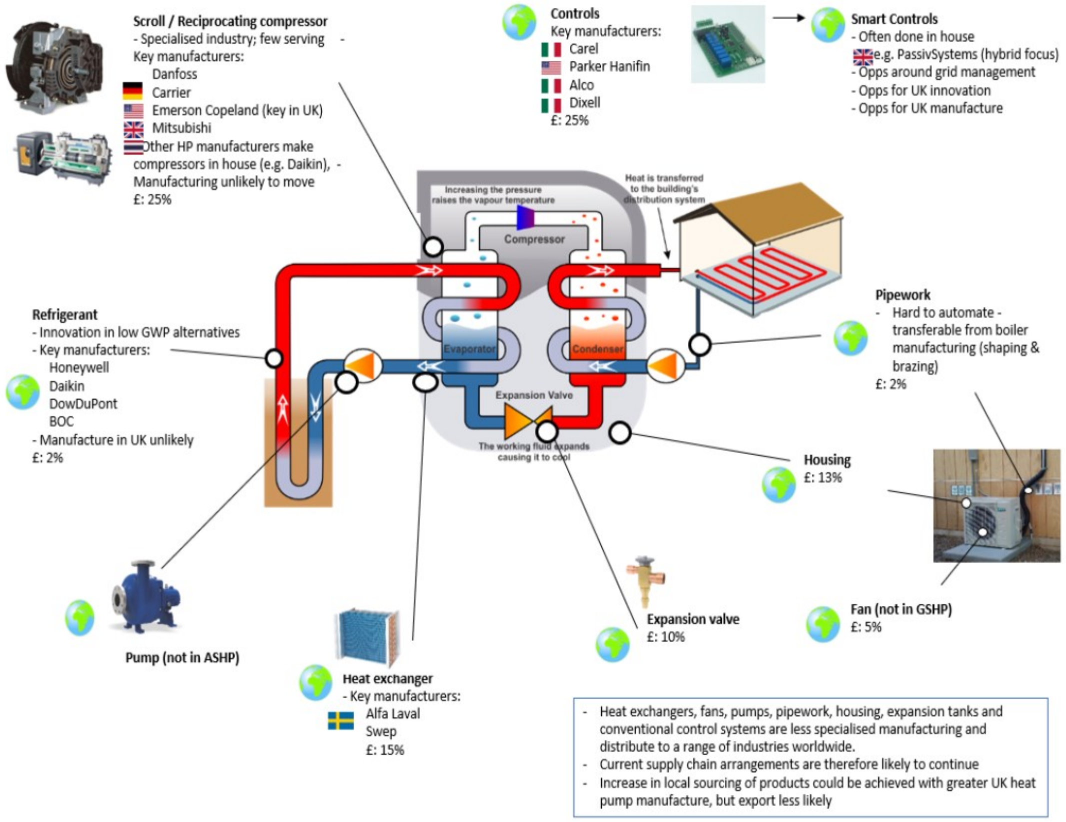

Figure 2.6 The components of heat pumps, proportions of their values and key manufacturers (BEIS, 2020c)

The dominant refrigerant type used in the UK market is R410A with nearly 75% of the total market share. It is followed by R134a and R32. The global warming potential (GWP) of R410A is 2088 which is higher than R134A (GWP 1300) and R32 (GWP 675). The use of R32 is increasing due to lower environmental impacts. Moreover, the market for carbon dioxide-based natural refrigerants (GWP 1) is increasing. It is possible to reach high efficiencies with lower GWP refrigerants without compensating the performance; however, they perform in low temperatures. Therefore, new buildings or highly improved existing houses could be suitable for natural refrigerants (BEIS, 2020c).

Heat pumps, gas boilers and air conditioners require similar raw materials during their production phases despite their technological differences. The UK has a well-established production line for the boiler and air conditioning industry; however, the majority of the heat pumps are imported from Asia and Europe. These manufacturers produce air conditioning systems with heat pumps in the same facilities; therefore, there is a potential for manufacturing heat pumps in the UK (BEIS, 2020c).

The current heat pump uptake figures do not provide sufficient heat pump demand for manufacturers to create a production line for heat pumps and their components. Additional markets supporting the heat pump manufacturers (heating, cooling, air conditioning) prevent changing the manufacturing location because of insufficient growth in heat pump figures. Therefore, the existing supply chain system will likely continue in the following short-medium term if heat pump uptake is not accelerated (BEIS, 2020c).

Heat pump manufacturers have other technologies in their portfolios (heating, cooling air conditioning) so these well-established production lines could be used for a faster transition. Existing assembly lines could be used for a quick shift which would be lower than a year. The existing boiler industry could be used by reshaping the production lines and re-skilling the workforce. Providing sufficient demand for manufacturing is key to stimulating investments in the UK heat pump manufacturing industry. In 2019, the UK heat pump market has provided 2000 full-time jobs to support heat pump installations. Engineering skills to support UK manufacturing is well established; however, more installers are required in high heat pump uptake scenario which creates added value to the UK economy. The number of people working in the boiler industry is around 6000 which stands as a potential workforce. Heat pump components are currently manufactured all around the world and have established specialised systems. Therefore, it is unlikely to see a shift in manufacturing locations in the medium-term projection (BEIS, 2020c). More emphasis should be given to;

- Training of installers,
- R&D for higher efficiencies,
- Develop UK-optimised heat pump solutions,
- Innovation in smart control systems,
- Modularity in heat pump components,
- Circular economy business models.

2.1.3. Heat Pumps Deployment Costs

Heat pumps are two to four times more efficient than gas boilers so accelerating heat pump uptake would help to reduce heating demand while shifting to electricity from natural gas. However, gas boilers are cheaper than heat pumps in terms of installation and running costs. Moreover, heat pumps may require upgrades in heat distribution systems and energy efficiency improvements which increases the upfront cost of heat pump uptake (Nesta & BIT, 2022a). A study conducted by the Regulatory Assistant Project (Rosenow, 2022) indicates that an efficient heat pump with a greater than 3.0-3.2 COP value is cheaper than a gas boiler in terms of heating costs (Figure 2.7). When heat pump efficiency drops below 3.0 COP they become a more expensive heating type, so proper installation to have higher efficiencies is significant.

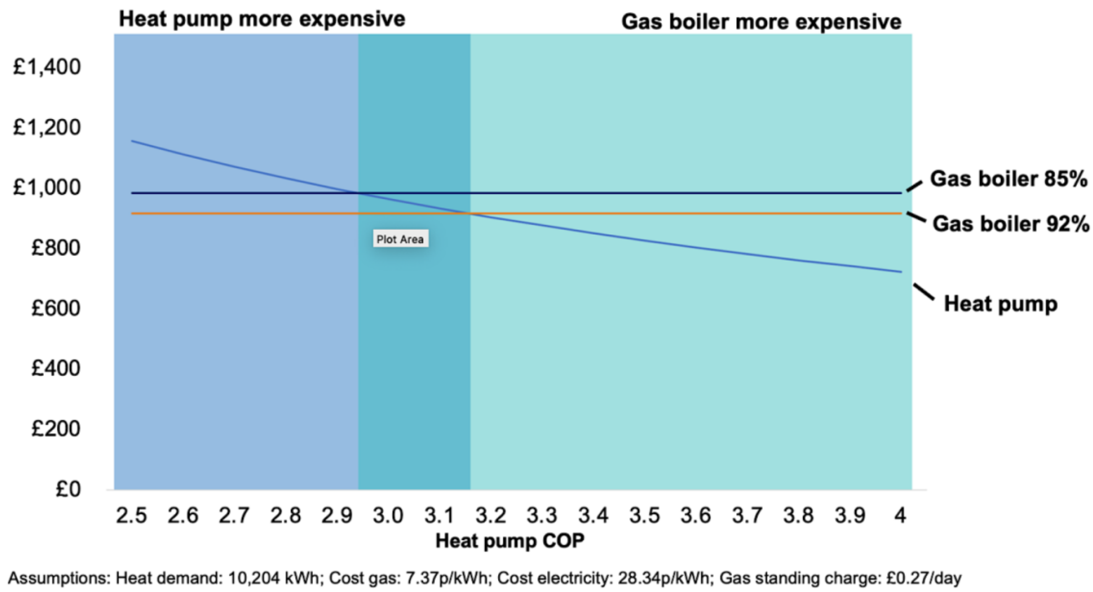

Figure 2.7 Heating cost of heat pumps and gas boilers by heat efficiency (Rosenow, 2022)

Nesta & BIT (2022b) conducted a survey with 1801 homeowners about consumers' perspectives on various heat pump prices compared to gas boilers. Results illustrate that only 25% of end-users are willing to pay the full cost of a heat pump when it is around £10,000-£12,000 which is £9000 more than an average boiler price. This price range represents the current heat pump installation cost, so only a quarter of people would choose the heat pump at the current price range. When the heat pump price is lowered to the £2000-£4000 price range the number of homeowners who are willing to pay the full cost increases to 44%. Even though in heat pump costs £1000 more than gas boilers in this scenario, less than half of the consumers only willing to choose this path. In the same survey, 71% of the consumers find installation costs high, and 63% find running costs high.

Awareness of heat pumps stands as another barrier according to the survey (Nesta & BIT, 2022b). 58% of the end-users find the installation of a heat pump difficult. Eight in ten people who attended the survey stated that they did not hear about heat pumps and five in ten understood the basic operation principle. Nearly five in ten stated that they are not convinced of the benefits of heat pumps to the environment.

The Behavioural Insight Team conducted an online survey with 8016 UK homeowners about incentives to increase heat pump uptake (Nesta & BIT, 2022c). They have investigated reducing the installation cost with government grants, financing options with interest-free loans, reducing installation time and reducing running costs. The results show that reducing the installation costs creates the highest increase in heat pump uptake by +10 percentage points (pp). It is followed by interest-free loans and lower running costs with +9 pp and +7 pp. Reducing installation time does not have any impact according to the study. When these incentives are combined the highest increase in heat pump uptake occurs in the low installation and running cost scenario with +30 pp followed by interest-free loan and low running cost scenario with +24 pp. This study suggests that reducing the upfront cost is the most important step from the homeowners' perspective. Lower running costs and providing financing options also have the potential to increase heat pump deployment.

Countries embrace fuel price increases differently based on their dependence on fossil fuels. France is the lowest affected country with around a 20% increase in gas and around a 3% increase in electricity because of its high nuclear share in the electricity mix (Figure 2.8). Italy and the Netherlands saw the highest increases in electricity prices with more than 100%. The UK has seen higher increases in gas prices with around 55% increase than electricity with around 25% which is similar to Germany and France. Given heat pump efficiencies, these changes are in favour of heat pumps in terms of the heating cost.

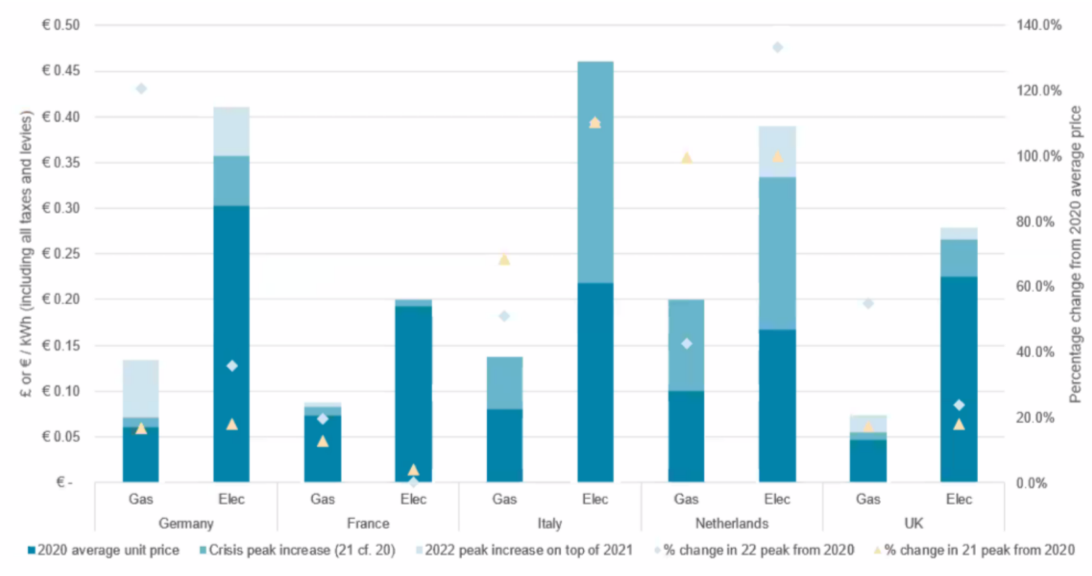

Figure 2.8 Fuel prices and percentage change by years in several European countries (Delta-EE, 2022 as cited in EHPA, 2022c)

2.2. Energy Efficiency in Houses

The UK government has published a new standard for houses, Future Homes Standard, aiming to reduce carbon emissions coming from new houses built after 2025 by around 75-80% than existing regulations. Option 1 (Future Homes Fabric) aims to provide 20% improvements on the current Part L standards based on a semi-detached home. This includes reducing heat loss through building fabric components (walls, windows, floor and roof). Option 2 (Fabric plus technology) aims to provide 31% improvements on the standard by minor efficiency improvements in building fabric and low carbon heating technologies and renewables (MHCLG, 2019).

The Net Zero pathway requires an investment of around £12 billion per year until 2050 with a total investment of £360 billion (CCC, 2020) (Figure 2.9). 70% of the total investment is required for upgrading residential homes, and 22% of this investment is expected for upgrading energy efficiency in homes in line with Government's estimate to achieve the EPC standard C. The total yearly investment is expected to increase until 2030 with high-efficiency improvements and low carbon heat uptake with a peak of £14 billion; however, it will reduce gradually to £8 billion for a period by 2035-2045 and £6 billion by 2050.

According to the Climate Change Committee (CCC, 2020), the uptake of energy efficiency measures in existing homes is expected to reach 77.3 million cumulative installations by 2050 (Figure 2.10). The highest contribution comes from behavioural measures including peak/off-peak time usage and multi-zonal heating controls with 28.3 million installations. Roof, wall and floor insulations also play an important role with 20.7 million installations in total.

A study conducted by Vásquez et al. (2016) analysed the housing stock condition of Germany and the Czech Republic with a dynamic Type-Cohort-Time stock-driven modelling. The study assesses the effects of the European energy reduction policies on different countries and boundary conditions by different renovation rates. Results show that the same policies on renovation create different energy reduction levels due to differences in house archetypes and developments; therefore, country-specific policies are required. This approach could also be applied to the sub-national level to separate older housing stock areas from highly insulated ones in the UK.

A study conducted by Meek (2021) analyses more than 2000 domestic heat pump installations from the Ofgem dataset and indicates that the average forecasted efficiency of 510 ASHPs is 3.25 whereas the actual efficiency is only 2.71. Gleeson and Lowe (Gleeson & Lowe, 2013) emphasized in their heat pump trial analysis that the highest efficiencies have been seen in new build installations in Denmark with optimum design parameters (weather compensated control, variable speed circulation pumping, minimal use of backup heaters, etc.). Moreover, Gleeson (2016) indicates that existing practices such as sub-contracting or piece-work payment could increase the performance gap. Another field trial done in the UK shows that heat pumps are sensitive to design and commissioning (Roy et al., 2010). The performance of heat pumps varies significantly from one installation to another. Many occupancies faced difficulties understanding the operation of heat pumps and instructions. Moreover, UK installations perform worse than European field trials mainly because of the UK's old and inefficient housing stock. It is commonly argued that heat pumps performed better in efficient houses as they use lower flow temperatures (Flower et al., 2020). Moreover, savings from energy reductions are maximised with heat pumps when the house is refurbished.

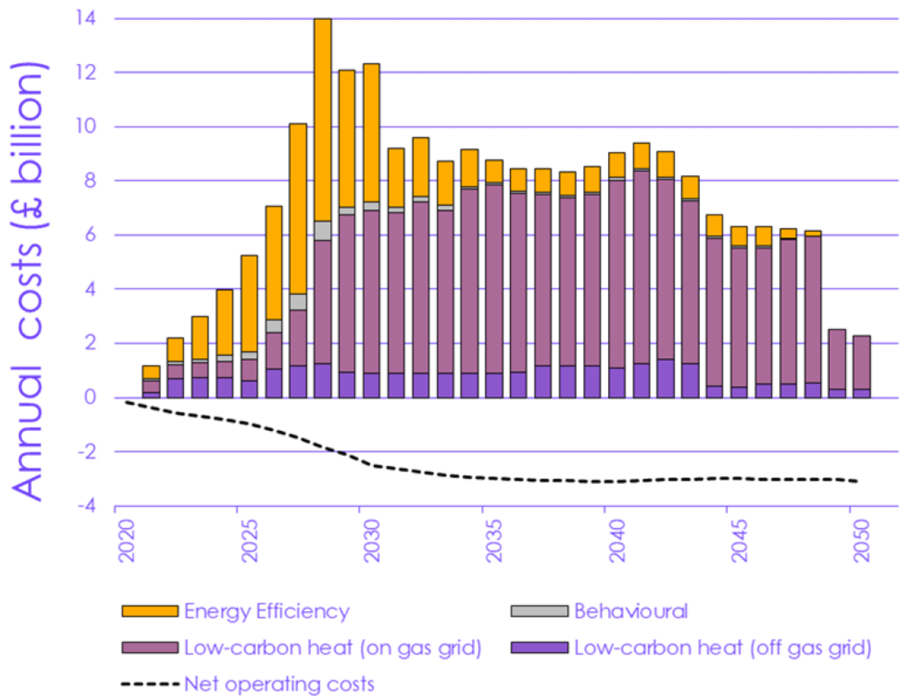

Figure 2.9 Household annual costs for existing homes (CCC, 2020)

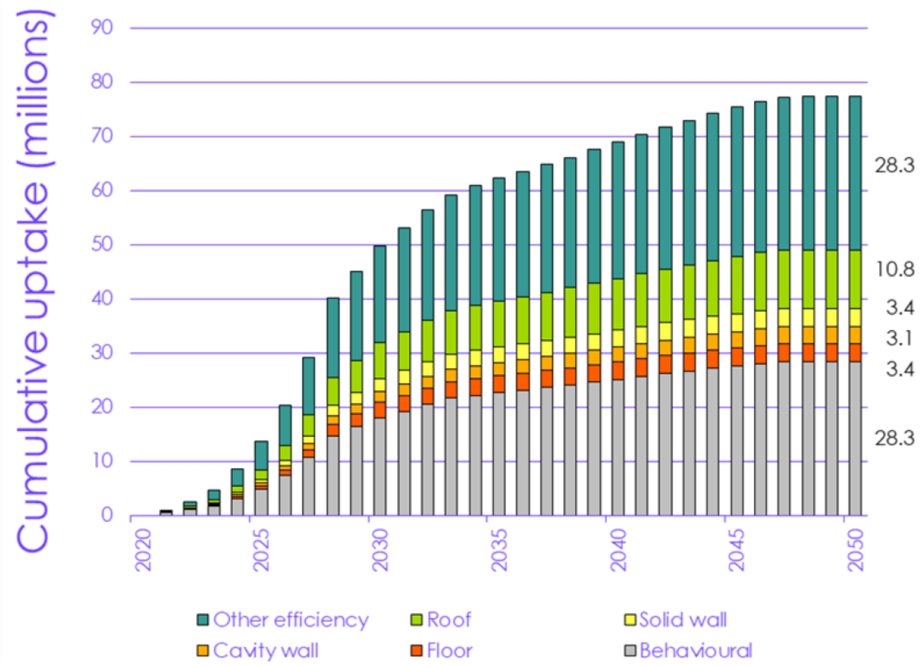

Figure 2.10 Energy efficiency measures deployment numbers in existing homes (CCC, 2020)

2.3. Demand Side Management (DSM)

Demand Side Management (DSM) is described as direct or indirect load management on the demand side of the meter (Gellings & Chamberlin, 1987). DSM aims to match the demand with optimised supply as a cheaper alternative. DSM has three main categories: energy efficiency, demand-side response and on-site backup (Warren, 2014). Energy efficiency aims to reduce energy demand through higher efficiencies and conservation of energy. Demand-side response, however, focuses on reducing peak time energy usage by shifting energy consumption. This could be achieved by price-based or incentive payment-based operations. On-site backup could be achieved by generation and storage such as hot water storage tanks used in houses.

2.3.1. Control Strategies

There are two types of control strategies to achieve flexible energy and building. Rule-based controls (RBC) rely on a parameter and a threshold value to switch on/off according to the condition. This parameter could be indoor temperature, and when the threshold is reached the heat pump will switch on/off. Model predictive control (MPC) relies on the optimisation of the model to identify the best solution for operation. This control could depend on several parameters within a specific time period (Péan et al., 2019). MPC outputs tend to exceed RBC outputs in terms of achieving the control goals; however, it requires more expertise and resources. RBC, on the other hand, can be designed simply without compromising better performance results. Therefore, the design of the control strategy is crucial for robust results(Le et al., 2020).

Rule-based controls (RBC) have several objectives;

- Load shifting with fixed schedules
- Peak shaving
- Reducing energy costs by energy price schedules
- Increasing usage of renewable sources in building scale

RBC could help to provide significant performances in terms of cost savings or energy flexibility in a simple manner without complex models; however, RBC also has several lacks in terms of poor dynamic interaction such as optimising the heat pump operation for a time period. MPC provides further improvements via optimisation but also requires more investments (Péan et al., 2019).

Model predictive controls (MPC) stand in several formats based on their goals such as Economic MPC. It aims to reduce costs by optimising operations relying on energy price differences. Other objective functions could also be used in MPC models aiming to reduce non-renewable energy consumption, reducing CO_2 intensity or peak shaving (Péan et al., 2019).

2.3.2. Thermal Energy Storage (TES)

Thermal energy storage (TES) systems, also called buffer storage tanks, are well-recognised DSM strategies to provide electricity load shifts from peak time to off-peak time (Arteconi et al., 2013). The principle behind a TES system is that the tank works as a battery, so energy is stored in the tank during off-peak times by charging the tank and then drawn during peak times by discharging. Different electricity prices in peak and off-peak times provide cost savings to consumers.

Previous studies investigated the required capacity of buffer tanks to provide a shift in demand. A recent study reviewing the integration of heat pumps with thermal energy storage indicates that building energy consumption could be reduced by 9% to 62% depending on size and applications. They could also help to reduce peak loads by 12% to 57% (Sultan et al., 2021). According to a study conducted by Kelly, Tuohy and Hawkes (Kelly et al., 2014a) indicates that 1000 L of hot water tank can provide optimised heat pump operation in only off-peak time periods. However, they have also seen a 60% increase in heat pump electricity demand which results in higher heating costs. Arteconi, Hewitt and Polonara (Arteconi et al., 2013) found that an 800 L buffer tank is required for a house using radiators; however, when the heat distribution system is changed to an underfloor heating system a smaller size buffer tank, 500 L, could sufficiently provide the required output. Water tanks provide great flexibility; however when standing losses are considered larger tank sizes create reductions in the system efficiency because of thermal losses (Péan et al., 2019). Kreuder and Spataru (2015) focused on the heat pump operation to reduce demand peaks and found that winter load peaks could be reduced from 6 GW to 2 GW. Another study presenting the results of a field trial indicates that electricity demand during the day has more evenly spread; however, overheating problems are mentioned by occupancies (Sweetnam et al., 2019). Long-term demand-shifting results have negative consequences on occupancies despite successful short-term demand-shifting results being seen during the day. There are also other barriers affecting buffer tank applicability. Higher tank sizes require higher storage volumes in the house; however, UK houses have very limited space. Moreover, most common electricity tariffs such as the Economy 7 tariff offers low electricity prices during the night when the outside temperatures are low; therefore, the efficiency of the heat pump reduces in this strategy.

2.4. Models and Techniques for Low Carbon Heating Technologies

2.4.1. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is an analytical tool to assess the environmental impacts of a product or process by analysing the entire life cycle (raw material acquisition, production, use and disposal phases). It aimed to reduce cost while improving performance; therefore, it has been widely used during the last couple of decades (Curran, 2013). In the 1970s, the first modern LCA study was conducted named as Resource and Environmental Profile Analysis (REPA) focusing on the energy supply by coal (Klöpffer & Grahl, 2014). Increasing waste problems and obstacles in energy supply have created the requirement for LCA analysis in environmental policies. LCA methodology is developed throughout the years and promoted by international journals focusing on LCA studies. ISO 14040 and 14044 standards are created for LCA methodology in the early 1990s (BSI, 2020; ISO, 2006a, 2006b)

The analysis has four stages:

- defining *goal and scope* to identify the purpose of the study,
- *life cycle inventory analysis* to collect data of the unit processes of products and analyse,
- *life cycle impact assessment* to evaluate environmental impacts,
- *interpretation* to evaluate results and compare them with potential solutions.

Life cycle assessment has several principles to create consistency between studies (Finkbeiner et al., 2006). These principles are summarised below:

- LCA focuses on the entire life cycle phases of a product including raw material extraction, manufacturing, use and disposal phases. This approach could help to identify the highest potential impact among life cycle phases.
- LCA mainly focus on environmental impacts, so economic and social aspects are outside the scope of the LCA. However, other methods and tools could be integrated with LCA for a more comprehensive approach.
- LCA has a functional unit which creates a relative approach. All inputs, outputs and results are related to that functional unit, so two LCA analyses of the same product could have different results because of their functional units.
- LCA stages use other phases' results, so the iterative approach improves the consistency of the results.
- LCA requires transparency for all steps due to overcoming the complexity of the analysis.
- LCA explores all impacts on the environment, human health and resources; therefore, trade-offs could be assessed with this comprehensive approach.

Defining the goal is the first step in explaining the objective and range of the study. The description of the functional unit and unit processes should be defined clearly so the entire product system could be analysed. This is a priority for a standard LCA study. Another important step is identifying the system boundary. When two studies focusing on the same product and topic may have different results due to the differences in methodology, data quality and system boundaries; therefore, the system boundary plays an important role in the accuracy of the results (Klöpffer & Grahl, 2014).

Life cycle inventory (LCI) analysis is the dominant phase which includes the compilation of inputs and outputs throughout the entire life cycle phases (ISO, 2006a). Materials and energy used in the processes, transportation and emissions into the air, soil and water should be identified in line with the system boundary. Several software packages exist to help organise flow charts such as Gabi, SimaPro, and Umberto (Klöpffer & Grahl, 2014). The results of SimaPro and Gabi are compared in a previous study, and it is identified that notable differences are seen despite similarities in many cases (Herrmann & Moltesen, 2015). Differences in impact assessment methods and databases are identified as the major reason for the differences (Heijungs & Guineév, 2012).

Life cycle impact assessment (LCIA) is the second major phase of life cycle assessment with LCI analysis. It includes the selection of impact categories, category indicators and characterisation models. Environmental problems and human health issues have created a common impact category list for different damage categories such as climate change, human toxicity, eutrophication, resource depletion, etc. (Klöpffer & Grahl, 2014), (Heijungs & Guineév, 2012).

The interpretation phase is the reporting stage where results of the inventory analysis and impact assessment categories are presented, and conclusions are drawn. The emphasis should be given to the impact categories relevant to the study's objectives. Comparative assessment of contributions from different phases or different products could be thoroughly analysed within the system boundary (Klöpffer & Grahl, 2014), (Heijungs & Guineév, 2012).

Life cycle assessment (LCA) studies are commonly used in the built environment. Environmental implications of buildings or low carbon technologies and their entire life cycle impacts are widely assessed. Hossain and Ng (2018) conducted a comprehensive review of 181 papers on the life cycle assessment of buildings and circular economy topics, and the results show that the majority of the LCA studies have a cradle-to-grave boundary with 45% followed by cradle-to-gate (22%) and cradle-to-site (13%). The most common inventory assessment methods were CML, IPCC, ReCiPe and TRACI. In terms of data usage, only 9% of the studies used first-hand data and 31% used second-hand data. Nearly 50% of the studies used adopted databases and 15% used combined data sources (first-hand, second-hand, and adopted databases). Adapting CE principles or extending the full life cycle of buildings is very rare among these studies.

Environmental implications of individual heat pumps or comparative analysis with conventional heating systems are widely discussed (Table 2.1). A recent study conducted by Marinelli *et al*. (2019) shows that GHG emissions coming from fossil fuel heating technologies stand as a barrier to achieving European targets and heat pumps provide sustainable solutions to this problem. The reviewed studies illustrate that air source heat pumps (ASHP) have higher environmental impacts than other heat pump types (ground source heat pumps and water source heat pumps) due to high energy requirements in the use phase. The major contributor to the entire life cycle of these products is the electricity consumption utilized in the use phase. On the other hand, refrigerants also play an important role to reduce emissions, so the emphasis is also given to the production phase of the refrigerants (Huang & Mauerhofer, 2016), (Chen et al., 2012). Nitkiewicz and Sekret (2014) compared an electric heat pump, absorption heat pump and gas boiler in their studies and the results illustrate that heat pumps have lower eco-indicator than gas boilers whereas they have higher damage to human health. Moreover, the absorption heat pump has lower environmental impacts than the electric heat pump overall. The performance of an electric heat pump is very relevant to its efficiency and electricity mix in Poland which is 90% from coal currently. Koroneos and Nanaki (2017) show in their studies that acidification is the major environmental impact with 73.5% during the entire life cycle of a GSHP. It is followed by the greenhouse effect (14.5%), eutrophication (9%) and other environmental burdens (3%). Higher oil and lignite share in the electricity mix in Greece and the manufacturing stage are the major phases dominating these emissions. A study conducted in Turkey illustrate that GSHP is an effective system in terms of energy consumption when compared with coal and gas boiler; however, environmental impacts are greater than conventional systems (Abusoglu & Sedeeq, 2013). The manufacturing phase and the use of refrigerant are responsible for these negative impacts. The environmental impacts of domestic heat pumps are assessed in a UK study and compared with gas boilers (Greening & Azapagic, 2012). The results show that ASHP has 82% higher overall impacts than the gas boiler and 73% higher impacts than GSHP and WSHP. However, heat pumps show lower results than gas boilers in several categories (global warming, fossil resource depletion and summer smog impacts). ASHP has higher environmental impacts than other heat pump types due to lower energy efficiencies. The use phase stands as the major contributor to the entire life cycle stage. A recent environmental amortization study indicates that energy savings from replacing electric heaters with an air source heat pump could compensate for the environmental impacts of the ASHP (Latorre-Biel et al., 2018). When underfloor heating is used for the heat distribution system environmental amortization is around 10 years whereas low-temperature radiators and conventional radiators may require 33% and 45% more time respectively. Lin *et al*. (2021) carried out a comparative assessment of hybrid heat pumps and condensing gas boilers, and the results show that hybrid heat pumps could reduce GHG emissions by 30%. Moreover, terrestrial acidification, photochemical oxidant formation, particulate matter formation and fossil depletion impact categories has 13% to 48% lower results for hybrid heat pumps. However, gas boiler has 3 to 6 times less emissions in human toxicity, water depletion and metal depletion categories.

Life cycle cost analysis of heat pump systems and economic indicators are also analysed in several LCA studies. A previous study conducted in Australia by Lu *et al*. (2017) indicates that air source heat pumps are financially more attractive than ground source heat pumps in a life span of 20 years. When the life span is increased to 40 years ground source heat pumps create more financial savings due to higher efficiencies. A comparative study of environmental impacts and economic implications of a heat pump, coal boiler and gas boiler shows that the heat pump creates the lowest environmental impacts among these technologies whereas the heating costs of the heat pump are higher than boilers when the COP is between 2.5-3.0 (Chen et al., 2012). Zhu, Tao and Rayegan (2012) found in their studies that the payback time of a ground source heat pump is 12-15 years without incentives. However, incentives (in this case 35% of the upfront cost) could reduce the payback time significantly (to 2 years). Another comparative assessment of a geothermal heat pump and LPG greenhouse heating system study conducted in Italy indicates that the estimated payback time for energy is around 1 year for the geothermal heat pump, and it increases to 2.25 years for carbon emissions (Russo et al., 2014).

All reviewed studies show that life cycle assessment study results vary based on the differences in the functional unit, the scope of the study and the system boundary. The results of comparative studies also show that conventional heating technologies have higher impacts on GHG emissions whereas heat pumps could have higher impacts in other categories. The use phase is generally the major contributor to the impact categories; therefore, differences in the electricity mixes in different countries create various results. Moreover, the efficiency of the heat pump also differs in these studies based on climate conditions and system design. Thus, every study represents a unique condition within its boundary.

GHG emissions can be measured in three different categories as territorial-based, consumption-based and production-based impacts (J. Barrett et al., 2013). According to Intergovernmental Panel on Climate Change (IPCC, 1996), territorial-based emissions indicate emissions occurred within national territories and exclude international transports such as international aviation and shipping. Countries are required to submit their territorial emissions annually. Consumption-based emissions, on the other hand, refer to the final consumption and exclude exports which are relevant for the territorial basis (J. Barrett et al., 2013). Production-based emissions are similar to consumption-based emissions, but exports are also included in this calculation (Peters, 2008).

Table 2.1 Studies adopting life cycle assessment (LCA) Methodology

Reference	**Method**	**Key findings**
Marinelli *et al*. (2019)	Life cycle assessment (LCA)	Heat pumps could help to achieve European targets due to low GHG emissions compared to fossil fuels.
Latorre-Biel *et al*. (2018)	Life cycle assessment (LCA)	Energy savings from replacing electric heaters with ASHP could compensate for the environmental impacts of the ASHP. The underfloor heating system has a lower payback time than radiators.
Lu *et al*. (2017)	Life cycle cost (LCC)	ASHP is financially more viable than GSHP when the life span is 20 years; however, GSHP creates more savings when the life span is increased to 40 years.
Koroneos and Nanaki (2017)	Life cycle assessment (LCA)	The proportion of the environmental impact of a GSHP during its life cycle is acidification (73.5%), greenhouse effect (14.5%), eutrophication (9%) and other impacts (3%).
Huang and Mauerhofer (2016)	Life cycle assessment (LCA)	GSHP has the potential to reduce energy consumption by 40%, and contribute to global warming, acidification, eutrophication and soil temperature change.
Russo *et al.* (2014)	Life cycle cost (LCC)	The estimated payback time for a geothermal heat pump is 1 year for energy and 2.25 years for carbon emissions.
Nitkiewicz and Sekret (2014)	Life cycle assessment (LCA)	Absorption and electric heat pumps have lower environmental impacts than gas boiler whereas gas boiler has lower damage to human health.
Abusoglu and Sedeeq (2013)	Life cycle assessment (LCA)	GSHP creates energy demand reductions whereas it has higher environmental impacts than coal and gas boilers due to the manufacturing phase emissions.
Chen, Zhang and Ma (2012)	Life cycle assessment (LCA)	When heat pump COP is between 2.5-3.0 it has better environmental performance than coal and gas boilers.
Greening and Azapagic (2012)	Life cycle assessment (LCA)	Gas boiler has lower environmental impacts than heat pumps in all categories except the global warming, fossil resource depletion and summer smog categories. ASHP has higher impacts than GSHP and WSHP.
Chen, Zhang and Ma (2012)	Life cycle cost (LCC)	When the heat pump COP is between 2.5-3.0 the heating cost of the heat pump is greater than the coal and gas boiler.
Zhu, Tao and Rayegan (2012)	Life cycle cost (LCC)	Incentives could help to reduce payback time significantly from 12-15 years to 2 years.

2.4.2. Energy System Modelling (ESM)

The oil crisis in the 1970s created a need for energy system models to create stability in the energy system. When the importance of climate change was realised the models focused on the environmental perspective. Changes in the energy system (penetration of renewable sources) have created variable generation and cost implications which should be reflected in the modelling. Sectoral demand (domestic, industrial, commercial, public, transport, etc.) and energy supply balance with social and economic aspects are covered within various models during the following years (Hall & Buckley, 2016).

Energy systems modelling has various analytical approaches, methodologies and mathematical techniques. The commonly used concepts are explained below (Hall & Buckley, 2016), (Hourcade & Robinson, 1996):

- *Top-down approach:* This approach focusses on macro-economic metrics to analyse economy-wide responses. Individual sectoral demand and energy could be divided into limited categories to investigate income distribution effects.
- *Bottom-up approach:* This approach focusses on the end-user side of the system with the deployment of technologies. Cost, performance, and emissions data is used to reduce the efficiency gap between existing system and potential technologies.
- *Hybrid approach:* Top-down and bottom-up models could be connected with a soft-link (using existing models) or hard-link (integrating the features of two models).
- *Econometric method:* This method uses the previous dataset to calculate future outcomes by using statistical techniques.
- *Macro-economic method:* This method uses energy as a whole system; therefore, it requires expertise.
- *Economic equilibrium method:* This method also focusses on the entire system whereas the emphasis is given to the connection between economic sectors.
- *Optimisation models:* Mathematical optimisation is used in these models by identifying an objective function to minimise cost, demand, or emissions.
- *Simulation models:* These models simulate the uptake of technologies and consumer behaviours by a logical representation.
- Multi-criteria models: These models evaluate a set of measures by decision analysis.
- *Accounting models:* These models describe the performance of an energy system in terms of resource, environment, social and cost-related decisions.

Various energy system models have been developed and widely used (Table 2.2). Several of the models and their purposes are reviewed. MARKAL is a linear-programming model introduced in 1981 (Fishbone & Abilock, 1981). The model explores the national energy system with energy supply technologies (possible renewable) through cost optimisation. It covers all sectors and calculates medium- and long-term results. Department of Energy & Climate Change (DECC- It became part of BEIS in 2016) has developed a policy tool (DECC 2050 Pathways Calculator) for the UK to calculate energy supply based on UK's environmental emission targets (HM Government, 2010). Medium- and long-term results are calculated in 5-year time steps. The Dynamic System Investment Model (DSIM) is developed by Strbac, Aunedi and Pudjianto (2012) to explore energy demand and supply coupled with storage and variable generation. The model could calculate hourly or yearly results with long-term investment decisions. The Energy System Modelling Environment (ESME) model was developed by the Energy Technologies Institute (ETI) in 2007 to accelerate low carbon heating technologies in the UK (Heaton, 2014). It is structured as a cost optimisation model to meet UK's 2050 targets while maintaining the energy structure. Yearly fluctuations and long-terms results could be calculated in the model. Spataru and Barret (2015) introduced a dynamic energy agents model (DEAM) to calculate demand and supply for sectors and provide hourly loads to the electricity system. The model is relying on weather conditions, occupancy patterns, heating and renewables so electricity, heat and gas demands could be calculated. Another model introduced by Barret and Spataru (2015) is DynEMo which is a dynamic energy model. The model investigates energy demands for sectors based on different time and weather conditions and the scenarios to meet this demand with renewable energy sources by simplifying individual technologies. Short-, medium- and long-term results could be calculated with daily, weekly, and seasonal time resolution. EnergyPLAN is a tool introduced by Lund *et al.* (2021) to explore sustainable energy technologies focusing on sectors on the demand side and supply through electricity, gas and heating. Yearly results could be provided with hourly time steps.

Energy systems models previously mentioned above have been used to investigate sectoral trajectories in terms of energy demand and supply side of the system. Low carbon technologies, specifically heat pumps, are also assessed through energy system modelling to explore demand side management through thermal energy storage tanks.

Coupling an air source heat pump with a thermal energy storage tank has been investigated to explore the optimum size of the heat pump and buffer tank and their impact on electricity loads (Marini et al., 2019). The model provides optimum heat pump sizes under different tank sizes for five different houses and four different scenarios. Another study investigating thermal energy storage and heat pump operation in a nearly zero energy building shows that an 800 L tank size sufficiently provides demand flexibility (Bechtel et al., 2020). However, financial results of the demand side management indicate that this is not a viable option for consumers due to high investment cost which is not compensated by electricity costs. This is mainly due to the lack of incentives in Luxembourg. Kelly Tuohy and Hawkes (2014b) investigated the time-shift performance of an air source heat pump coupled with a buffer tank with a building simulation model in a detached house in the UK. The results illustrate that 1000 L of a buffer tank is required to shift peak-time loads to the off-peak time period sufficiently. This has created a demand flexibility for the energy system; however, it has also increased electricity consumption by 60%. Moreover, heating costs and CO_2 emissions were also increased due to higher demands. Another energy simulation model investigating the role of thermal energy storage systems with heat pumps indicates that 500 L of thermal energy storage tank could store enough energy to create a 3-hour shift in electricity loads with an underfloor heating system (with 30-40 °C flow temperature range) (Arteconi et al., 2013). When the heat distribution system is changed to radiators (with a 45-55 °C flow temperature range) the tank size should be increased to 800 L to supply heating demand.

Table 2.2 Models and studies adopting the energy system modelling (ESM) approach

Reference	**Method**	**Key findings**
Lund *et al*. (2021)	EnergyPLAN	EnergyPLAN focuses on sustainable energy technologies through sectoral demand and supply by electricity, gas and heating.
Bechtel *et al*. (2020)	Energy Systems Model (ESM)	The model calculates the required buffer tank size as 800 L to provide demand flexibility; however, it is a costly measure due to high installation and heating costs.
Marini, Buswell and Hopfe (2019)	Energy Systems Model (ESM)	The optimisation model provided the required heat pump sizes for different thermal energy storage tank usages.
Spataru and Barret (2015)	DEAM	The dynamic energy agents model (DEAM) calculates demand and supply for sectors and provides hourly loads
Barret and Spataru (2015)	DynEMo	The dynamic energy model (DynEMo) calculates time and climate-varying energy demand for sectors and supply with renewables.
Heaton (2014)	ESME	ESME model is classified as a cost optimisation model for UK's 2050 targets.
Kelly Tuohy and Hawkes (2014b)	Energy Systems Model (ESM)	The required tank size is calculated as 1000 L with a building simulation model. However, the buffer tank also increases energy consumption by 60%
Arteconi, Hewitt and Polonara (2013)	Energy Systems Model (ESM)	The size of the buffer tank varies (500 L or 800 L) based on the heat distribution system. When low-temperature water flow is coupled with underfloor heating lower tank size (500 L) could provide the required outcome.
Strbac, Aunedi and Pudjianto (2012)	DSIM	The dynamic system investment model (DSIM) explores energy demand and supply to model storage and short-term decisions with investment plans.
HM Government (2010)	DECC 2050 Pathway Calculator	DECC 2050 Pathways Calculator investigates energy supply and policies to meet UK's environmental emission targets.
Fishbone and Abilock (1981)	MARKAL	A linear-programming model to explore the national energy system with energy supply through cost optimisation.

2.4.3. Integrated Approaches

Life cycle assessment (LCA) and energy systems modelling (ESM) methodologies are widely used individually (Table 2.3). ESM has been extended to other resources and could also be extended to CE research. Studies about ESM and LCA suggest different frameworks, however, they share a common interest in CE principles. The integrated application of these methods has also been investigated in the literature previously to provide a comprehensive approach (Astudillo et al., 2018).

A very recent small-scale case study is examined by Quest *et al*. (2022) by integrating life cycle assessment with energy system modelling. The operation of different heating and power systems is optimised with the energy model and their environmental impacts are evaluated with LCA. The optimisation scenario offered a shift from the gas boiler to CHPs, heat pumps and PV systems. The results show that a nearly 40% reduction in GHG emissions is expected in the cost-optimised scenario and more than 50% reduction in the CO_2-optimised scenario. However, eco-toxicity results also expect a 22% increase due to oversized battery storage. Hybrid applications of solar technologies with heating and cooling systems are investigated in a recent study (Wang et al., 2021). A multi-objective optimisation model is coupled with the life cycle assessment methodology to assess the solar-assisted natural gas combined cooling, heating and power (CCHP) system. The results show that solar collectors help to reduce acidification impact by 6.7% and respiratory effect by 28.4%. Blanco *et al*. (2020) evaluated the environmental emissions of the energy sector by integrating the JRC-EU-TIMES model with life cycle assessment. The scenarios investigated future emissions of the EU's 80-95% CO_2 reduction targets. The results show that overall impact results decreased by 20-40% with strict policy implementation whereas toxicity impacts increase by 35-100%. Volkart, Mutel and Panos (2018) conducted a study to assess the transition from fossil fuels to renewables in the energy system by integrating energy systems modelling with life cycle assessment. The partial equilibrium model provided the pathways between energy systems, and sustainability insights are created by life cycle assessment. The results show that coal, oil and biomass technologies create hotspots in the environment and human health. Mining, heat and power generation, transportation and cultivation industries are the major contributors to these hotspots; however, these impacts are expected to reduce by 2060 with more renewable penetration and a reduction in energy intensity. The environmental impacts of electricity production technologies in Spain are investigated by Garcia-Gusano, Garrain and Dufor (2017). The TIMES model is used to create future scenarios and LCA provided environmental impacts based on these scenarios. The results show that the 80% reduction scenario has higher environmental impacts than the BaU scenario due to the higher deployment of renewables. Metal requirements for solar PV and wind turbines create ozone depletion and acidification problems. However, damage to human health and ecosystems is reduced by phasing out fossil fuels.

Volkart *et al.* (2017) created an integrated approach of a multi-criteria sustainability analysis with an energy system model to evaluate climate protection scenarios in Switzerland. The results indicate that a reduction in fossil fuels could be achieved with strong policy actions. Carbon Capture and Storage (CCS) could help to achieve policy targets as lower costs whereas fossil-fuel-based energy systems will remain. The emissions from low carbon power systems are analysed in a previous study by combining energy systems modelling and life cycle assessment (Pehl et al., 2017). A climate protection scenario compares the emissions of fossil fuels with carbon capture storage (CCS) against nuclear, wind and solar power for 2050. The results show that low carbon sources (wind, solar and nuclear) create the lowest residual sector emissions. Overall emissions in the global power sector show modest increases with decarbonisation. UK's 2050 emission targets are assessed with the integration of the TIMES model and environmental input-output model in a previous study (Scott et al., 2016). Future energy scenarios are created based on UK's policy and climate objectives, and the results show that embodied emissions coming from a new low carbon energy system is lower than emissions from low carbon energy sources; however, some of these emissions occur outside of the UK. Therefore, it is not counted in UK's territorial emissions. Hertwich *et al.* (2015) investigated the environmental impacts of large-scale climate-mitigation technologies (PV, solar thermal, wind, hydropower) by integrating life cycle assessment with IEA's BLUE Map scenario. The baseline scenario results show significant increases in emissions whereas the BLUE Map scenario offers lower emission levels despite doubling the electricity supply. Pietrapertosa *et al.* (2009) created a framework for the integration of LCA, ExternE (Externalities of Energy) and comprehensive analysis (a bottom-up model) to investigate energy systems. This approach creates a case study in Italy to investigate the environmental impacts of sustainable strategies adopted in energy systems. The results show that renewable technologies are crucial for future energy supply systems; however, more focus should be given to the manufacturing and disposal phases of these technologies.

Table 2.3 Studies adopting an integrated approach of energy systems modelling (ESM) and life cycle assessment (LCA)

Reference	**Method**	**Key findings**
Quest *et al.* (2022)	ESM + LCA	Optimisation of replacing a gas boiler with low carbon technologies (heat pumps, CHPs and PVs) is evaluated with a life cycle assessment approach
Wang *et al.* (2021)	MOO + LCA	Environmental impacts of solar technologies on natural gas combined cooling, heating and power (CCHP) system are evaluated with a multi-objective optimisation (MOO) model
Blanco *et al.* (2020)	JRC-EU-TIMES + LCA	EU's future energy system is analysed by integrating energy system modelling and life cycle assessment methodology
Volkart, Mutel and Panos (2018)	Partial equilibrium model + LCA	The partial equilibrium model provides the pathways between energy systems and sustainability insights are created by life cycle assessment
Pehl *et al.* (2017)	Equilibrium model + LCA	Future scenarios are created by the inter-temporal equilibrium model and emissions are analysed with life cycle assessment methodology
Garcia-Gusano, Garrain and Dufor (2017)	TIMES + LCA	The energy model provided future scenarios for the energy system and LCA investigated the environmental implications of these targets.
Volkart *et al.* (2017)	MARKAL + MCDA	Climate protection scenarios are modelled with the Swiss MARKAL model and environmental impacts are evaluated with multi-criteria decision analysis
Scott *et al.* (2016)	TIMES + EIO	Future energy scenarios are created by the energy model and emissions are calculated with the environmental input-output model.
Hertwich *et al.* (2015)	ESM + LCA	IES's BLUE Map scenario is integrated with life cycle assessment methodology to evaluate the impacts of renewable electricity generation sources
Pietrapertosa *et al.* (2009)	Comprehensive analysis + ExternE + LCA	The integrated approach investigates the environmental impacts of sustainable strategies adopted in energy systems.

2.5. Overview of Targets, Policies and Regulations

During the last three decades, the UK has achieved the highest reductions in per-capita CO_2 emissions among the major high-income economies (Our World in Data, 2021). This has mainly been delivered by the decarbonisation of electricity. The UK is the first major economy set a target of achieving Net Zero carbon emissions by 2050; however, it is not possible to reach this target without decarbonising residential heating.

The Clean Growth Strategy is published in 2017 aiming to accelerate clean growth with low carbon technologies, energy efficiency improvements, decarbonising energy and low carbon transportation (BEIS, 2017). It addressed the challenges of decarbonising heating and set out actions such as the Renewable Heat Incentive to support low carbon heating technologies. The main proposals for the strategy aim to reduce UK emissions through energy efficiency in industry and housing, low carbon transportation, clean power generation and enhancing natural resources which account for 38%, 24%, 21% and 15% of UK emissions respectively. Energy efficiency through low carbon heating is one of the key policies required to improve the standards of 1.2 million new boilers installed each year in England including the installations of control devices to save energy (BEIS, 2017).

New residential applications are the majority of the heat pump market which was around 10,500 units per year. However, this represents a small proportion when it is compared with the number of new residential units completed which is around 175,000 per year approximately (Etude, 2018). According to the Climate Change Committee, at least 2.5 million heat pumps need to be deployed by 2030 to continue further progress of decarbonisation (CCC, 2018). This figure has been updated to 1 million heat pump installations per year by 2030 to track the Net Zero pathway, and the total heat pumps installed in homes should reach 5.5 million of which 3.3 million are in existing buildings by 2030 (CCC, 2020). The UK government also set a target aiming to reach 600,000 heat pump installations per year by 2028 to accelerate heat pump uptake (BEIS, 2020a). Moreover, the use of natural gas will be banned from new buildings after 2035.

Domestic Renewable Heat Incentive (RHI) is introduced in 2014 and supported consumers who installed a renewable heating system by providing an upfront payment and quarterly incentives over seven years. The upfront payment was £1,700 for an air source heat pump and £3,500 for a ground source heat pump. Annual incentives are calculated based on potential heating and hot water details on the EPC of the property. According to Ofgem (2022), 65,000 domestic heat pumps have been deployed in seven years. This is very low when compared with other European countries. The number of heat pumps sold in 2020 was around 400,000 in France only (EHPA, 2022a). In line with UK's further decarbonisation plan (80% reduction in GHG emissions is increased to the Net Zero target) domestic RHI has been replaced recently with Boiler Upgrade Scheme (BUS) (BEIS, 2022a). This grant provides support to homeowners living in England and Wales who replaces their conventional heating system with a low carbon heating system such as a heat pump. The amount of support is an upfront payment of £5000 for an air source heat pump and £6000 for a ground source heat pump. The Scottish government also introduced a slightly higher subsidy named Home Energy Scotland loan (HES, 2022). This grant provides a cashback of up to £7500 and an interest-free loan of up to £2500 (in total £10,000) for heat pumps.

The Heat Pump Ready Programme is introduced by BEIS to support the development of heat pumps by creating a collaboration between individuals and the industry (BEIS, 2021e). It is funded by Net Zero Innovation Portfolio (NZIP) aiming to support low carbon technologies with a £1 billion fund. The amount allocated for the Heat Pump Ready Programme is around £60 million.

There are currently 1100 qualified heat pump installing companies in the UK based on Microgeneration Certification Scheme (MCS) database (BEIS, 2021d). Heat Pump Association (HPA, 2020) suggest that the number of heat pump installers needs to reach at least 12,400 by 2025 and 50,200 by 2030 in line with 300,000 heat pump installations per year by 2025 and 1 million by 2030. Moreover, 130,000 people are required to have retrofit job skills as installers, assessors and co-ordinators to close the gap in the energy efficiency market (BEIS, 2021d).

The UK heat pump market has similarities with the Netherlands due to similar climate conditions and high dependence on natural gas for heating (Table 2.4). The share of natural gas in heating is 83% in the Netherlands and 78% in the UK. However, the number of heat pump sales in the Netherlands was five-time greater due to key policies supporting the growth. Annual heat pump sales per 1000 households are around 8.4 and 1.5 respectively. The success of the Dutch market is due to successful policy mechanisms promoting heat pump sales. Increasing the levy on gas and reducing on electricity creates a more attractive heat pump market in terms of heating costs. Moreover, subsidies for low carbon heating technologies have been providing 20-40% of investment costs since 2008 (Table 2.5).

France, Germany and Scandinavian countries are also comparable markets with higher heat pump uptake values compared to the UK; however, different climate conditions and reliance on fossil fuels require more assessment to implement successful policy achievements (BEIS, 2020c). The highest heat pump sales per household occur in Norway with 49.6 due to the high electricity share in heating (85%). Policies supporting low carbon heating technologies such as subsidies for heat pumps and banning oil boilers from new-builds since 2000 and from existing houses from 2020 created this shift.

On the other hand, Sweden has supported district heating and the share of district heating in the total heating mix is 50%. The carbon tax on fossil fuels for heating has been introduced as €110/tCO_2e in 2020; therefore, higher gas prices compared to electricity have created a shift towards heat pumps.

France and Germany have high cumulative heat pump sales numbers (537,000 in France and 178,000 in Germany); however, the number of heat pumps per 1000 households is relatively low when compared with Scandinavian countries. France has set a 38% renewable target for heating by 2030. They have created a support scheme providing tax credits of up to 30% of investment costs for energy efficiency and renewable energy technologies (up to €8,000 for each). Subsidies supporting renewable heating technologies and interest-free loans have created a rapid development in the heat pump market. Carbon tax on fossil fuels (€45/tCO_2e in 2020) also increased gas prices.

Germany has set a target of 50% climate-neutral heating by 2030. In order to achieve this target renewable technologies are supported. Renewable Energies Heat Act requires a 14% renewable share in heating and cooling in new buildings. Moreover, standalone oil boilers are expected to be phased out from 2026. The national emissions trading system has identified a carbon price for fossil fuels in 2021 as €25/tCO_2e, and it will be increased to €55/tCO_2e in 2025. On the other hand, Market Investment Programme provides incentives for oil boiler replacements which is around 35-50% of total investment costs.

Table 2.4 Heating characteristics of countries (Data sources: EHPA, 2022a; Vivid Economics & Imperial College, 2017)

Countries	**Heating share in total energy consump.**	**CO_2 emission share in total energy emissions**	**Heating Fuel Mix**					**Annual HP sales per 1000 h.holds**	**Gas price (p/KWh)**	**Electricity price (p/KWh)**
			Gas	Elect.	Oil	Bio-fuels	Dist. heating			
Germany	39%	24%	43%	10%	26%			4.4	6	27
France	26%	19%	42%	15%	21%	12%		17.4	8	18
Netherlands	24%	17%	83%	7%				8.4	7	15
Norway	11%	3%		85%				49.6		14
Sweden	21%	7%		38%		5%	50%	24.1	10	18
UK	34%	26%	78%	12%				1.5	5	17

Table 2.5 Key targets, policies and incentives (Data sources: (BEIS, 2020c; Lowes et al., 2022; Vivid Economics & Imperial College, 2017)

Countries	Policies
Germany	- 50% climate-neutral heating by 2030 - Renewable Energies Heat Act requires a 14% renewable share in heating and cooling in new-builds - Grants and loans for retrofit - EnEV building code for new-builds with higher requirements in 2009 - Renewable heat obligations for new-builds in 2016 - National emissions trading system for fossil fuels (€25/tCO_2 in 2021 and €55/tCO_2 in 2025) - Market Investment Programme provides 35-50% of the total investment cost (oil boiler replacement or renovation) - Banning standalone oil boiler from 2026
France	- 38% of heating coming from renewables by 2030 - Subsidy (tax credits, grants, interest-free loans) on residential renewable heat (MyPrimeRenov, Eco-PTZ) - Regulation on banning direct electric heating in new-builds - Carbon tax on fossil fuels (€45/tCO_2e in 2020)
Netherlands	- A reduced levy on electricity and increased levy on gas - Subsidy for renewable heat (20-40% of upfront and installation cost since 2008) - All new buildings to have an EPC of 0.4 (Almost Energy Neutral) in 2020 - Support for innovation
Norway	- Subsidies for heat pumps - Subsidies for domestic heating infrastructure - Energy performance labelling - Banning oil boilers from existing in 2020 and new-builds from 2000
Sweden	- Carbon tax on fossil fuels for heating (€110/tCO_2e in 2020) - Tax deduction on HP installations in households - Support for district heating - Heat pump electricity tariffs
UK	- Domestic Renewable Heat Incentive provided subsidies for 7 years since 2014 - The boiler Upgrade Scheme is introduced in 2021 to provide grants (£5000 for heat pumps) for low carbon heating technology installations - Scottish government provide Home Energy Scotland (HES) loan (up to £2500 for heat pumps) and a cashback scheme (up to £7500 for heat pumps) - The Heat Pump Ready Programme supports collaboration between individuals and the industry - Future Homes Standard for new-build with higher thermal envelope and air-tightness requirements

The energy efficiency of the building stock has been increasing in the UK. The number of houses having an energy efficiency rating (EER) of A to C was only 14% in 2014; however, it reached 46% in 2020 (DLUHC, 2022). Improving the energy efficiency certificate (EPC) to at least a band C could help to save around £282 on energy costs per year. Moreover, the average CO_2 emission savings of 1.6 tonnes per dwelling could be achieved with the same efficiency improvement. However, the majority of the building stock still requires energy efficiency improvement. Climate Change Committee suggests 7.5 million energy efficiency improvements (through insulating walls, roofs, windows, etc.) in existing houses by 2030 to achieve a 15% reduction in space heating (CCC, 2019b). The UK government introduced the Green Homes Grant in 2020 which provides two-thirds of the energy efficiency improvement costs (up to £5000); however, it is closed to new applications in 2021. Moreover, the Sustainable Warmth competition (funding for local authorities to install energy-saving upgrades for low-income households) is also closed in 2022. More incentives should be introduced to improve the efficiency of the housing stock to achieve at least an EPC rating of C in all existing houses by 2035 (BEIS, 2021d).

The UK Government also introduced Future Homes Standard to upgrade Part L and Part F of the building regulations for new buildings (MHCLG, 2019). This standard aims to reduce GHG emissions by 75-80% more than current levels by tightening existing insulation levels and reducing heat losses in the building fabric. RIBA Council introduced a challenge for designers, architects and industry to reduce operational energy demand, embodied carbon and water use through higher benchmarks for buildings (RIBA, 2019). As space heating plays a significant role in operational energy and carbon emissions, the importance of heat pumps as a low carbon technology becomes crucial to reach these benchmarks.

Even though the current heat pump uptake numbers are quite limited for now in the UK, more incentives and advances in the manufacturing process could help to increase the deployment rate. Subsidies supporting heat pump installation costs, reduced electricity levies and increased levies on gas could provide rapid growth in the heat pump market. Heat pump installer training, stimulating demand with campaigns (grants, subsidies, education) and support from energy suppliers could provide the required stimulation to accelerate heat pump uptake (Nesta & BIT, 2022a). According to a study conducted by the Department of Energy & Climate Change, in a mass market scenario, cost reductions are expected compared to current costs of around 18% for Ground Source Heat Pumps (GSHP) and 20% for Air Source Heat Pumps (ASHP) (DECC, 2016b, 2016a). These reductions will probably create a higher deployment rate in the future. However, another concern is the outcome of existing conventional heating systems which will be inoperative; therefore, reuse and recycle options of these systems should be considered in a life-cycle-wide approach.

2.6. Circular Economy Design Thinking in the Built Environment

2.6.1. Resource Efficiency and Circular Economy (CE)

The extraction of global resources has risen from 26.7 billion tonnes in 1970 to more than 100 billion tonnes in 2020 (Circle Economy, 2020), and it is expected to reach 184 billion tonnes in 2050 based on the International Resource Panel (IRP) projection under existing trend scenario (IRP, 2017). Moreover, annual waste production is also expected to increase from 2.0 billion tonnes to 3.4 billion tonnes by 2050, and a third of this is not managed properly to reduce the negative impacts on the environment (World Bank Group, 2018). On the other hand, material productivity was the same since 1970, and productivity has started to decrease since 2000 because of the shift of production from high-productivity countries to low ones (Ekins & Hughes, 2017).

The circularity of the global economy was 9.1% in 2018 and it is reduced to 8.6% in 2020 due to higher raw material extraction rates, increasing material stock levels and insufficient levels of end-of-life processes (Circle Economy, 2020). More than half of the material entering the economy is used as short-lived products reaching their end-of-life within a year. The remaining materials are used as long-term stock such as buildings and infrastructure. Sustainable market and circular design concepts are dependent on the design phase of a product where the features of the product are defined (Stahel, 2016). The design phase is majorly responsible for the environmental impacts of the product occurring during its entire lifecycle. Therefore, creating sustainable and circular materials, products, buildings and built environment is only possible with modular and reusable approaches by phasing out waste.

With this problem in mind, the EU agreed on “EU Waste Framework Directive 2008” and “Closing the Loops: An Action Plan for the Circular Economy in 2008 and 2015 respectively. The action plan provides guidance for resource efficiency and waste management practices to the transition towards a Circular Economy and aims to have 70% of Construction and Demolition Waste (CDW) being recycled by 2020 (European Commission, 2015).

The context of Circular Economy in the Built Environment requires the following definitions to be known:

Resource Efficiency (broad concept): This term aims to create more output and greater value with less input by using resources efficiently in a sustainable way and reducing their environmental impacts (European Commission, 2011, p.3)

Material Resource Efficiency (in the built environment): ECORYS (2014, p. 15) describes this term as “the efficiency of resource input against the actual resource output (extraction/waste) or resource input vs. a physical function provided (i.e. tonnes of material used (ending up in the building) per m^2 of floor space created)”. This concept focuses on the environmental impacts of the buildings during their construction, occupancy, maintenance and demolition process.

Circular Economy: This economic model has been introduced in the 1960s as a concept that utilizes high-efficiency in material and energy flows through reduce, reuse and recycle options (Du, 2016, p. 71).

Circular City: The main aim of this concept is to reduce resource consumption in economic growth and production activities. Circular cities should also provide community engagement, cooperation social and environmental justice and equity (Williams, 2017, p. 30)

Circular Building: This term has been defined by Pomponi and Moncaster (Pomponi & Moncaster, 2017) as “a building that is designed, planned, built, operated, maintained and deconstructed in a manner consistent with CE principles”.

Sustainable Development Goals (SDGs) have been described as a plan for people, planet and prosperity (United Nations, 2015). SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) have direct correlations with CE principles (Schroeder et al., 2018). On the other hand, according to a study conducted by Opoku (2016) Goal 3 (good health & well-being), Goal 6 (clean water & sanitation), Goal 7 (affordable & clean energy), Goal 9 (innovation & infrastructure) and Goal 11 (sustainable cities & communities) are directly relevant to the built environment; therefore, circular economy principles related to the built environment could have high impacts on these goals. CE strategies coupled with sustainable design and low carbon energy technologies in the built environment could be a driver for 2030 SDG targets.

2.6.2. Circular Economy (CE) Strategies

The Circular Economy (CE) definition has been widely used in the literature (Table 2.6). Several studies have systematically reviewed the literature to identify CE features and perspectives (Ünal & Shao, 2019), (Elia et al., 2017), (Pomponi & Moncaster, 2017), (Lieder & Rashid, 2016), (Ghisellini et al., 2016). Implemented studies and concepts on different levels (macro, meso and micro levels) are analysed based on the CE framework. According to a review study conducted by Kirchherr, Reike and Hekkert (2017), Circular Economy (CE) system aims to replace end-of-life operations with reducing, reusing, recycling and recovering material usage in the production and consumption stages. It could operate on three levels: micro level such as products; meso level such as industrial parks; and macro level such as cities and nations. The perception of CE also differs among people (ibid). Some authors in the literature equate the CE concept with ‘recycling’ and some of them neglect ‘reduce’ in their definitions. The waste hierarchy is not clarified in one-third of the definitions, and more than half of the definitions are lacking systems perspective. On the other hand, economic prosperity is seen as the dominant perspective among previous studies whereas more focus should be given to the environmental implications and social aspects. Only one out of five definitions include the consumer as an enabler of CE so more emphasis should also be given to the end-user side of the system.

Table 2.6 Studies adopting the Circular Economy (CE) concept

Reference	**Area**	**Key findings**
Kirchherr, Reike and Hekkert (2017) Elia, Gnoni and Tornese (2017) Pomponi and Moncaster (2017) Lieder and Rashid (2016) Ghisellini, Cialani and Ulgiati (2016) Ünal and Shao (2019)	review	These studies systematically reviewed the literature to identify Circular Economy (CE) features and implemented studies on different levels (macro, meso and micro levels).
Karali and Shah (2022)	Low carbon technologies	The study investigates the collection and recycling strategies for critical raw materials for low carbon technologies
van Oorschot et al. (2022)	renewable energy technologies	The study develops a metal stock and flows system in renewable energy technologies to improve material efficiencies and reliance on critical raw materials
Baars *et al.* (2021)	electric vehicles	Circular economy strategies are investigated with scenario analysis to reduce the reliance on raw materials
Rahla, Mateus and Bragança (2021)	buildings	A tracking system for materials, energy and water flows is proposed to reduce embedded emissions
Rufí-Salís *et al.* (2021)	urban agriculture	The environmental performance of the Material Circularity Indicator (MCI) is investigated
Bonsu (2020)	electric vehicles	The study conducted semi-structured interviews to investigate circular strategies
Jensen, Purnell and Velenturf (2020)	offshore wind	Direct reuse and low-impact recovery options for end-of-life stages of offshore wind farms are investigated
Watari *et al.* (2019)	electric vehicles	End-of-life strategies for lithium batteries are proposed with higher recycling rates
Whicher *et al.* (2018)	general	A national-level circular economy action plan ecosystem is proposed for Scotland
Genovese *et al.* (2017)	chemical and food industry	A comparison of traditional and circular production systems within the chemical and food industry is investigated

Karali and Shah (2022) investigated the collection and recycling strategies for critical raw materials for low carbon technologies from a circular economy perspective. The results show that end-of-life recovery will still be limited in 2050 when the current practices continue; however, enhanced collection and recycling could provide 37%-91% of critical material demand through secondary materials. Moreover, recycling low carbon technologies could also provide potential economic value and employment opportunities. Another study conducted by van Oorschot *et al.* (2022) indicates that energy transition with renewable energy supply creates pressure on urban mining of metals through larger metal demand. Developing a metal stocks and flows system in renewable energy technologies could help to improve material efficiencies and reliance on critical raw materials. Circular economy strategies could help to reduce the demand for primary metals and close the metal cycles by improving collection and recovery rates. A previous study focusing on the need for circularity in offshore wind deployment in the UK states that current practices do not consider the end-of-life phase in a circular manner so the society can benefit from retained material value (Jensen et al., 2020). Therefore, it is necessary to have direct reuse and low-impact recovery before recycling and remanufacturing and to design for durability, recovery and modularity.

A recent study has investigated circular strategies for buildings (Rahla et al., 2021). Tracking materials, energy and water flows could help to reduce embedded emissions during production, construction, use and end-of-life stages. The reusability and recyclability of construction materials could be enhanced with a circular economy approach such as material passports. Rufí-Salís *et al.* (2021) have investigated the environmental performance of the Material Circularity Indicator (MCI) in urban agriculture. The results show that MCI in the agricultural systems was dominated by water; therefore, circular strategies affecting other materials become insignificant. Encouraging micro-level circular metrics is crucial to identify individual trade-offs and the impacts of applying circular strategies. A study conducted by Genovese *et al.* (2017) compared the performances of traditional and circular production systems within the chemical and food industry. The results indicate that circular strategies could provide significant environmental benefits; however, they also face economic challenges due to establishing circular supply chains. Therefore, top-down governmental support is required rather than bottom-up initiatives at the supply chain level.

Baars *et al.* (2021) have investigated the circular economy strategies for electric vehicle batteries to reduce reliance on raw materials. Different scenarios investigated various reuse and recycle rates of electric vehicles and batteries, Co recovery rate, battery replacement rates before the end-of-life of the vehicle and new chemistry adoption to reduce the amount of Co used in the batteries. The results show that primary Co demand could be reduced through implementing CE strategies such as higher recycling and reuse rates, innovation in battery manufacturing and rapid replacement of old batteries. Bonsu (2020) has also conducted a study about circular strategies in the electric vehicle (EV) industry by carrying out semi-structured interviews. The results illustrate that circular strategies should not only focus on recycling materials and repurposing end-of-life products but also emphasize the importance of the closing-loop approach. Systemic thinking towards addressing value chain and scenario thinking should be enhanced for policies to achieve sustainable goals. Another study focusing on circular economy strategies in electric vehicles (EV) indicates that current recycling rates of lithium batteries (<1%) could create material scarcity due to supply constraints; therefore, the deployment of EVs could be disrupted (Watari et al., 2019). Moreover, additional 300 $MtCO_2$ emissions from vehicle operation could be seen in 2050 due to insufficient lithium battery production. These problems could be prevented with circular strategies in the end-of-life stage of electric vehicles. A recycling rate of 80% could reduce the stress on natural deposits by providing secondary materials for manufacturing.

EU's 'Circular Economy Action Plan' has been utilised to create a circular ecosystem for Scotland in a previous study (Whicher et al., 2018). Implementing this action plan at a national or regional level could help to accelerate the transition into a circular economy. The study has defined twelve actions under four thematic areas: business, support and finance; skills and education; promotion and awareness; and policy and regulation.

2.7. The Islands of Orkney as a Case Study

The Paris Agreement declare that the reliance on fossil fuels and energy imports makes islands vulnerable to climate change. There are about 2400 islands in Europe which have 15 million inhabitants representing 2% of the European population (European Commission, 2018). Islands are the most vulnerable areas affected by climate change through disasters; therefore, studying on the island level is a priority to reduce negative social impacts. On the other hand, implementing renewable energy sources could have positive impacts on environmental implications. Moreover, a reduction in energy imports could also result in lower energy prices so economic benefits could be achieved. These opportunities make islands an excellent candidate for energy system models to test low carbon energy technologies and scenarios on the island level (Prina et al., 2021).

Small islands represent isolated areas due to their remote location and lack of interconnections from the mainland. This generally creates a dependency on imports of fossil fuels for the transport and heating sectors (Marczinkowski & Østergaard, 2019). The majority of the small island around the world are dependent on imported diesel and other oil products to produce electricity or heat (Gioutsos et al., 2018). Smaller-scale electricity production, transportation costs of energy supply and volatility in oil prices creates energy security problems, and creates economic pressure on islands; therefore, local resources become much more important for island energy systems to tackle vulnerability (Marczinkowski & Østergaard, 2019). Most islands have a higher potential for renewables such as wind and solar which are well-developed technologies. However, small islands are a suitable testing ground for more novel technologies such as wave, tidal, ocean thermal energy, biofuel and concentrated solar power systems (Gioutsos et al., 2018)

Islands have different energy system structures than the mainland due to distinctive characteristics (Prina et al., 2021). The major differences could be summarised as below:

- The national surrounding has an impact on the renewable energy type and potential
- The population of the island varies based on seasons due to tourism
- Availability of clean water could be limited
- Waste management activities could be limited especially during the tourism season
- Higher energy prices due to energy imports and transportation costs
- Higher installation costs in technologies due to smaller-scale economies established in islands
- Higher CO_2 emissions due to marine transport

Energy systems and models are widely used at the insular level in the literature. Prina *et al.* (2021) reviewed 43 studies using bottom-up energy system models applied at the island level. The results indicate that about 37% of the studies used models designed for island applications, and the remaining used macro- or micro-level applications. Methodology, time resolution, sectoral coverage and objective function are the major constraints implemented by country-level models. On the other hand, insular level models have additional constraints such as water desalination, energy storage, demand response and maritime transport utilised in the model. Gioutsos *et al.* (2018) compared six different islands to analyse the cost-optimal configuration of the electricity system with higher renewable energy shares. The results indicate that 40-80% penetration of renewable energy technologies, particularly wind energy, could create a reduction in the levelized cost of electricity. Further deployment of renewables creates higher costs due to additional costs of storage options; however, cost reductions in lithium-ion batteries in the following years could make battery storage economically viable. Another study reviewing energy storage and demand side management options in islands indicates that pumped hydro and battery storage are the major technologies used in islands (Groppi et al., 2021). The battery storage option is mainly used for small-scale applications whereas the pumped hydro storage option is beneficial for larger systems. These options could help to reduce excess electricity production and increase grid capacity with variable renewable energy sources. Low carbon heating, specifically heat pumps, and energy efficiency improvements in buildings are also key solutions to reduce energy consumption on the demand side.

The Scottish islands have a huge potential for renewable energy which could be used in the UK energy system. Matthew and Spataru (2021) have assessed the impacts of renewable sources, specifically marine and wind energy, on Scottish islands with an energy system model. The results indicate that interconnections between Scottish islands could help to reduce the variability of supply and prices by geographic diversity. Dependency on dispatchable generation during low renewable production and increased cost of onshore wind and marine energy could be reduced by supply diversity.

In 2016, Orkney has generated 120% of its electricity demand which is more than the island's needs. The major energy source is wind power with several community-owned and commercial turbines, and more than 500 domestic-scale wind turbines (Figure 2.11) (OREF, 2022). The total renewable energy capacity is 57 MW in Orkney. The majority of this energy comes from renewable wind energy but solar, biomass, tidal and wave also exist on smaller scales. However, Orkney still imports a significant amount of fossil fuels for domestic heating, transport and industry. The Orkney distribution system is connected to the mainland via two 33kV submarine cables with a capacity of 40 MW. Another 220 MW capacity transmission cable project has been approved by Ofgem in 2019. This allows exporting of excess electricity to the Scottish mainland and importing electricity when generation is stopped on the island (OREF, 2015).

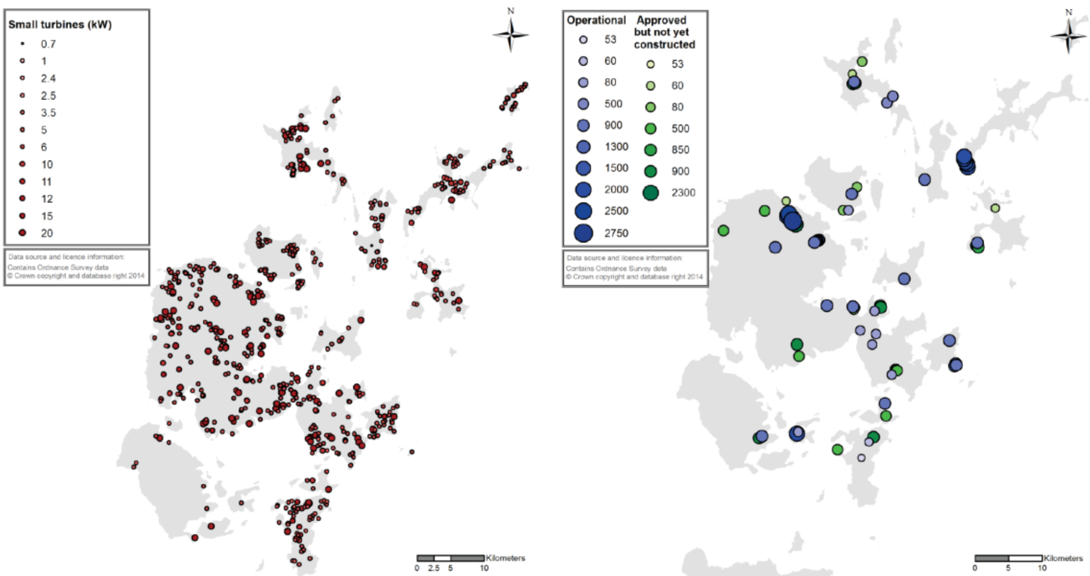

Figure 2.11 Location of small wind turbines (up to 50kW) (left), and large wind turbines (50kW and above) (right) (OREF, 2015)

Transport is responsible for 45% of the total energy use with 343 GWh. It is followed by buildings with 268 GWh (35%). The majority of building energy consumption occurs in the domestic sector with 170 GWh and is followed by the commercial and industrial sector with 63 GWh and the public sector with 35 GWh. The main heating fuel types used in Orkney's domestic sector are electricity with 51.8% and oil with 42.7%. The dominant heating technology is oil boilers and followed by electric heaters (OREF, 2015). Heat pumps are also widely used in Orkney both domestically and larger scale. The number of heat pumps deployed in Orkney was more than 1000 in 2021 (Figure 2.12). When the results illustrated per 1000 households Orkney has 117 heat pumps. This is the second-largest heat pump uptake figure after Na h-Eileanan Siar among the Scottish local authorities (Nesta, 2021).

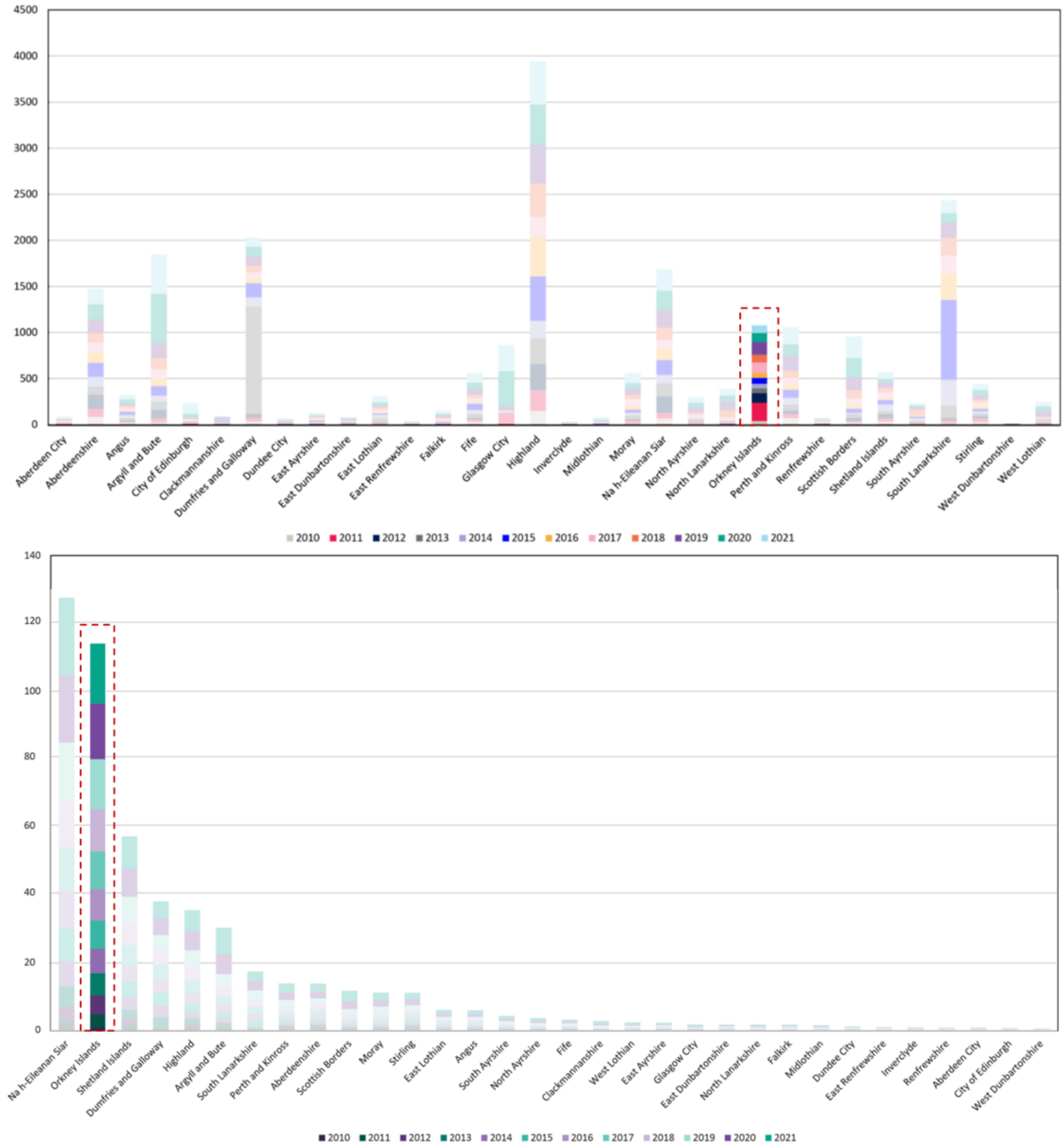

Figure 2.12 MCS-registered heat pump installations per local authority (above), and per 1000 properties (below) (Nesta, 2021)

The Surf and Turf project has been introduced in Orkney to utilise excess electricity to generate hydrogen through electrolysing. SMart IsLAnd Energy systems (SMILE) project has been funded by European Union (Horizon 2020) to investigate smart grids and flexibility of electricity systems in three island case studies, and Orkney is one of them (CES, 2017). The aim of the project is to explore storage options such as hot water cylinders, thermal batteries and EV chargers using demand side response strategies. ReFLEX (Responsive Flexibility) is another major project (£28.5 million) aiming to create an integrated energy system (IES) in Orkney (ReFLEX Orkney, 2020). IES will work as the control platform and coordinate energy components as an automated system. Storage technologies, for instance, will be used to charge/discharge based on electricity cost, local renewable energy generation and constraints. These projects offer various advantages to the energy system of Orkney due to energy security problems. High potential of renewable energy requires demand side flexibility and storage alternatives which these projects are trying to find solutions to.

Orkney's Fuel Poverty Strategy report indicates that 63% of households are living in fuel poverty in Orkney. The reasons creating a high fuel poverty figure are lower average income, higher heating costs, older housing stock conditions and climate. Orkney's average household income is around £30,000 which is £5000 lower than the Scottish average (OIC, 2017). The natural gas average price is around 3.17 p/KWh whereas the average electricity price in northern Scotland is 16.51 p/KWh; therefore, heating costs are higher on the island due to no natural gas availability (ScottishPower, 2021). Even though Orkney generates its electricity from local renewable sources electricity prices are assumed to be 2.5 pence higher than southern Scotland figures. This could be because households are not changing their tariffs based on lower price opportunities. Another major contributor to fuel poverty is the condition of the housing stock. Orkney's housing stock is older than the national average, and 25% of it is built before 1919. This creates an energy efficiency problem in the housing stock and consequentially higher energy demand figures. Therefore, retrofitting Orkney houses is crucial to reduce energy consumption. The final factor affecting Orkney's fuel poverty is climate. Even though the temperatures do not drop below 2ºC in winter due to the Gulf stream Orkney has a long winter season and strong wind speeds. This also affects the efficiency of the housing stock. In order to tackle fuel poverty, several actions need to be taken such as energy efficiency improvements in housing stock and a competitive energy market to reduce prices (OIC, 2017).

Orkney has a huge potential for energy supply from renewable sources; therefore, heat pump uptake could help to reduce fossil fuel reliance and energy demand due to higher efficiencies of heat pumps than conventional heating systems. Island communities are ideal candidates to investigate real-life problems and implement solutions to the challenges. Therefore, Orkney is selected as a case study to investigate environmental, energy and cost-related savings under different heat pump uptake scenarios in line with the projects aiming to investigate demand side flexibility.

2.8. Gaps in Literature

In the previous section, literature has been reviewed to investigate the overview of heat pump technology, market, deployment costs, targets, policies and incentives. Moreover, models and techniques used to assess low carbon technologies are analysed with circular economy strategies. From the systematic literature review several gaps were identified:

- The built environment puts major pressure on the natural environment. Transitioning to a circular economy is vital. The UK's Net Zero target requires strong commitments, and heating-related emissions are one of the major problems. Higher heat pump deployment rates are expected due to the decarbonisation of heating in buildings. Heat pumps are still an expensive heating technology when compared with gas boilers. To overcome this problem reductions in heating and investment costs are required. Financing the replacement of existing heating technologies with heat pumps requires more investigation.
- Life cycle-wide approaches have been heavily taken to evaluate environmental impacts. These implications of heat pumps are widely discussed in the literature, and the use phase is the major contributor to the impacts. Increased renewable share in the UK's electricity mix has not been discussed during the last decade; therefore, a life cycle assessment (LCA) of heat pumps with the current and future electricity mixes in line with the government's targets is needed.
- Energy system models (ESM) try to create stability in the energy system through variable generation and cost optimisation. Demand side management through control strategies and thermal energy storage tanks are widely discussed in the literature. However, there is still a lack of information about the operation and performance of heat pumps and storage tanks.
- Integration of LCA and ESM methods was also investigated in the literature. However, most of the studies focused on the environmental impacts (mainly GHG emissions) of energy production technologies on a larger scale at the supply side of the system. The lack of a methodological approach which does not have system thinking creates difficulties between actors and consistent development of circular practices.
- Circular Economy (CE) is mainly equated with 'recycling' concept in the literature and economic prosperity is the dominant factor. However, more emphasis should be given to the social and environmental aspects with end-users as an enabler of CE.
- Small islands are vulnerable areas facing economic pressures due to high imports of fossil fuels used for electricity production and heat. Selecting these areas as a case study will help to explore utilising local energy resources through low carbon technologies.
- In Orkney, buildings are the second higher energy consumer after transportation and the majority of the energy is used in buildings by the domestic sector. The major heating fuel types are electricity and oil, and Orkney generates electricity from

renewables more than its needs. Therefore, the electrification of heating is in progress. Orkney has the second highest number of heat pumps deployed by 1000 households among Scottish local authorities so investigating heat pump uptake scenarios with renewable electricity generation is crucial for Orkney.

- Previous studies focusing on individual low carbon heating technologies have difficulty assessing overall impacts at the national or island level. Moreover, Orkney has an older housing stock than the national average; therefore, building stock modelling is a novel element for the accuracy of the study.
- Nearly two-thirds of households are living in fuel poverty in Orkney due to lower average income and higher energy prices than on the mainland. A financial analysis of heat pump uptake scenarios in line with government targets towards a circular economy perspective is required to overcome this problem.
- National targets on decarbonising heating require strong commitments in terms of electrification of heating by heat pumps and energy efficiency improvements of houses. However, a holistic approach considering not only the end-user side by investigating archetype level savings but also system thinking with achieving macro level targets is missing.

Chapter 3

Proposed Methodological Approach

This study aims to create a comprehensive integrated methodological approach to support the UK's Net Zero target which has ambitious targets in terms of decarbonising space heating as stated in Chapter 2. The consequences of heat pump uptake scenarios have been assessed in this study (Figure 3.1) through quantified methods consisting of:

- a life cycle assessment (LCA) of chosen low carbon heating technologies (in this case air source heat pumps and ground source heat pumps) utilised in the UK houses for decarbonisation, and scenario analysis in line with government targets,
- an energy system modelling (ESM) to optimise the performance of an air source heat pump coupled with a thermal energy storage tank for Orkney houses,
- a building stock model (BSM) of Orkney's domestic sector to understand the housing stock condition and evaluate the energy efficiency improvement requirements,
- an economic model analysing the life cycle cost (LCC) of an air source heat pump and potential savings when existing heating systems are replaced in Orkney,
- a heat pump diffusion model (HPD) to quantify hourly electric load curves of heat pumps under different electricity tariffs for house archetypes and the Orkney electricity system.

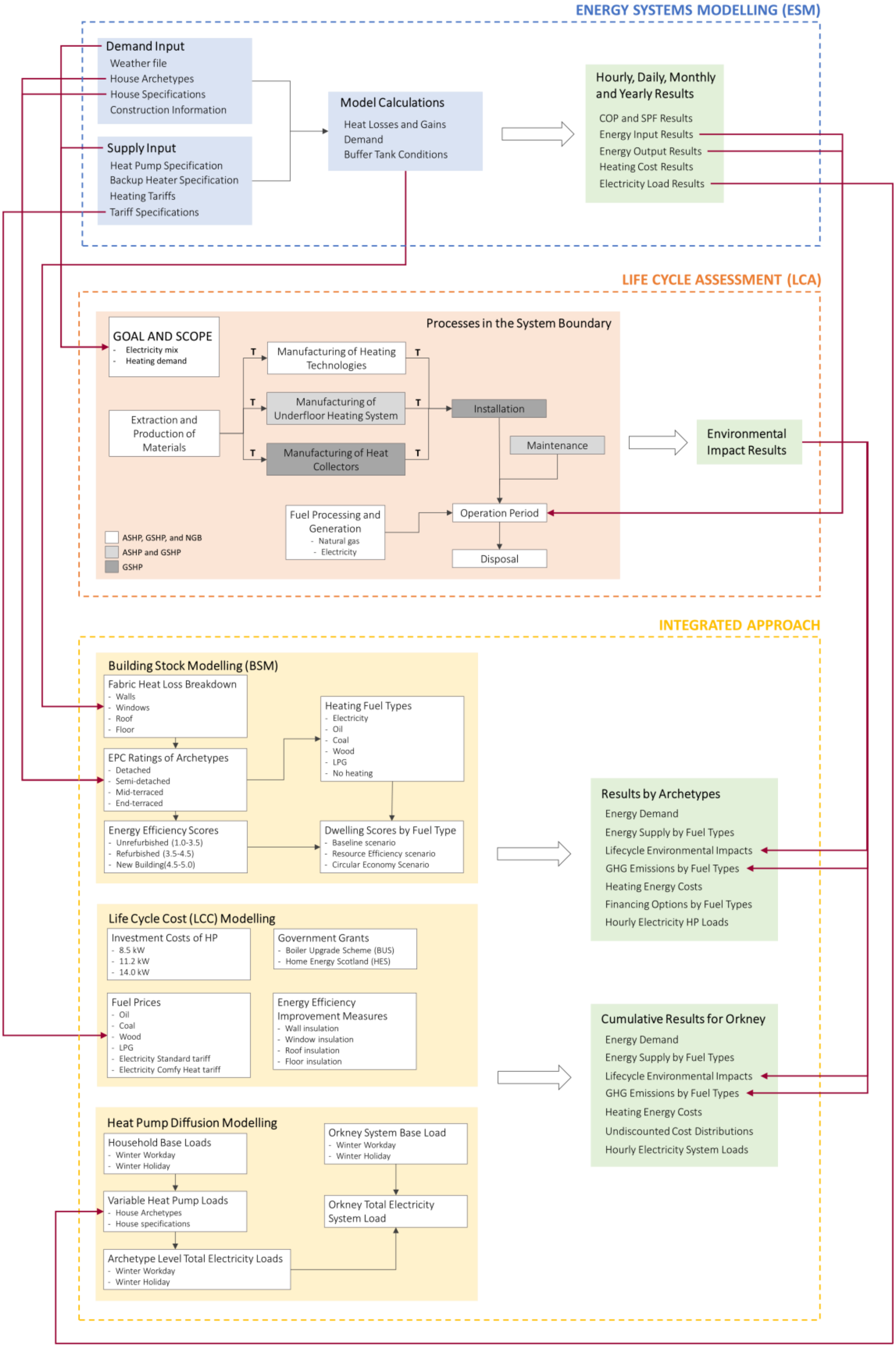

Figure 3.1 A schematic diagram of the proposed integrated approach methodology

The environmental burdens associated with heat pumps and gas boilers are analysed with a life cycle assessment methodology for the UK to evaluate the current outlook with the existing electricity mix. The goal and scope of the study and the processes in the system boundary have been identified. The results are illustrated for the baseline year and the year 2050 in line with government targets. Hybrid applications of heat pumps and gas boilers, different manufacturing location, electricity mixes and energy efficiency improvement measures are investigated with circular strategies to generate insights for the future.

The energy model investigates the major contributor stage (use phase) of the LCA analysis to reduce energy consumption by optimising the performance of the heat pump with demand side management. A previously developed energy model (Spataru and Rassol, 2016) has been developed further with higher temporal resolution and more details. Different house archetypes (detached, semi-detached, mid-terraced, end-terraced), building specifications (unrefurbished, refurbished, new building), thermal energy storage tank sizes (250L, 500L, 750L, 1000L), flow temperatures (35 °C, 45 °C, 55 °C) and electricity tariffs (Standard, E7, Comfy, E12, E20) are investigated for Orkney as a case study. The reason behind choosing an island as a case study, specifically Orkney, is to be able to overcome the economic pressures and high fuel poverty levels Orkney is facing. The model aims to reduce energy consumption and heating costs by regulating off-peak and peak time variable heat pump operation depending on electricity prices.

The integrated approach has chosen an island as a case study to create a testing ground and demonstrate the applicability of the study. Moreover, Orkney has chosen due to high energy prices and fuel poverty levels despite the high renewable energy potential is exist specifically for wind energy. Therefore, a building stock model (BSM) analysis is conducted for Orkney based on Energy Performance Certificate (EPC) ratings. Existing heating fuel types used by house archetypes and energy efficiency improvement (EEI) requirements are identified. The life cycle assessment results illustrate the environmental burdens of heating technologies for an average UK home. However, the integrated approach requires results per different house archetypes; therefore, life cycle assessment results are revised for the Orkney case study. The economic part of the energy model investigates the life cycle cost analysis of an air source heat pump and discounted savings when existing conventional heating systems are replaced with heat pumps. Financing options with and without government support are analysed to provide an outlook to the end-users. A previously developed heat pump diffusion model has been integrated with the energy model to analyse the electrical load curves at household and island levels.

The types of results produced at both house archetype and Orkney level for different scenarios are below:

- Energy demand
- Energy supply by fuel types
- Life cycle environmental impacts
- CO_2e emissions by fuel types
- Heating energy costs
- Financing options for fuel types
- Undiscounted cumulative cost distributions
- Hourly electricity heat pump loads
- Hourly electricity system loads

The integrated approach examines the current situation in Orkney and conducts a scenario analysis for 2050 to create a pathway for a low carbon future. Moreover, financing options evaluate the effectiveness of existing subsidies and grants and provide suggestions based on successful examples from other countries. A housing stock model for Orkney has been created based on time series of population and dwellings. Investigating individual results provides a comprehensive perspective to the end-users. Providing household-level results for replacing an existing conventional heating system with a heat pump could be beneficial for consumers to understand energy, environmental and economic implications. On the other hand, cumulative savings at the Orkney level could provide a framework for policymakers to introduce new schemes to reach the Net Zero target.

The following chapters explain each model individually.

- Chapter 4 describes the life cycle assessment analysis of heat pumps and gas boilers in the domestic sector in the UK.
- Chapter 5 describes the energy system model developed to optimise the operation of an air source heat pump coupled with a thermal energy storage tank in Orkney.
- Chapter 6 describes the integrated model (life cycle assessment, energy system modelling and building stock model) and its application to Orkney as a case study.

Chapter 4

Life Cycle Assessment (LCA)

4.1. Introduction

This chapter focuses on the comparison of different environmental impact categories for key technologies to decarbonise heating in domestic buildings in the UK. Heat pumps and gas boilers are key technologies in the decarbonisation of buildings and have been selected as relevant cases to test our hypotheses and methods. Their impacts on low carbon heating targets have been assessed through a life cycle assessment (LCA) methodology for the current year, and future scenarios have been developed to assess their environmental impacts through LCA to understand the impacts of the replacement of existing technologies with new ones. The functional unit of the study is decided as ‘generating 1 kWh of thermal energy for domestic heating’, to investigate environmental burdens associated with these heating technologies. Hybrid applications of heat pumps with gas boilers also assessed as hybrid technologies will also play a significant role in the future according to government targets. Moreover, the impact of changing the manufacturing location is also investigated.

This chapter extends the analysis presented in a conference proceeding (Sevindik & Spataru, 2020) and a published journal paper (Sevindik et al., 2021).

4.2. Methodology

A life cycle assessment (LCA) approach has been undertaken to evaluate the environmental impacts of low carbon heating technologies for the domestic sector in accordance with ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b). The first step of this study focuses on the current situation of heating technologies (air source heat pump, ground-source heat pump and natural gas boiler) in the baseline scenario. Then, a scenario analysis is conducted to evaluate the impact of these heating technologies in standalone or hybrid options for future government plans and targets.

4.2.1. Goal and Scope

The goal of this study is to evaluate the potential environmental impacts of residential space heating in the UK by developing life cycle models for an air source heat pump (ASHP), ground-source heat pump (GSHP) and natural gas boilers (NGB). This comprises a scenario analysis with the objective of achieving the Net Zero target by 2050.

The functional unit of the study is decided as ‘generating 1 kWh of thermal energy for domestic heating’. However, cumulative results have also been presented to investigate lifetime environmental burdens associated with these heating technologies. The LCA software SimaPro 8.0.3 (PRé Sustainability, 2014) has been used to model the products and the ReCiPe Midpoint (H) method (Huijbregts et al., 2017) has been used for life cycle impact assessment.

4.2.2. Inventory Data and Assumptions

System Description and Boundary

System specification and material requirements of heat pumps and gas boilers, and data for these products have been taken from a previous study (Greening & Azapagic, 2012) that analysed the environmental implications of these products in the UK. Heat pumps are decided as air to water and ground to water, and heating is provided by underfloor heating. Underfloor heating system is designed as a screed system covering a 150 m^2 area. Material requirements of heat pumps and gas boiler are illustrated (Table 4.1). The capacity of the systems and operation period have been assumed as 10 kW and 2000 hours/year. The total space heating demand is assumed to be 20,000 kWh/year for both heat pumps and gas boiler which represents an average UK household yearly heating demand. All technologies are considered maintenance-free; however, it is assumed that refrigerant needs to be top up by 6% yearly as losses occur. The total lifetime of both heat pumps and gas boiler has assumed as 20 years.

Table 4.1 Material requirements for heating technologies (Data source: Greening & Azapagic, 2012).

		ASHP			GSHP				NGB
Material	Unit	Heat pump	Under-floor heating system	Mainte-nance	Heat pump	Under-floor heating system	Heat Collector System	Mainte-nance	Gas boiler
Polyolester oil	kg	2.7			1.7				
R-134A	kg	4.9		5.9	3.1			3.7	
Rockwool	kg								8.0
Low-alloyed steel	kg	32.0			20.0				115.0
Reinforcing steel	kg	120.0			75.0		33.0		
Stainless Steel	kg	5.0							5.0
Bentonite	kg				3.8				
Sand	kg		4650.0			4650.0			
Cement	kg		900.0			900.0			
Copper	kg	36.6			22.0				3.0
Aluminium	kg		126.0			126.0			7.5
Brass	kg						6.6		0.1
Polyvinylchloride	kg	1.6			1.0				
HDPE	kg	0.5					301.2		0.9
LDPE	kg		101.0			101.0	4.7		
Polystyrene	kg		66.0			66.0			
Elastomere	kg	16.0			10.0				
Ethylene Glycol	kg						167.0		
Total	kg	219.3	5843.0	5.9	136.6	5843.0	512.5	3.7	139.5

The system boundary of gas boilers and heat pumps includes extraction and production of raw materials, transportation of raw materials for assembly, manufacturing of heat pumps and gas boilers, manufacturing of underfloor heating system for heat pumps, manufacturing of heat collector for GSHP, transportation of products to the distributor, transportation of products to the installation site, installation of GSHP as it requires drilling, operation period which includes natural gas processing for boilers and electricity generation for heat pumps, maintenance of refrigerant for heat pumps and disposal of materials (reuse, recycling, landfilling, etc.) (Figure 4.1). The installation phase is only considered for GSHP as it requires drilling, which is an extensive installation when compared with ASHP and gas boilers. As two types of heat collectors exist for GSHP (horizontal and vertical), this study only included the horizontal one for simplicity. The difference between the two types is the amount of pipework for heat collectors, the heat carrier liquid and the type of machines to dig the ground. The maintenance stage is only considered for heat pumps as there will be losses in refrigerant during the operation period; therefore, an annual top-up is required. Additionally, the underfloor heating system is only included for heat pumps as replacing the gas boiler will require either resizing the radiators or the installation of an underfloor heating system to achieve higher efficiency.

Therefore, in this study, the underfloor heating system is included in the system boundary of heat pumps. However, renewing the gas boiler does not require any system change; therefore, no new heating system is proposed.

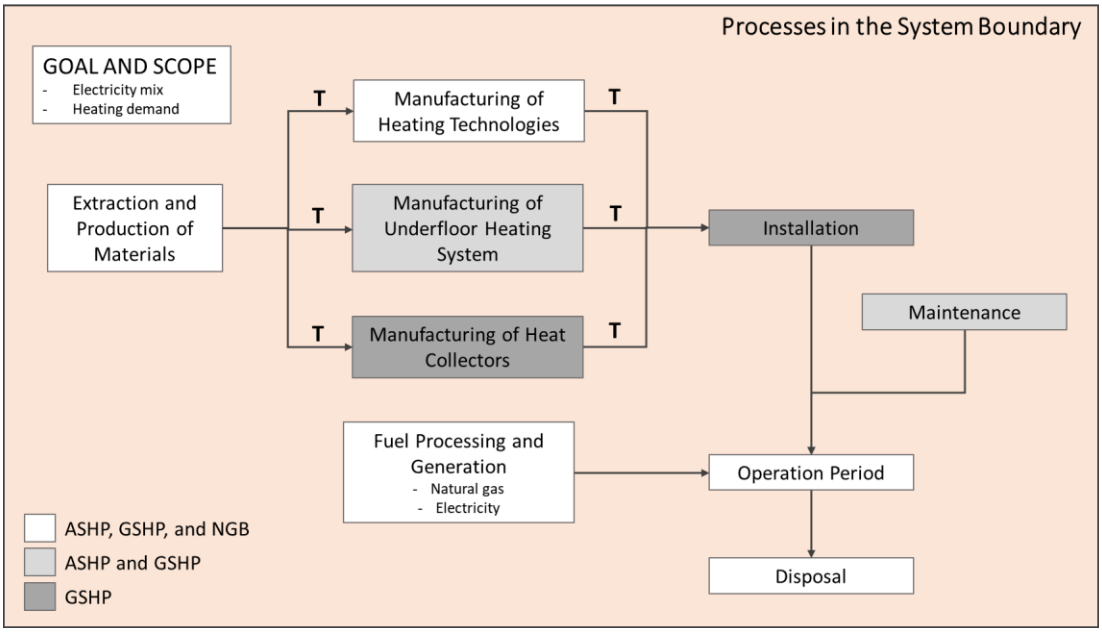

Figure 4.1 The life cycle of air source and ground source heat pumps and gas boilers (T: Transport)

Transport

Heat pump installations in the UK market heavily rely on imports. A total of 69% of ASHP and 59% of GSHP are manufactured outside of the UK (BEIS, 2020c). Europe is the dominant market as 70% of imported products are manufactured there. When individual countries are investigated, Sweden has the highest imported heat pump amount followed by South Korea, Spain, Italy, the Czech Republic, and Germany. This study, therefore, selects Europe as the manufacturing location for heat pumps. Ecoinvent generic values (100–200 km) have been used for raw materials and assembly transport assumptions (Wernet et al., 2016). Heat pumps are assumed to be manufactured in Europe and transported to the UK (Table 4.2). Within this process, raw materials are transported 200 km by railway and 100 km by a large truck (16–32 tonnes). After the assembly of the heat pump, it is transported to the distributor 500 km by railway and 200 km by a large truck (16–32 tonnes). Then, the installation site distance has been assumed as 200 km and the products have been transported by a small truck (3.5–7.5 tonne). The underfloor heating system (UHS) and heat collectors (HC) are assumed to be manufactured in the UK; therefore, transport distances for manufacturing have been assumed as 200 km by railway and 100 km by a large truck (16–32 tonne), and installation distance has been assumed as 200 km. Natural gas boilers are assumed to be manufactured in the UK; therefore, transport for raw materials has been assumed as 200 km by railway and 100 km by a large truck (16–32 tonne). Distances from manufacturer to distributor and installation site have been assumed as 200 km.

Table 4.2 Transport assumptions (Data source: Wernet et al., 2016)

Transport of;			Rail	Truck (Large)	Truck (Medium)	Truck (Small)
Heat Pumps	raw materials to manufacturer	km	200	100		
	products from manufacturer to distributor	km	500	200		
	products for installation	km				200
Gas Boiler	raw materials to manufacturer	km	200	100		
	products from manufacturer to distributor	km			200	
	products for installation	km				200
Underfloor Heating System	raw materials to manufacturer	km	200	100		
	products for installation	km			200	
Heat Collectors	raw materials to manufacturer	km	200	100		
	products for installation	km		200		

4.3. Scenario Analysis

The study offers a scenario analysis to assess the environmental impacts of heat pumps and gas boilers through LCA to understand the implications of the replacement of existing technologies with new ones. In this section, three scenarios have been developed for the year 2050. In the next section (Section 4.4), three more alternative scenarios have been developed for hybrid applications of technologies and another transport scenario. The latter is separated from the first three because they are assessed according to both the baseline model and also the Circular Economy (CE) scenario.

Circular Economy (CE) scenario: High technology development and high consumer engagement are supported by policies; therefore, more efficient houses and low carbon technologies expect a reduction in energy demand. The decarbonisation of electricity is provided by increased offshore wind capacity, and the share of natural gas is nearly eliminated. Larger roles for heat pumps are provided and gas boilers are replaced with low carbon technologies such as stand-alone heat pumps (10.7 million) or hybrid heat pumps (7.1 million). The number of gas boilers will reduce to 5 million and the remaining heating demand will be provided by district heating and biomass. A reduction in material demand and better waste treatment options are assumed with high policy support (Table 4.3).

Resource Efficiency (RE) scenario: A reduction in energy demand is expected but this decrease is lower than the CE scenario. The decarbonisation level of electricity is similar to the CE scenario. The deployment of heat pumps is limited (8.5 million), and the number of gas boilers is similar to the CE scenario; therefore, applications of hydrogen play a significant role in this scenario. High technology development and policy support are expected, but consumer support is relatively limited compared to the CE scenario.

Limited Growth (LG) scenario: Limited energy efficiency and technology development is assumed; therefore, residential heat demand is expected to reduce with the lowest number among other scenarios. The decarbonisation of electricity is not finished, and the deployment of heat pumps is very limited; therefore, the majority of heating demand will be provided by gas boilers. Slow adaptation to circular economy principles and low consumer engagement are expected.

Table 4.3 Summary of system specifications and assumptions for scenarios (Data sources: (Greening & Azapagic, 2012)[1],(Passarini et al., 2018)[2],(Environment Agency, 2020)[3], (Etude, 2018)[4], (BEIS, 2020f)[5], (CCC, 2015)[6],(National Grid, 2019)[7], (CCC, 2019b)[8], (RIBA, 2019)[9]

Drivers	Baseline		Circular Economy (CE)		Resource Efficiency (RE)		Limited Growth (LG)		Sources
Recycling rates for materials	Steel	75%	Steel	100%	Steel	90%	Steel	80%	[1,2,3]
	Copper	61%	Copper	100%	Copper	85%	Copper	75%	
	Alumi nium	69%	Alumi nium	100%	Alumi nium	90%	Alumi nium	80%	
	Plastics	32%	Plastics	100%	Plastics	80%	Plastics	60%	
	Refrige rant	80%	Refrige rant	100%	Refrige rant	90%	Refrige rant	80%	
SPF and Efficiency	ASHP	2.8	ASHP	4.2	ASHP	4.0	ASHP	3.6	[4,5,6]
	GSHP	3.4	GSHP	4.6	GSHP	4.4	GSHP	4.2	
	NGB	90%	NGB	95%	NGB	95%	NGB	95%	
Efficiency improve ments			25%		15%		8%		[7,8,9]
Heat pump uptake (million)	ASHP	0.13	ASHP	10.48	ASHP	5.73	ASHP	0.81	[7]
	GSHP	0.02	GSHP	0.18	GSHP	0.13	GSHP	0.09	
	Hybrid HP	0.02	Hybrid HP	7.07	Hybrid HP	2.71	Hybrid HP	0.83	
	Gas Boiler	21.99	Gas Boiler	5.20	Gas Boiler	5.86	Gas Boiler	22.14	

4.3.1. Electricity Mix

The use phase of heating technologies has a significant impact on LCA analysis, accounting for 74% of overall impacts; therefore, updating the electricity mix of the UK to the current situation would help to see more accurate results. The current electricity mix of the UK for the year 2018 has been identified for the use phase of heat pumps (Figure 4.2) (DUKES, 2019). In 2018, 40.2% of electricity was produced from natural gas. Nuclear and wind accounted for 19.9% and 17.4%, respectively. The remaining comes from bioenergy, solar and coal.

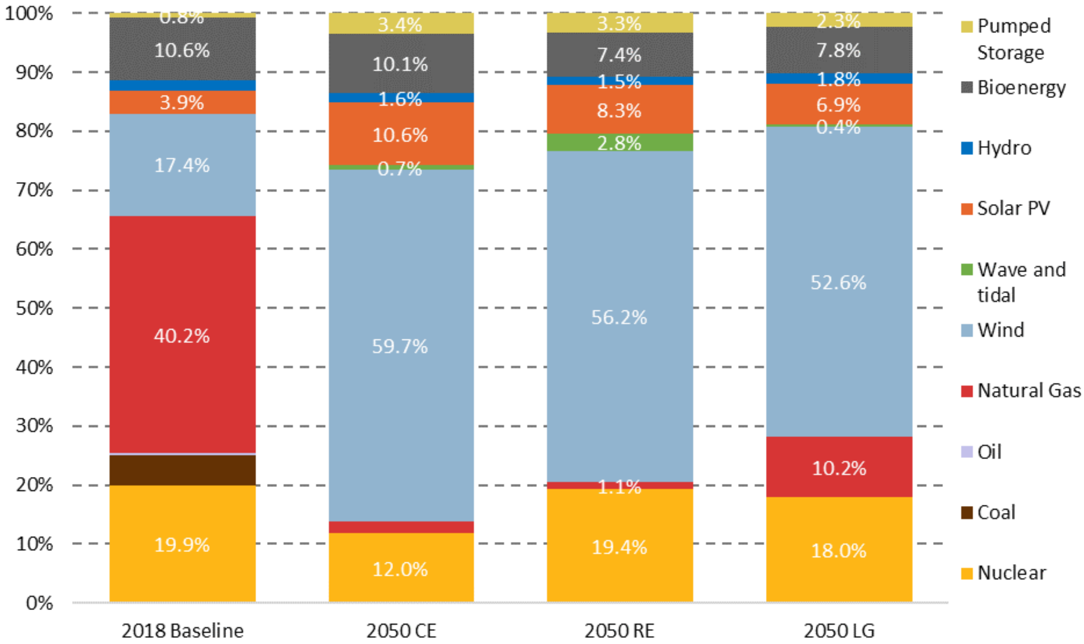

Figure 4.2 Electricity mix of the UK in different scenarios used in LCA analysis (Data sources: DUKES, 2019; National Grid, 2017)

According to National Grid, more than one-third of UK electricity was produced from natural gas and offshore wind capacity, around 10GW, in 2018 (National Grid, 2019); however, more deployment of wind energy is expected in the future. The UK Government has revised its offshore wind capacity target from 30GW to 40GW by 2030 (BEIS, 2020d). Therefore, National Grid's electricity mix scenarios have been adopted for the UK's future electricity mix ('Community Renewables', 'Two Degrees', and 'Steady Progression' scenarios adapted to 'Circular Economy', 'Resource Efficiency' and 'Limited Growth' scenarios, respectively) (Figure 4.2). All three scenarios assume a significant increase in wind energy but different shares. In 2050, the RE scenario assumes that 56% of electricity will be produced from wind energy and the remaining will come from nuclear, solar and bioenergy, which account for 19%, 8% and 7%, respectively. In the CE scenario, wind energy reaches 60% of total electricity production. Solar and bioenergy increase to 10% each; therefore, the share of nuclear energy reduces to 12%. The LG scenario, however, assumes the least wind energy share with 53%; therefore, natural gas still has a share of 10% of total electricity production. The proportion of energy sources in high voltage processes in the Ecoinvent database has been modified to update current and future electricity mixes.

4.3.2. Efficiency of Technologies

One of the main impacts on energy demand in a heat pump is the Coefficient of Performance (COP) which identifies the ratio of energy needed according to its efficiency. The Seasonal Performance Factor (SPF) represents the average COP for heat pumps during the heating season. According to BEIS monthly reports since 2014, average ASHP and GSHP efficiencies are calculated as 3.2 SPF and 3.5 SPF (BEIS, 2020f). These values vary for legacy applications and new installations. Legacy ASHP applications have an average of 2.5 SPF and new installations have 3.4 SPF. Legacy GSHP installations, on the other hand, have an average of 2.9 SPF and the new ones have 3.8 SPF. Field trials in the UK and Europe show similar results with an average SPF of 2.6 and 3.2 for ASHP and GSHP, respectively (Etude, 2018). Therefore, average SPFs for heat pumps have been considered as 2.8 for ASHP and 3.4 for GSHP. The efficiency of NGB is considered as 90% for the baseline model (Table 4.3).

Current heat pump efficiencies vary between manufacturer test data and field trials. Correct sizing and better installation of heat pumps provide higher efficiencies; thus, it could be possible to reach manufacturers' test efficiencies in the future. Over the years, the efficiency of heat pumps is expected to increase with the help of advances in the market. CCC assumes a 0.5 increase in COP of heat pumps between the 2020 and 2030 period (CCC, 2015). Therefore, future scenarios in this study assume higher efficiencies varying between 3.6-4.2 for ASHP and 4.2-4.6 for GSHP (Table 4.3). GSHPs are expected to have a lower increase in COP than ASHP due to their high outlet temperature and modest difference in the ground temperature around the heat collector (ETI, 2019). Therefore, efficiency improvement in GSHP is expected to be lower than in ASHP.

4.3.3. Decommissioning

The lifetime of both technologies has been assumed to be 20 years, and at the end of their life cycle metal components are recycled and the rest is landfilled. UK and Europe recycling rates have been reviewed, and steel, copper, aluminium and plastics have been assumed as 75%, 61%, 69% and 32% recycled (Passarini et al., 2018). 80% of refrigerant is assumed to be reused after 20% losses during the decommissioning (Greening & Azapagic, 2012).

Gas boilers and heat pumps are electrical and electronic equipment (EEE) covered by the WEEE Regulations under category 1 and category 12. They both have similar targets as 85% recovery and 80% recycling rates (Environment Agency, 2020). However, these benchmarks will likely increase if the UK continue to progress towards Net Zero targets. Therefore, all scenarios expect an increase in recycling rate; however, the CE scenario assumes the highest recycling rate with 100% for all components. High policy support and public engagement could help to achieve 100% recycling and recovery options.

4.3.4. Efficiency Improvements in the Residential Sector

The need for space heating could be less in the future. Thermal efficiency improvements through retrofitting existing houses and setting higher benchmarks for new buildings mean that by 2050, domestic buildings could use up to 26 per cent less energy for heat compared to today (National Grid, 2019). The CCC (CCC, 2019b) assumes a 15% reduction in energy consumption in the residential sector by 2030 through energy efficiency improvements in existing buildings. The Royal Institute of British Architects (RIBA, 2019) has set a challenge for designers to reach at least a 75% reduction in operational energy in domestic buildings by 2030. Therefore, different measures have been taken for future scenarios. RE and CE scenarios assume a 15% and 25% reduction in heat demand in an average household. The LG scenario, however, considers only 8% energy improvement measures as the economy faces limited economic growth (Table 4.3).

4.4. Hybrid and Transport Scenarios

In the previous section, model simulations are conducted based on individual heating technologies without focusing on hybrid applications. However, the UK Government and National Grid have decarbonisation targets for heating, and scenarios show that there will be a need for hybrid options in the future. Additionally, Asia is a dominant market, and some companies manufacture their heat pumps in Asian countries. Moreover, South Korea is the second country that the UK has the highest heat pump imports (BEIS, 2020b). Therefore, this section investigates the impact of changing the manufacturing location and hybrid options according to the baseline scenario and CE scenario, which were modelled in the previous section. Three scenarios are investigated as:

Transport (SK) scenario assumes that heat pumps are manufactured in Asia and average ROW (rest of the world) production values have been used in SimaPro. South Korea has been chosen as a manufacturing country to identify the main shipment method and distance as a transoceanic freight shipment of 12,400 nm (22,965 km). Table 4.4 shows the remaining transport methods and distances. In this scenario, the manufacturing location of the underfloor heating system and heat collectors have not been changed.

50% Hybrid scenario assumes half of the energy required for heating has been produced by ASHP or GSHP and the remaining comes from NGB.

75% Hybrid scenario assumes 75% of heating energy has been provided by heat pumps and the remaining 25% is produced by the gas boiler.

The changes for these three scenarios are applied to both the baseline and the CE model to compare the impacts of these scenarios in the current year and an alternative of the year 2050.

Table 4.4. Transport assumptions of manufacturing in Europe and Asia (Data sources: Greening & Azapagic, 2012; Wernet et al., 2016)

Transport of;			Rail	Truck (Large)	Truck (Small)	Sea Freight
Transport (EU)	raw materials to manufacturer	km	200	100		
	products from manufacturer to distributor	km	500	200		
	products for installation	km			200	
Transport (SK)	raw materials to manufacturer	km	200	100		
	products from the manufacturer to distributor	km		200		22,965
	products for installation	km			200	

4.5. Results & Discussion

4.5.1. Baseline Results

The simulation results have been illustrated per functional unit, and the lifetime results are divided into the amount of total space heating demand for both heat pumps and gas boilers as the functional unit is decided as 'generating 1 kWh of thermal energy for domestic heating'. However, lifetime environmental impacts are also provided in the graphs to show the impact of technologies during their lifetime.

Environmental impacts of the baseline scenario for air source heat pump (ASHP), ground source heat pump (GSHP) and natural gas boiler (NGB) have been illustrated in Figure 4.3. ASHP has the highest impacts on average, and GSHP and NGB have 17% and 51% lower results than ASHP on average, respectively. When individual impact categories were investigated, the results illustrated that NGB has the lowest impact in all categories except Climate Change (CC) [1] category.

[1] **CC** (Climate Change), **OD** (Ozone Depletion), **TA** (Terrestrial Acidification), **FEU** (Freshwater Eutrophication), **MEU** (Marine Eutrophication), **HT** (Human Toxicity), **POF** (Photochemical Oxidant Formation), **PMF** (Particulate Matter Formation), **TE** (Terrestrial Ecotoxicity), **FE** (Freshwater Ecotoxicity), **ME** (Marine Ecotoxicity), **IR** (Ionising Radiation), **ALO** (Agricultural Land Occupation), **ULO** (Urban Land Occupation), **NLT** (National Land Transformation), **WD** (Water Depletion), **MD** (Metal Depletion), **FD** (Fossil Depletion).

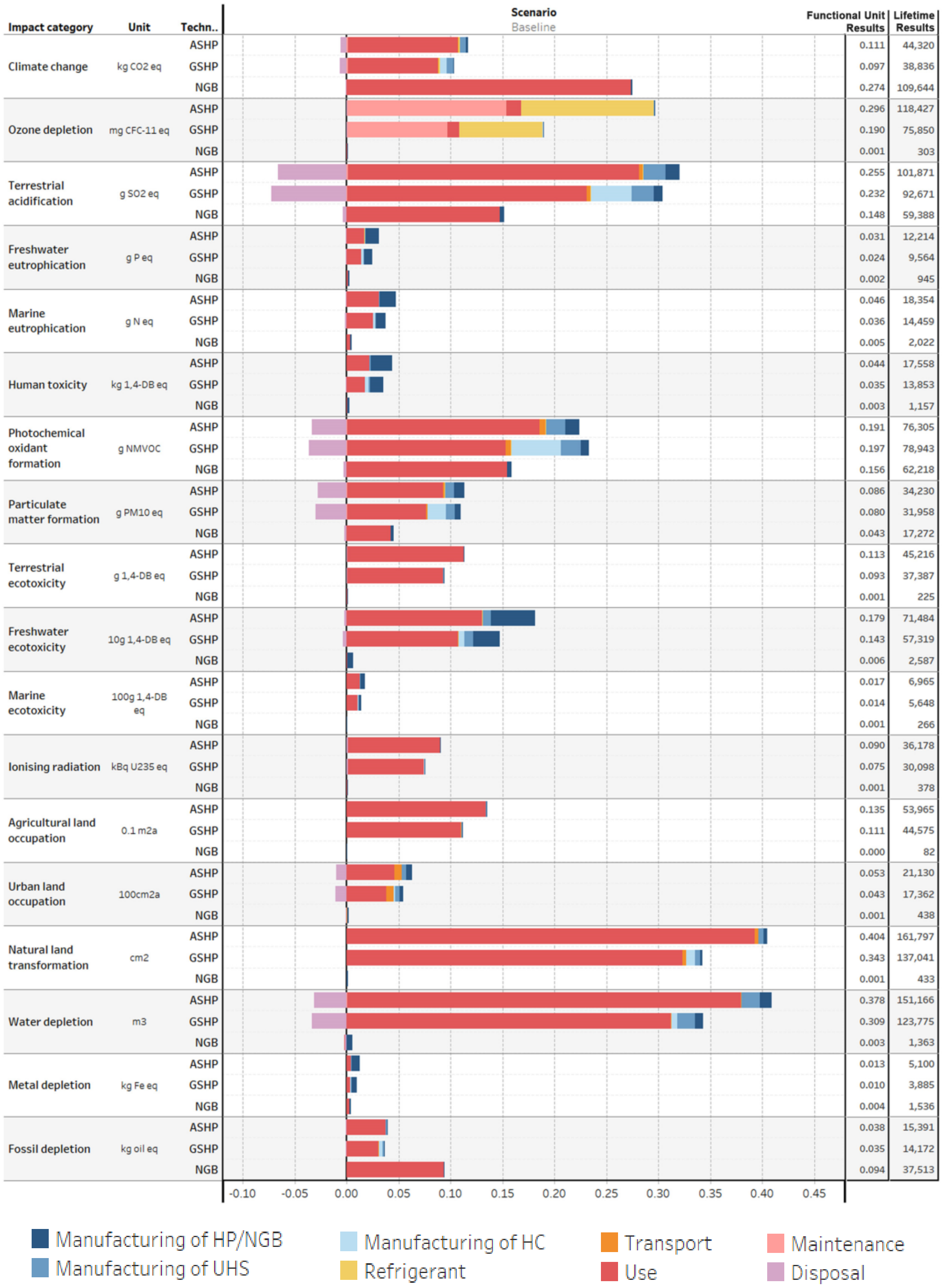

Figure 4.3 Lifecycle environmental impacts of heat pumps and gas boiler for baseline scenario (HP: Heat pump, NGB: Gas boiler, UHS: Underfloor heating system, HC: Heat collector)

This study illustrates that emissions for ASHP and GSHP are reduced to 0.111 kg CO_2e/kWh and 0.097 kg CO_2e/kWh (Figure 2), respectively, compared with the literature (Greening & Azapagic, 2012), where there was a reduction from 0.276 kg CO_2e/kWh and 0.189 kg CO_2e/kWh. This is mainly because of the decarbonisation of the electricity mix through the high deployment of wind energy to replace coal and some part of natural gas during the last decade. The carbon intensity of the gas boiler is more than double both heat pumps with 0.241 kg CO_2e/kWh. NGB has 96.2 t CO_2e lifetime emissions, much higher than ASHP (42.3 t CO_2e) and GSHP (38.8 t CO_2e).

The two highest contributor phases of the life cycle assessment are the 'use' and 'manufacturing' phases, which are responsible for 74% and 14% of all environmental impacts on average. The manufacturing of heating technologies, underfloor heating systems and heat collector phases accounts for 17%, 20% and 12% for ASHP, GSHP and NGB, respectively. It is important to keep in mind that the manufacturing of heat pumps occurs outside of the UK, which does not have an impact on the UK's territorial emissions; however, it will have an impact on consumption-based emissions of the UK or global emissions. The disposal phase accounts for 6%, 7% and 3% of total impacts for ASHP, GSHP and NGB, respectively; however, these impacts are negative due to contributions from the reuse of refrigerants and recycling of materials at the end of their life cycle. The refrigerant and maintenance phases account for only 3% of both heat pumps and have no impact on the gas boiler as there is no refrigerant use in boilers. The transport phase, on the other hand, is only responsible for 1% of total environmental impacts.

When heat pumps are compared, GSHP has 17% lower results than ASHP as it requires less electricity because of its higher efficiency. The impact of heat collectors is relatively low in most of the categories, except the Terrestrial Acidification (TA), Photochemical Oxidant Formation (POF) and Particulate Matter Formation (PMF) categories. The reduction in the use phase in these categories is higher than the impact of manufacturing the heat collectors, so overall the environmental impact of GSHP remains lower than ASHP. The POF category is the only category in which GSHP has 3% higher results than ASHP because the impact of the manufacturing of heat collectors is greater than the reduction in the use phase. The highest difference between heat pumps occurs in the Ozone Depletion (OD) category with 36% because of lower refrigerant requirements. Metal Depletion (MD), Freshwater Eutrophication (FEU), Marine Eutrophication (MEU), Human Toxicity (HT) and Freshwater Ecotoxicity (FE) are the remaining categories that have more than 20% difference. Even though the disposal phase does not have a significant impact overall, there are several categories in which the disposal phase has higher impacts for heat pumps, such as TA, POF, PMF and ULO categories, accounting for 29%, 18%, 35%, and 22%, respectively.

4.5.2. Results from Future Scenarios

Scenario analysis aims to investigate the impact of changes planned in line with the government's targets and national policies. The Circular Economy (CE) scenario results expect the highest reductions for all heating technologies, and the Limited Growth (LG) scenario expects the lowest. Overall reductions in CE, RE and LG scenarios are 44%, 42% and 31% for heat pumps and 27%, 18% and 12% for the gas boiler (Figure 4.4).

In the CE scenario, the highest changes are in CC, TA, POF, PMF, NLT and FD categories with an average of 75% reduction in heat pumps. The lowest change occurs in the OD category with a 2% reduction only as the amount of refrigerant is the same in future scenarios. Even though the RE and LG scenarios have lower results than the CE scenario, trends are the same. However, several categories expect an increase for all scenarios such as FE, ME, and MD. The main source of this impact is the heavy metals utilised in the high deployment of wind energy that will be provided by offshore wind farms; therefore, emissions to the water will be expected during their disposal. Another toxicity category, human toxicity, also expects a lower reduction for all scenarios from 8% to 14% for heat pumps. Additionally, the major source of metal depletion comes from the life cycle of electricity because the high deployment of renewables requires more metal resources. On the other hand, there are several categories in which the RE scenario performs better than the CE scenario, such as MEU, TE, FE, ME and ALO. The main reason for this impact is that the CE scenario has the highest renewable share in the electricity mix, and this has higher toxicity and land occupation results; however, the RE scenario has a lower renewable share and higher nuclear energy in the electricity mix. Therefore, the negative impacts created by renewable energy are greater in the CE scenario. The LG scenario still has natural gas in the mix; therefore, the LG scenario still performs worse than both scenarios.

The reductions in NGB are very limited when compared with heat pumps. This is due to limited efficiency in the gas boiler. The reductions come from efficiency improvements in houses which will require less heat demand; therefore, the gas boiler expects similar reductions in all phases.

When the contributors to changes in future scenarios are investigated, only the use and disposal phases have an impact on categories. Figure 4.5 shows their weighted results, illustrating the importance of the use phase. Even though some categories are expecting significant increases in the disposal phase (ranging from 535–1286%), their weighted results are less than 1% when they are compared with the use phase. The highest disposal phase impact occurs in the OD category, with an increase of 20% and 9% for CE and RE scenarios and a decrease of 3% for the LG scenario.

Figure 4.4 Lifecycle environmental impact change of scenarios according to baseline

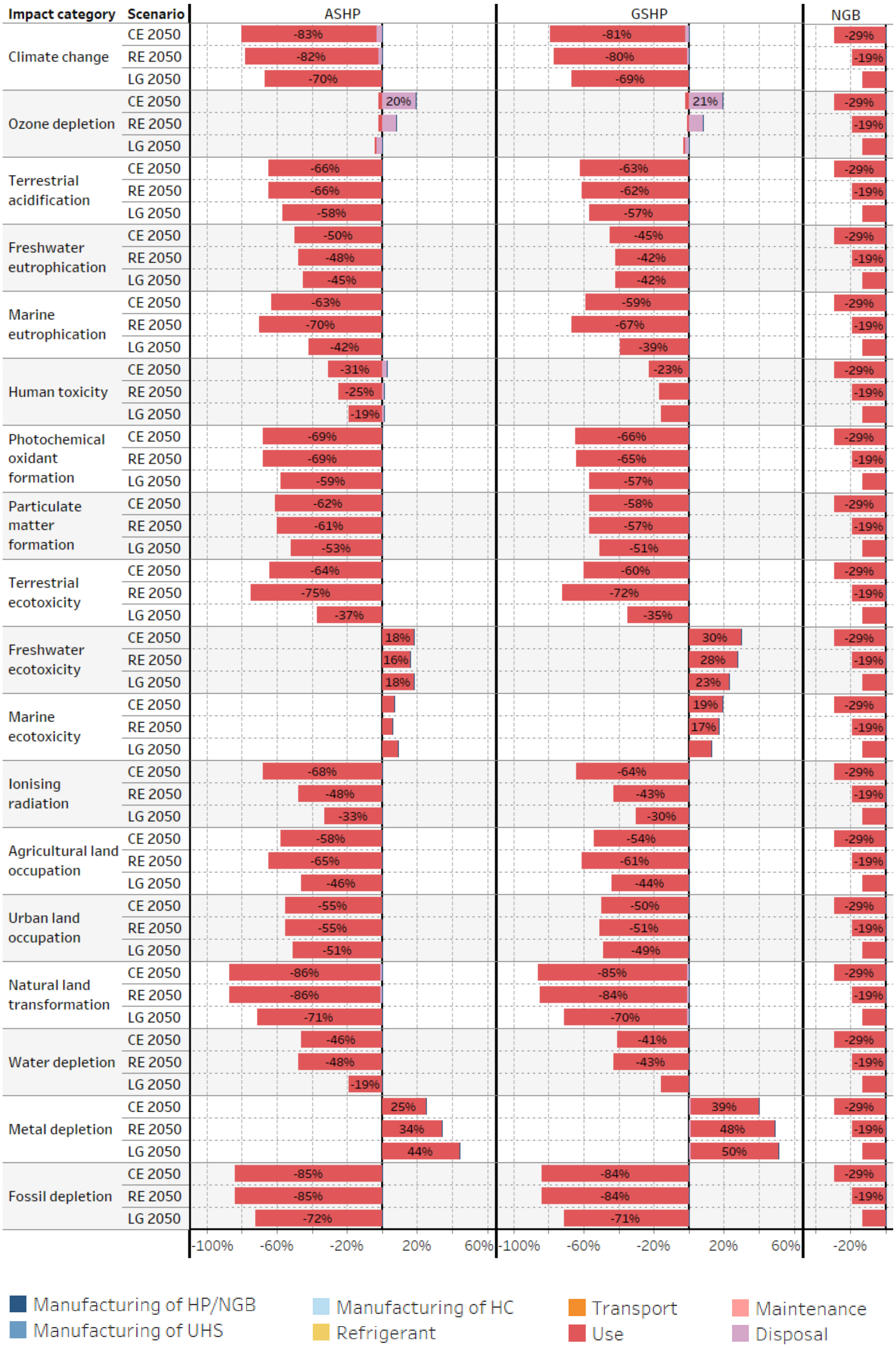

Figure 4.5 Lifecycle environmental impact change of phases in terms of phases

Finally, the material demand for heat pumps was compared with gas boilers before finalising the results. ASHP and GSHP require 2.4 and 2.2 times more metals when compared with boilers. Moreover, they require new material streams such as 5000 kg of minerals and 420 kg of plastics on average for the manufacturing and installation of underfloor heating and heat collectors. The increase in the metal depletion category in all future scenarios emphasises that this will create a requirement for new material and waste streams for the UK. Currently, the UK cannot process its whole waste production and with new waste streams, it will not be possible to cope with waste problems.

Future scenarios provide projections of environmental impacts by updating the electricity mix, heat demand, the efficiency of heating technologies and disposal numbers according to government targets and assumptions. However, the manufacturing phase of heating technologies and material requirements remain the same. This approach creates a limitation for the study as more efficient production lines could be enhanced and better products with less material requirements could be produced.

4.5.3. Transport and Hybrid Scenarios

4.5.3.1 Results from Baseline Model

The Transport (SK) scenario results illustrate that changing the manufacturing location does not have a significant impact on most categories according to the baseline scenario. ASHP results show that even though the average change is less than 1%, there are some categories that have higher results (Figure 4.6). The highest impact category is MEU with a 30% decrease from the baseline scenario. This reduction comes from the manufacturing phase which uses RoW values for the production of technologies. It means less biological pollution through nutrition discharge to the marine waters due to technological differences and electricity mixes used in the manufacturing phase. TA, HT and PMF categories are other high-impact categories with 13%, 11% and 8%, whereas with an increase, unlike the MEU category. [2]

During the life cycle phase analysis, only changes in the manufacturing of heat pumps, refrigerant and transport phases were considered. The manufacturing phase increases with an average of 27% in all categories, and the highest change occurs in the TE category with a 358% increase for ASHP (Figure 4.7). TA and PMF categories show increases of 226% and 58%, respectively. There are also several categories with negative impacts such as MEU and OD categories with a 92% and 19% decrease, respectively. The transport phase, on the other

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[2] **CC** (Climate Change), **OD** (Ozone Depletion), **TA** (Terrestrial Acidification), **FEU** (Freshwater Eutrophication), **MEU** (Marine Eutrophication), **HT** (Human Toxicity), **POF** (Photochemical Oxidant Formation), **PMF** (Particulate Matter Formation), **TE** (Terrestrial Ecotoxicity), **FE** (Freshwater Ecotoxicity), **ME** (Marine Ecotoxicity), **IR** (Ionising Radiation), **ALO** (Agricultural Land Occupation), **ULO** (Urban Land Occupation), **NLT** (National Land Transformation), **WD** (Water Depletion), **MD** (Metal Depletion), **FD** (Fossil Depletion).

hand, increases 17% on average in all categories and the highest contribution comes from TA, PMF, MEU and POF categories with 77%, 49%, 40% and 39%, respectively. The refrigerant phase, however, has a negative impact, and results decrease only 2% on average and the highest change occurs in IR, NLT and TE categories with a decrease of 18%, 8% and 7%, respectively. PMF and TA categories have also seen a 4% increase.

The results of GSHP show similarities with ASHP, with a decrease of 1% on average (Figure 4.6). The highest impact category is MEU with a 23% decrease, followed by a 9% and 8% increase in TA and HT categories, respectively. The changes in GSHP are relatively lower than ASHP as heat collectors in GSHP will still be manufactured in Europe in this scenario; therefore, the weight of the change becomes smaller in this technology.

The results of phases are also similar in manufacturing and refrigerants with a 26% increase and 2% decrease on average for GSHP (Figure 4.7). The highest impact categories are TE, TA, PMF and MEU categories in the manufacturing phase, and IR, TE, NLT, PMF and ULO categories in the refrigerant phase, like the ASHP results. The main difference between ASHP and GSHP occurs in the transport phase and the average change is 7%. Even though the highest categories are the same, the changes are less than ASHP.

The 50% Hybrid scenario results expect an increase of 32% and 20% on average in ASHP and GSHP, respectively (Figure 4.6). GSHP offers a higher increase or less reduction in all categories, resulting in fewer advantages than ASHP. The highest change occurs in CC and FD categories with a 76% and 79% increase for ASHP, and a 97% and 89% increase for GSHP, respectively. The MD category also expects an increase of 3% and 7% for heat pumps. The remaining categories result in a decrease, and the highest decrease occurs in TE, IR, ALO, NLT, and WD categories, varying between 49% and 38% for both heat pumps. Some categories have a less than 5% impact change, such as OD, FEU and HT categories.

In the 50% Hybrid scenario, the highest changes occur in the disposal phase with an average of 15% and 200% decrease for ASHP and GSHP (Figure 4.7). Even though the overall change is greater in GSHP, most of the contribution comes from MD and NLT categories with a decrease of 2951% and 531%. The reason for this reduction is that the amount of metals required for ASHP is greater than GSHP; therefore, this value is a positive value for ASHP. Thus, negative metal depletion values coming from NGB reduce the impact of ASHP. When other phases are analysed, the use phase expects a decrease of 33% and 29% for ASHP and GSHP, and the manufacturing phase expects an increase of 33% and 53%, respectively. The transport phase has an average change of 5% increase for both heat pumps.

Even though the use phase offers a reduction in all categories, the CC and FD categories expect an increase in all phases except the disposal phase. As gas boilers perform worse than heat pumps only in this category in the baseline scenario (Figure 4.3), the hybrid scenario offers the worst results in these categories. Moreover, the MD category also expects an increase even though it is less than 10%. However, in other categories, the use phase eliminates the increases created by the manufacturing and transport phases as the weight of the use phase is very large and creates negative results overall in all categories.

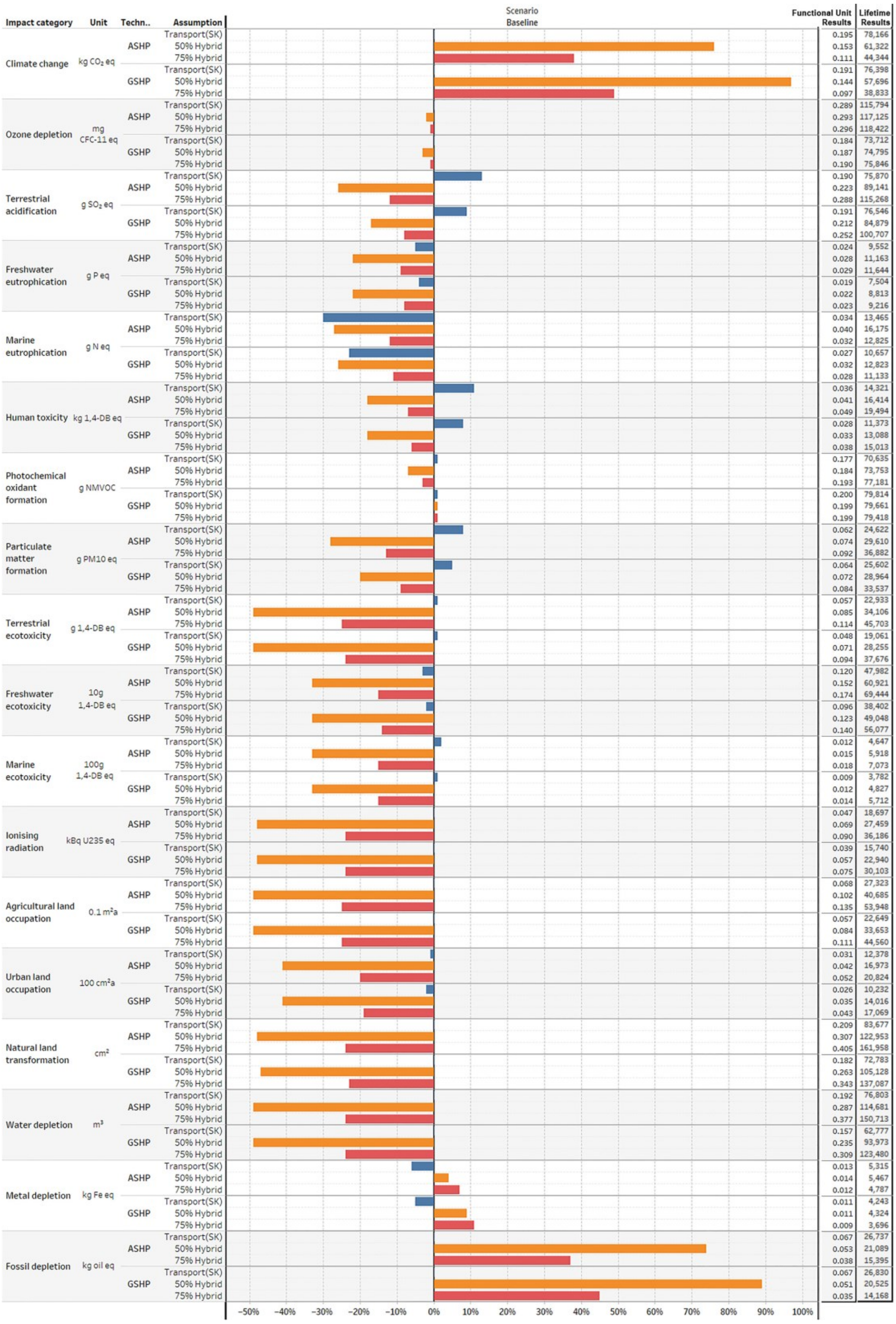

Figure 4.6 Lifetime environmental impact change of different transport and hybrid scenarios according to the baseline model

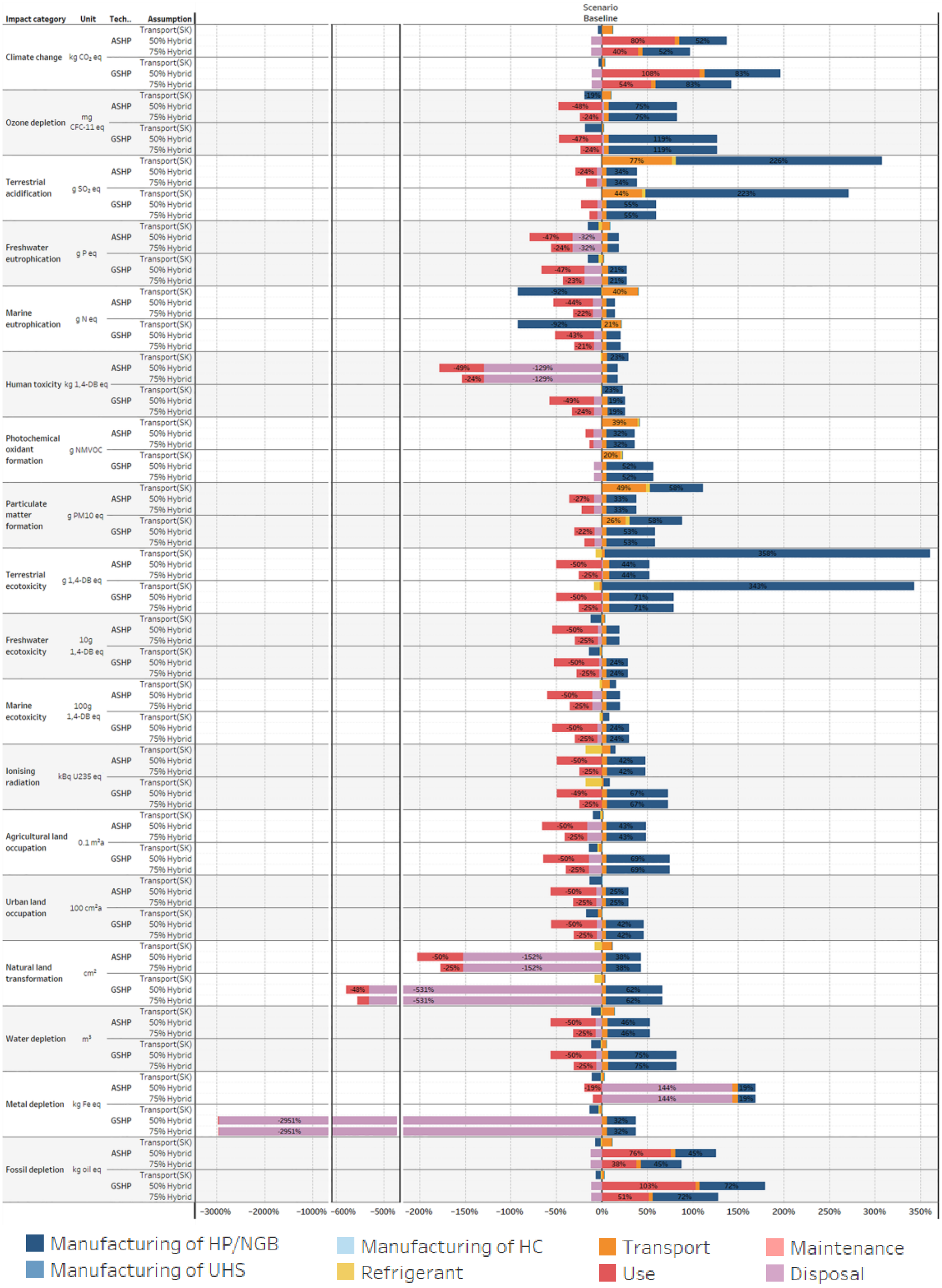

Figure 4.7 Lifetime environmental impact change of phases for transport and hybrid scenarios according to the baseline model

The 75% Hybrid scenario results offer less reduction than the half-hybrid scenario with an 11% and 9% decrease in ASHP and GSHP (Figure 4.6). Similarly, GSHP performs worse than ASHP in this scenario with an increase in CC and FD categories and a decrease in other categories; however, this scenario offers less decrease overall as the contribution of the gas boiler is less than the 50% Hybrid scenario. The highest changes occur in CC and FD categories with a 38% and 37% increase for ASHP, and a 49% and 45% increase for GSHP, respectively. The highest decreases occur in TE, IR, ALO, and NLT categories, varying between 24% and 19% for both heat pumps.

4.5.3.2 Results from CE 2050 Model

The Transport (SK) scenario results show that changing the manufacturing location could increase the environmental impacts on average by 3% and 1% for ASHP and GSHP, respectively, according to the CE 2050 model (Figure 4.8). The highest changes for ASHP occur in TA and PMF with a 68% and 34% increase. Additionally, results suggest a decrease in several categories with less than 3% except for the MEU category, which has a 53% reduction in the CE 2050 model. GSHP results show lower values than ASHP in all categories, but the highest contributors are the same impact categories.

The life cycle phase results illustrate that the highest contributor phases to the changes from the CE 2050 model are the manufacturing of heat pumps, refrigerant, and transport phases, similar to the baseline model (Figure 4.9). The results of changes in these phases are the same as in the baseline model; therefore, the changes in these phases have the same impacts on both the baseline and CE 2050 models.

Even though hybrid scenarios in the CE 2050 model have similar results as the baseline model in most of the categories, there is a significant difference in CC and FD categories as they are very sensitive to the use phase results. In the 50% Hybrid scenario, the highest changes occur in the FD category with a 490% and 333% increase for ASHP and GSHP, similar to the baseline model (Figure 4.8). The other category suggesting an increase is the CC category with 409% and 360% for both heat pumps. The impact of the MD category is lower than the baseline model in the CE model. Most of the remaining categories have a reduction of around 16–47%.

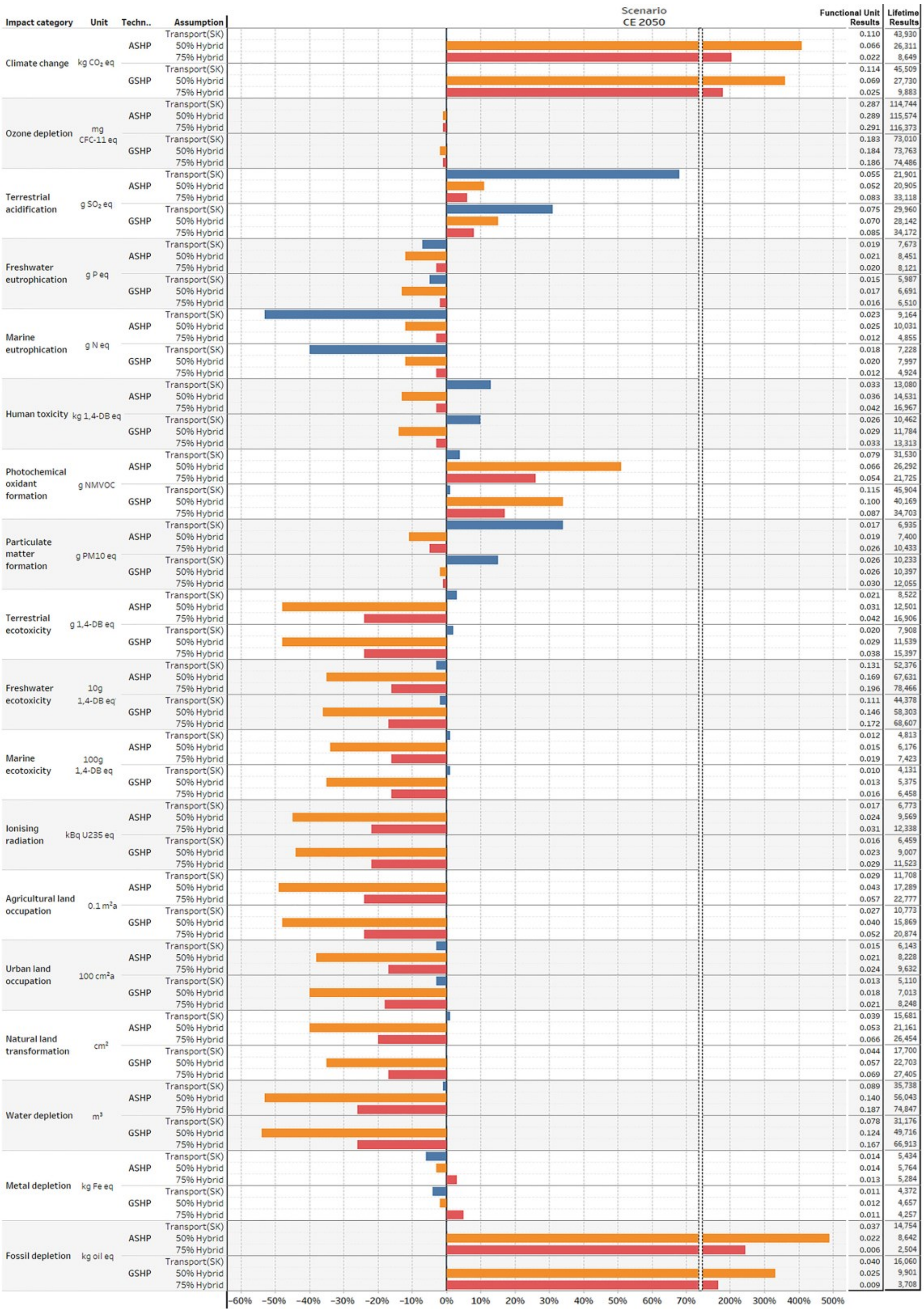

Figure 4.8 Lifetime environmental impact change of different transport and hybrid scenarios according to the CE 2050 model

The results of phases in the 50% Hybrid scenario illustrate that the highest changes occur in the manufacturing phase, with a 33% and 53% increase on average for both heat pumps (Figure 4.9). The transport phase creates an increase of 5% and 6% for ASHP and GSHP, respectively. The disposal phase, on the other hand, expects a decrease of 4% for ASHP and an increase of 8% for GSHP. However, the use phase suggests a decrease of around 5% on average for both heat pumps. Similar to the baseline model, the use phase offers a reduction in all categories and an increase for CC and FD categories with 482% and 563% for ASHP, and 533% and 622% for GSHP, respectively. The only exception is for the POF category, which was expecting a reduction in the baseline model and expecting an increase in the CE 2050 model. The main reason for this is that the result of NGB for this category is lower than heat pumps in the baseline model; however, in the CE 2050 model, NGB has a higher value and increases the average of hybrid results.

FEU, MEU, HT and PMF categories have a reduction varying between 9% and 18%, whereas the remaining categories expect higher reductions varying between 30% and 48%. In the CE 2050 model, hybrid scenarios offer an overall increase in contrast to the baseline model mainly because the change in the CC category is greater than in the baseline model and the weight of the use phase is lower in the CE 2050 model.

Similar to the baseline model, the 75% Hybrid scenario results offer less increase than the half-hybrid scenario with a 4% and 10% increase overall in ASHP and GSHP, respectively. The highest change occurs in CC and FD categories with a 205% and 246% increase for ASHP, and 181% and 167% increase for GSHP, respectively. The highest decreases occur in TE, IR, ALO and WD categories, varying between 19% and 22% for both heat pumps.

The changes in manufacturing, transport and disposal phases are similar to the baseline model in both hybrid scenarios, so there is no difference between the baseline and CE model and 50% and 75% Hybrid scenarios in these phases, except for the use phase.

The results of hybrid scenarios offer a benefit to reduce the negative impacts caused by heat pumps in most of the categories. Even though this creates an increase in CC and FD categories and CO_2e emissions, negative consequences could be prevented. Moreover, replacing gas boilers with heat pumps requires a transition period, and hybrid applications could help to create a smoother transition.

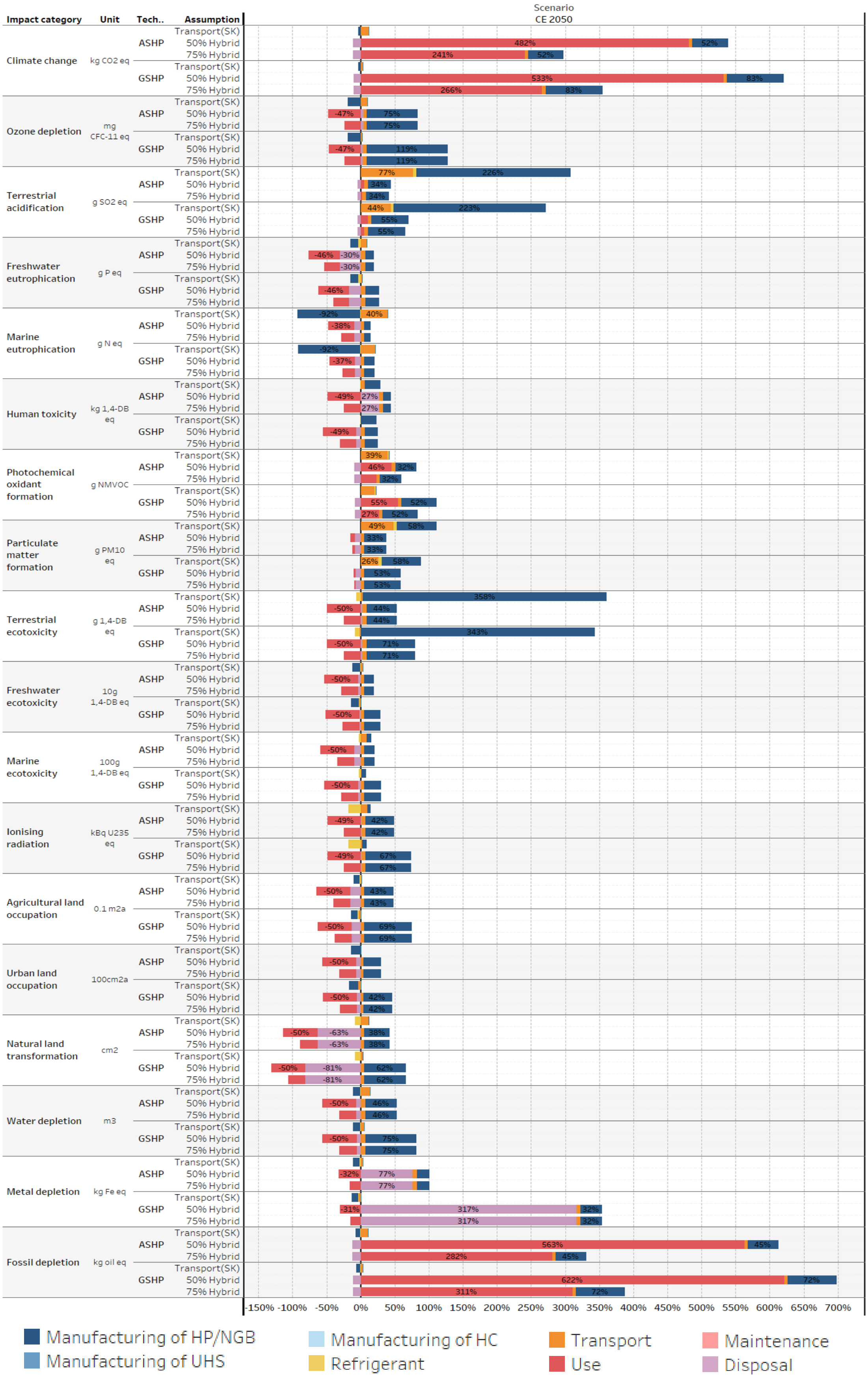

Figure 4.9 Lifetime environmental impact change of phases for transport and hybrid scenarios according to the CE 2050 model

4.6. Data Quality and Limitations

In order to validate the study, results are compared with the adopted study (Greening & Azapagic, 2012). Impact categories vary between different calculation methods, but several impact categories are common in most of the studies so only these categories are compared. The CC impact result of ASHP is 0.225 kg CO_2e/kWh in the baseline model, which is 18% lower than the adopted study (0.276 kg CO_2e/kWh). The GSHP result is 0.168 kg CO_2e/kWh for the baseline model and the result from the adopted study is 0.189 kg CO_2e/kWh, which is lower by around 11%. The OD category of the adopted study was 0.3 mg R11eq, which is 2% higher than this study (0.294 mg CFC-11eq). Additionally, TA category results for ASHP and GSHP were 0.86 and 0.59 g SO2eq, which is 2% and 8% lower than this study's results, respectively (0.842 and 0.638 g SO2eq). FEU and HT categories have higher differences that vary between 20% and 47%. The major reason causing these differences is the different methodologies used for the models. This study used the ReCiPe Midpoint (H) methodology; however, the adopted study used CML 2 Baseline 2001 methodology. Moreover, the adopted study used GaBi software, and this study used SimaPro software.

The limitation of the Transport (SK) scenario is that even though South Korea is used as a manufacturing location, rest-of-the-world (RoW) data for production assumptions and input data have been used in SimaPro due to the lack of data availability. Transport simulations are specific to South Korea; however, manufacturing data are not specific.

The impacts of the electricity mix, heat demand, efficiencies of technologies, lifetime of the products and disposal phase have been assessed for a sensitivity analysis. The parameters have been decided as:

- Doubling renewable share in the electricity mix;
- 50% increase in SPF (in this analysis, the efficiency of the gas boiler has been increased from 90% to 95%);
- 25% reduction in heat demand;
- 25% increase in product lifetimes;
- 25% increase in recycling rates of materials.

The results of sensitivity analysis indicate that electricity use has a significant impact on heat pump results. Doubling the renewable share in the electricity mix creates positive and negative impacts in several categories for ASHP (Figure 4.10). The highest influences occur on IR, NLT, FD, and CC categories with a decrease of around 41%, 41%, 40% and 34%, respectively. However, it could increase the results of TE, ALO, WD, FE, MEU and ME categories by 97%, 95%, 76%, 52%, 42% and 42%. The renewable share has no impact on NGB as it uses natural gas only.

A 50% increase in SPF creates an average of 29% reduction overall, and the highest changes occur in TE and ALO categories, accounting for 70% and 50%, respectively. The remaining categories expect a reduction range from 8% to 39%. Increasing boiler efficiency from 90% to 95% reduces all impact categories by an average of 4%.

A 25% reduction in demand has both negative and positive impacts on categories. Even though the lifetime results expect a reduction in this analysis, functional unit results fluctuate as the lifetime results are divided into heat demand, which is 25% reduced. Therefore, some categories react differently in the lifetime and functional unit results. The highest changes occur in TE and ALO categories, similar to SPF improvements for heat pumps. A similar issue occurs for the gas boiler and creates an increase of 4% overall, even though lifetime results are reduced.

Increasing the lifetime of products to 25 years increases the lifetime impact results as expected, with an increase of an average of 16%, 15% and 22% for ASHP, GSHP and NGB. However, functional unit results expect a decrease of 7%, 8% and 2% for the technologies, respectively.

A 25% increase in the recycling rates of materials also has a significant impact on several categories for heat pumps such as TE, MEU and ALO categories, with a reduction of 56%, 26% and 25%, and the WD category with an increase of 36% for heat pumps. However, its impact is relatively low for gas boilers.

This study thoroughly evaluates the environmental impacts of heat pumps and gas boilers with a scenario analysis; however, it has several limitations as followed:

- The life cycle assessment study analyses the entire life cycle stages from raw material extraction to the disposal phase of the technologies. The scenario analysis conducted in this study, however, only focused on the use phase. This is mainly because the use phase is the dominant stage so reducing the impacts from this stage is the priority. Moreover, modelling the reuse of secondary material in the manufacturing phase and implementing CE principles in the production stage is fairly complex in LCA analysis. Therefore, the impact of this stage is not analysed in scenario analysis.
- Changing manufacturing location from Europe/Germany to Asia/South Korea does not have much impact on overall scores. As the use phase is the major contributor to the impact categories changing manufacturing location does not have a significant impact. The generic RoW (Rest of the World) input data is used for the manufacturing phase because of the lack of data. Accessing data for manufacturing in South Korea requires extreme communication and time to collect data whereas the impact will be fairly limited. Therefore, only transport distances are revised for simplicity. However, this data would be collected for more accurate results for further studies.

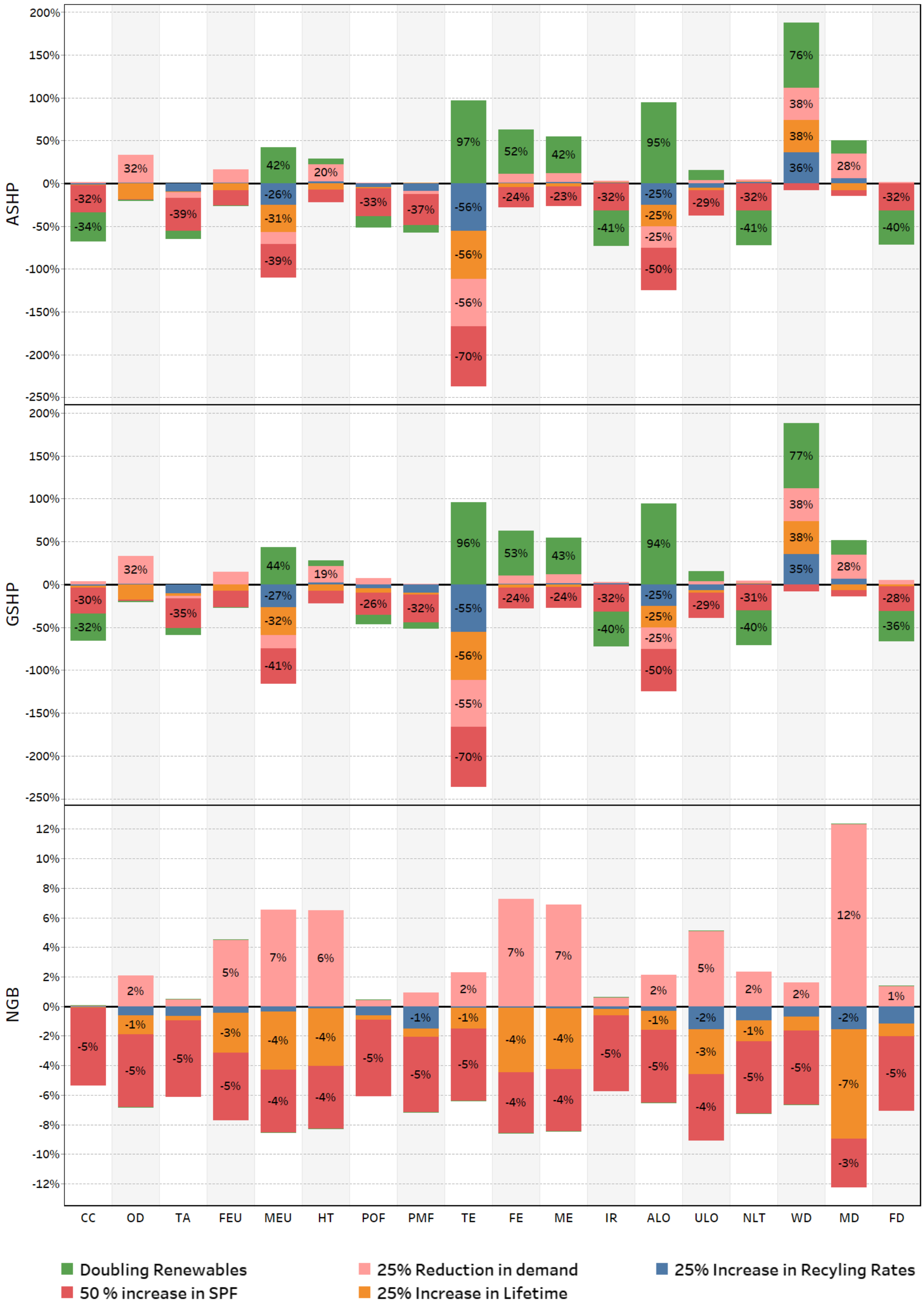

Figure 4.10 Impacts of different parameters on environmental results for heating technologies

4.7. Conclusions

This chapter evaluates the environmental impacts of key technologies (in this case air source heat pump, ground-source heat pump and natural gas boiler) through life cycle assessment to analyse the decarbonisation of heating in domestic buildings in the UK. Scenario analysis is conducted to investigate the current results with the government's future targets. Hybrid applications of heat pumps and gas boilers are also analysed to explore potential environmental savings. Three main scenarios are Circular Economy (CE), Resource Efficiency (RE) and Limited Growth (LG), and three alternative scenarios are Transport (SK), 50% Hybrid and 75% Hybrid.

The findings illustrate that replacing gas boilers with heat pumps could help to reduce lifetime CO_2e emissions by 78% (CE scenario), 77% (RE scenario) and 65% (LG scenario). The overall average impact is expected to be lower around 43% (CE scenario), 42% (RE scenario) and 31% (LG scenario). However, the following categories MEU, TE, FE, ME, ALO and WD perform 5% lower results in the CE than in the RE scenario. This is mainly because a higher renewable share in the electricity mix creates toxicity and land occupation problems; therefore, the CE scenario performs worse than the RE scenario in these categories.

Heat pumps provide significant reductions in the CO_2e emissions category; however, they do not provide sustainable solutions in other impact categories. Moreover, future scenarios expect reductions in most of the categories; however, several categories expect an increase in contrast to the remaining impact categories in all scenarios, such as freshwater ecotoxicity, marine ecotoxicity and metal depletion categories. It is important to point out that the high deployment of renewables, especially offshore wind farms, will have a positive impact in most of the categories, but also create toxicity problems and material scarcities.

Hybrid scenario results (50% Hybrid and 75% Hybrid) expect an increase in CO_2e emissions as boilers use fossil fuel, whereas the negative impacts coming from the remaining categories decrease. Therefore, a transition period that includes hybrid applications rather than replacing gas boilers individually should be provided to reduce negative impacts. In both hybrid scenarios, the overall results suggest a reduction in the baseline model (22% for 50% Hybrid scenario and 10% for 75% Hybrid scenario); however, the changes are 15% lower in the CE scenario. In the CC category, the changes are greater in the CE model as heat demand in the future will be relatively small; therefore, the importance of each phase will be higher to reduce the negative impacts. As the UK increases its ambitions to reach the 'Net Zero' target, actions for each phase should be considered thoroughly.

In the Transport (SK) scenario, changing the manufacturing location from Europe to Asia creates a 1% reduction in the baseline model and a 2% increase in the CE model. The reason for this slight increase is that the weight of the use phase is lower in the CE scenario due to efficiency improvements in houses and low carbon technologies, so the remaining phases comprise higher shares. As the main contributor to these changes is the manufacturing phase, better production lines through adapting CE principles could help to reduce the impact of the manufacturing phase. It is also important to reiterate that, even though the impact of the manufacturing phase is relatively smaller than the remaining phases (14% of the overall impact), the manufacturing of heat pumps has an impact in those locations where manufacturing takes place; therefore, this does not count in UK's territorial emissions.

Future scenarios show how decision-making could have a significant impact on environmental impacts. The CE scenario provides the best outcome among all scenarios without affecting economic growth. Reducing CO_2e emissions and preventing negative consequences are highlighted in the CE scenario. Achieving the Net Zero target requires strong commitments, and the results of future scenarios emphasise that the importance of impacts proposed by changes will reduce in time. Therefore, quick implementation of changes and stronger commitments are required in other areas as well, mainly energy efficiency improvement in houses (insulation, etc.), better-installed heat pumps with higher efficiencies and greener manufacturing solutions.

High demand for specific materials could enhance scarcities and environmental degradation related to resource extraction and processing. Circular economy principles through reuse and recycle options become more important in these situations. However, new strategies are needed to reach the 'Net Zero' target as it requires stronger commitments and more rapid market dissemination. Therefore, a comprehensive approach through a market introduction programme should be provided at the beginning before shifting from one technology to another. It is important to stress that different heating technologies require similar material demands and waste streams but with different amounts. High deployment of heat pumps in the CE scenario (17.7 million) will require high demand for metals and minerals, even though they do not have significant impacts on CO_2e emissions in the manufacturing phase. It would be of utmost importance to develop CE standards for the production of heat pumps, e.g., through procurement or eco-design, and include the use of secondary materials and the re-usability of all components. Developing a stock and flow system for materials could help to improve material efficiencies and reliance on raw materials. Moreover, top-down governmental support is required to establish circular supply chains rather than bottom-up initiatives at the supply chain level. Thus, a more comprehensive circular framework for decision-making tools could be created for sustainable design practice. A holistic approach should be considered where both territorial and consumption-based emissions are considered together for policies and future planning.

Chapter 4 has focused on the environmental impact of heat pumps compared with gas boilers. Future scenarios are also investigated to analyse future implications in line with government targets. The scenario analysis has created an approach to the end-user side of the system rather than focusing only on the manufacturing and installation phases. Previous studies investigated these heating technologies in the literature; however, each study is unique due to different goal and scope definitions, functional unit, system boundary and location of the study. Moreover, the UK electricity mix has been decarbonised during the last decade and the impact of this transition is not covered. Thus, investigating these heating technologies with the current electricity mix, hybrid applications, different manufacturing locations and the implications for 2050 in line with the government targets is a novel element for this research.

The study is mostly sensitive to the use phase; therefore, energy efficiency improvements and better-installed heat pumps with high COP values need more investigation. The next chapter (Chapter 5) will be about energy systems modelling which will try to optimize heat pump performance based on energy input, output and heating cost for different house archetypes and specifications. Hence, the measures to reduce use phase impacts will be explored.

Chapter 5

Energy Systems Modelling (ESM)

5.1. Introduction

This chapter aims to evaluate the performance of an air source heat pump with scenario analysis. As the major contributor stage to the environmental impacts in life cycle assessment (LCA) analysis is the use phase, this section optimises the heat pump operation by scenario analysis with different electricity tariffs, thermal energy storage tank sizes, heat pump sizes, flow temperatures and backup heater settings. Orkney is chosen as a case study due to high energy prices and fuel poverty levels. Moreover, islands are suitable testing grounds to analyse the entire energy system as a whole, so the replicability of the study is easier for other locations. Several objectives are identified to achieve the aim of the study:

- identify the best electricity tariff,
- investigate the need for a thermal energy storage tank,
- investigate the sizing of the heat pump,
- explore the need for a gas boiler backup heater,

to reduce energy consumption and heating cost.

This chapter extends the analysis presented in a published journal paper (Sevindik & Spataru, 2023).

5.2. Methodology

5.2.1. Model Description

The aim of the model is to optimize the system configuration and operation period by minimising energy consumption and cost. In terms of heating technology, Air Source Heat Pumps (ASHP) and gas boilers are used to provide the required energy and water demand and are supported by a thermal energy storage (TES) tank. In this section, only an air source heat pump is considered for the analysis. This is mainly because ground-source heat pumps require more comprehensive installation with land requirements and higher installation costs. Therefore, the applicability of air source heat pumps is easier and more common among consumers; therefore, only air source heat pump system is considered for simplicity.

The original energy model was built in Microsoft Excel (2021) and Visual Basic for Applications (VBA) macros are used to run simulations. It was developed for the Isle of Man (Spataru & Rassol, 2016) to explore the potential of using air source heat pumps (ASHP) as a technology to help the island to transition from fossil fuels to electricity. In the original model, three base case scenarios using the same building type with different characteristics (building footprint, U-values for external wall, air change rate, occupancy), and different ASHP sizes (kW) and storage tank sizes (L) were considered. The thermal model included three major components (demand, supply and consumption), and an economic model was developed for any combination of base fuel and financing arrangements specific to the Isle of Man.

In this research, the model has been developed further for Orkney considering different building archetypes (detached, semi-detached, end-terraced and mid-terraced), building specifications (unrefurbished, refurbished, new building), heat pump sizes (8.5 kW, 11.2 kW, 14.0 kW), thermal energy storage tank sizes (250L, 500L, 750L, 1000L), flow temperatures (35 °C, 45 °C, 55 °C), backup heater settings (gas boiler as a backup heater, no backup heater) and electricity tariffs (Standard, Economy7, Comfy Heat, Economy12, Economy20).

The time resolution of weather data (outside temperature and solar radiation) has been scaled down from monthly to hourly to have a higher temporal resolution. Apart from building archetypes, building specifications have been categorised. Thermal bridging, internal gains, thermal mass and standing loss for thermal energy storage tank calculations are included in the model for a thorough analysis. Heat pump specifications for different sizes and flow temperatures are taken from the manufacturer's website. Hourly heat pump maximum, medium and minimum capacities and COP curves are calculated by the model based on outside temperature and flow temperature. More details about these features are given on the following pages. The structure of the methodology is described in Figure 5.1.

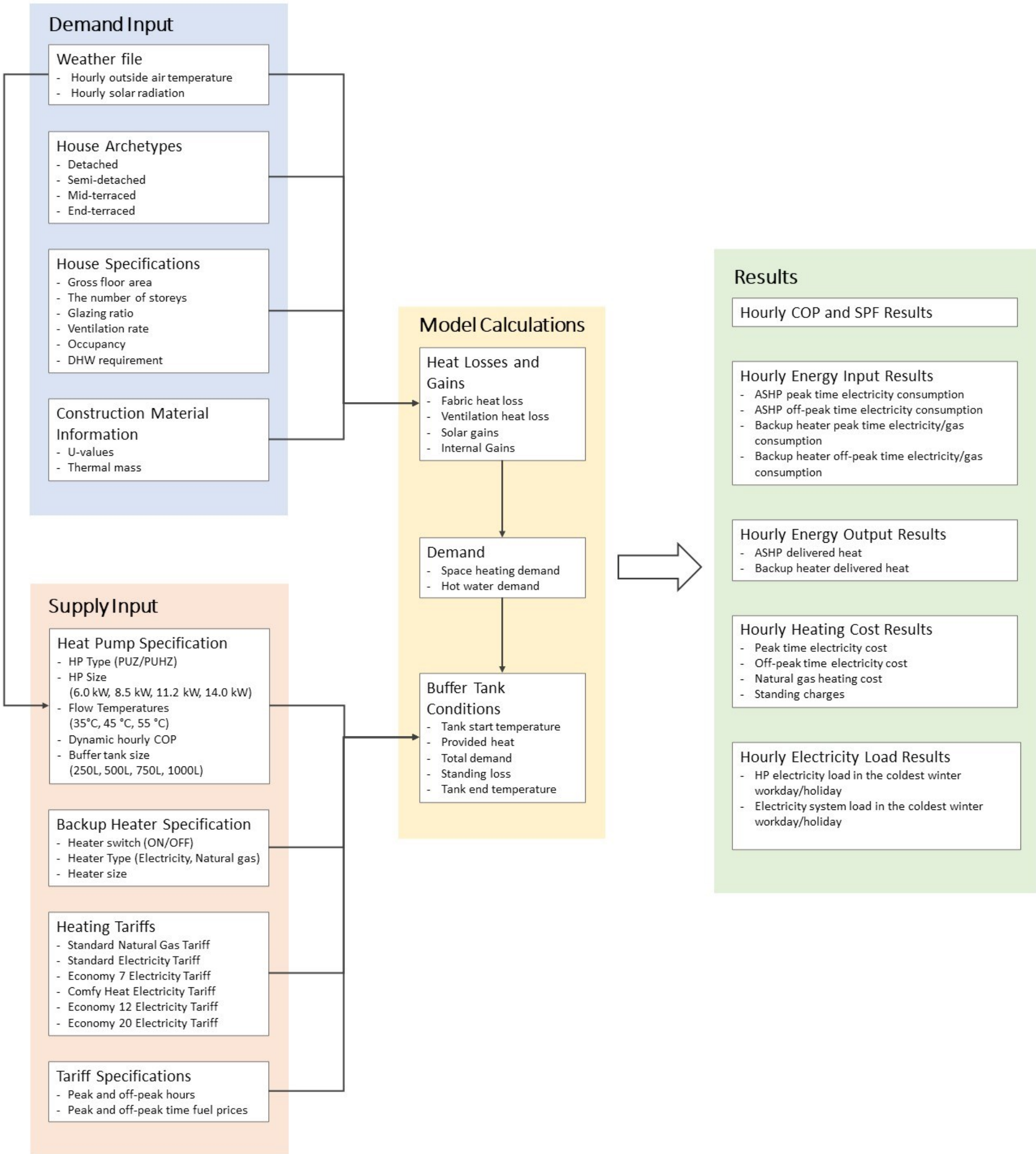

Figure 5.1 Energy system modelling (ESM) methodology structure

All simulations have been carried out for Orkney (Scotland/UK); therefore, hourly outdoor temperature and solar irradiation data have been collected from Renewables.ninja to calculate heat gains and losses (Figure 5.2) (Gelaro et al., 2017). The internal thermostat set point temperature is specified as 21 °C based on recommendations from World Health Organization (2018) and Public Health England (2014). A number of archetypes have been identified to represent the housing stock (*'Detached'*, *'Semi-detached'*, *'End-terrace'* and *'Mid-terrace'*) according to Scottish Government Statistics (Scottish Government Statistics, 2020) (Figure 5.3). These archetypes are used to analyse the variation of heating technologies' performance with different physical properties.

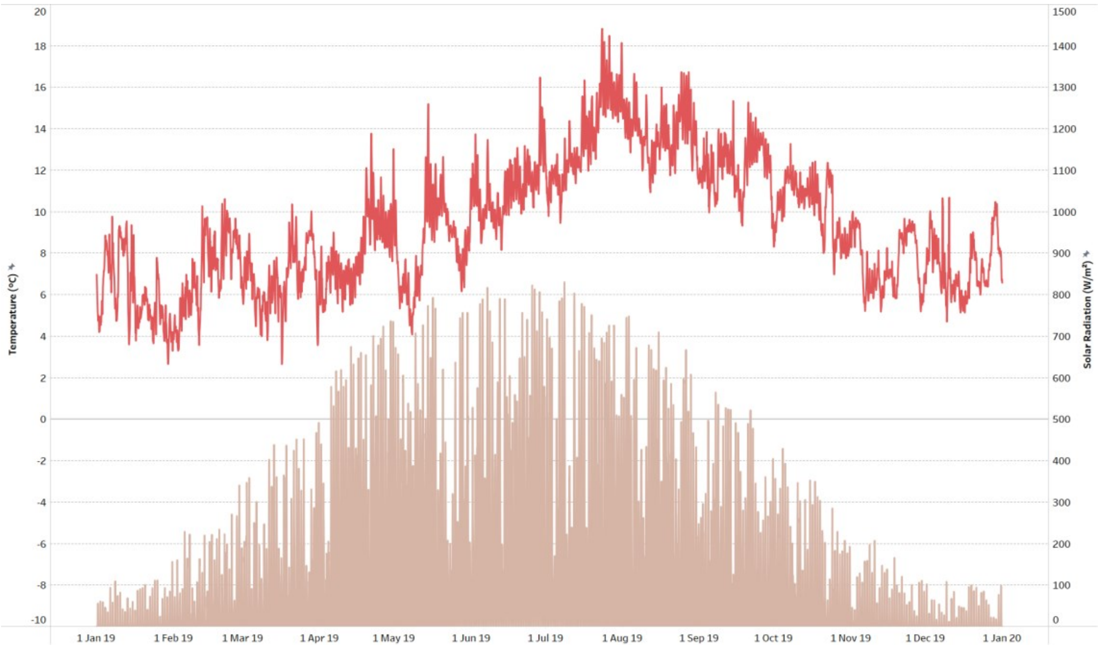

Figure 5.2 Hourly weather and solar data for Orkney (Data source: Gelaro et al., 2017)

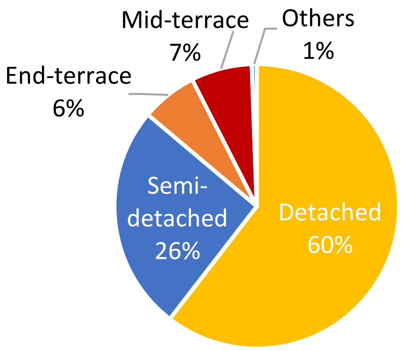

Figure 5.3 Orkney building archetypes (Data source: Scottish Government Statistics, 2020)

Building archetypes' specifications, building thermal properties, and specifications of building materials have been identified (Table 5.1, Table 5.2, Table 5.3, Table 5.4). Energy Performance Certificate (EPC) data (Scottish Government Statistics, 2020) has been used for information about the gross floor area of the houses, the number of storeys, room height and occupancy. Glazing ratio information and building thermal properties data have been taken from The Building Regulations Approved Document Part L1A (HM Government, 2014). The houses are named into three categories *'Refurbished'*, *'Unrefurbished'* and *'New Building'*. Data on domestic hot water (DHW) consumption, distribution of DHW throughout the day and heating patterns have been taken from Energy Saving Trust's report (Energy Savings Trust, 2008). The Government's Standard Assessment Procedure (SAP) for Energy Rating of Dwellings (BRE, 2014) has been used for generic values (plan aspect ratio, floor thickness, etc.).

Table 5.1 Orkney building archetypes' specifications (Data source: Scottish Government Statistics, 2020)

Archetype Specifications	Unit	Detached	Semi-Detached	End-Terrace	Mid-Terrace
Gross Floor Area	m2	115	79	75	74
Occupancy	p/m2	0.015	0.026	0.027	0.030

Table 5.2 Building specifications for the archetypes (Data sources: (Scottish Government Statistics, 2020)[1], (BRE, 2014)[2], (HM Government, 2014)[3], (Energy Savings Trust, 2008)[4],(WHO, 2018)[5], (PHE, 2014)[6]

General Specifications	Unit	Value	Reference
Storeys		2	1
Room Height	m	2.4	
Plan Aspect Ratio		1.4	2
Floor Thickness	m	0.2	
Glazing Ratio	%	0.25	3
Ventilation Rate	$l/s/m^2$	0.3	
DHW Usage (daily/person)	l	60	4
Window Transmittance factor		0.7	2
Window Frame Factor		0.7	
Solar Access Factor		0.8	
Setpoint Temperature	°C	21	5,6

Table 5.3 Building thermal properties for the archetypes (Data source: HM Government, 2014)

Thermal Specifications	Unit	Unrefurbished Building	Refurbished Building	New Building
Wall	W/m^2K	0.70	0.55	0.18
Roof	W/m^2K	0.35	0.16	0.13
Floor	W/m^2K	0.70	0.30	0.10
Window	W/m^2K	1.60	1.60	1.40
Thermal Bridging	W/m^2K	0.15	0.11	0.08
Ventilation heat loss	ac/h	0.40	0.40	0.40

Table 5.4 Thermal properties of building materials

Building Materials	Density (kg/m^3)	Specific Heat Capacity (J/kgK)
Common brick	1922	837
Aerated concrete	750	1000
Concrete (heavyweight)	2300	1000
Concrete (mediumweight)	1400	1000
Concrete (lightweight)	600	1000
Glass	2470	750
Plaster (gypsum)	1200	837
Plaster (heavyweight)	1300	1000
Plaster (lightweight)	600	1000
Plasterboard (gypsum)	950	840
Plywood (heavyweight)	700	1400
Plywood (lightweight)	560	2500
Timber	650	1200
Screed	1200	840

Electricity and gas tariff data have been collected for 6 different tariffs. Standard and Economy7 tariff has been gathered from ScottishPower (2021) to analyse Orkney electricity prices. Moreover, tariffs which are not yet available on Orkney such as Economy12 (Guernsey Electricity, 2021), Economy20 and Comfy Heat (Jersey Electricity, 2021) also analysed to investigate different options (Figure 5.4). The distribution of off-peak and peak hours during the day was identified according to tariff options (Figure 5.5). Standard tariff assumes that there is no peak time pricing so standard pricing is assumed as an off-peak tariff. Economy7 tariff assumes 7 hours of off-peak time during the night. The number of off-peak hours is very similar in the Comfy Heat tariff with 8 hours, but they are distributed throughout the day with 4 hours during the night and 4 hours during the day. Economy12 and Economy20 tariffs have 12- and 20-hours off-peak time with 2 hours during the day and the remaining is during the night.

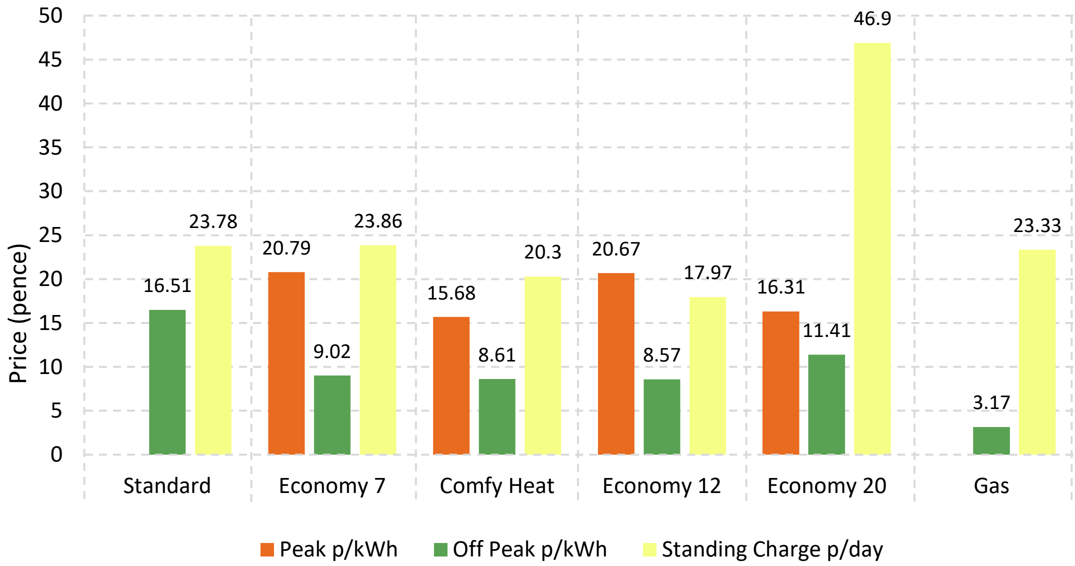

Figure 5.4 Electricity and Gas tariffs (Data sources: Guernsey Electricity, 2021; Jersey Electricity, 2021; ScottishPower, 2021)

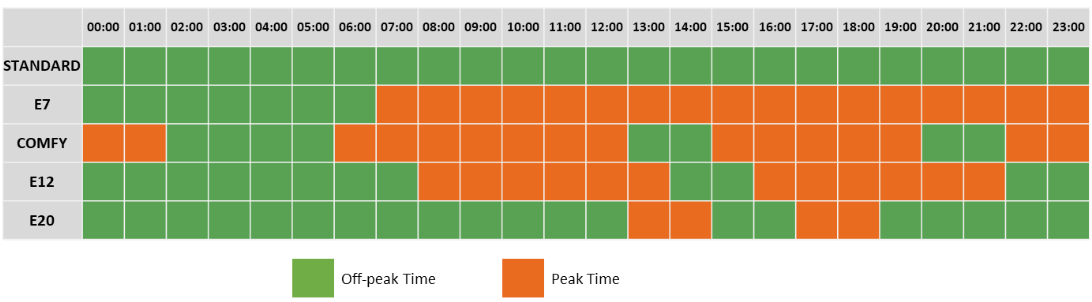

Figure 5.5 Distribution of off-peak and peak times during the day for electricity tariffs

Thermal energy storage tanks store energy in required times and help to avoid overpricing in peak times. Therefore, four different sizes of thermal energy storage tanks (250L, 500L, 750L, and 1000L) are tested in the model to explore lower peak time heating costs (Figure 5.6). Standing losses are calculated based on SAP document (BRE, 2014) and Hot Water Association (HWA, 2010) methodologies. In terms of the backup heater, both electricity and natural gas-fired heaters are tested. It has been assumed that condensing gas boiler has a 15kW size capacity with 90% efficiency, and the electric heater has an 8.5 kW size capacity. In scenario analysis, the performance of the heat pump is tested with and without these backup heaters in operation.

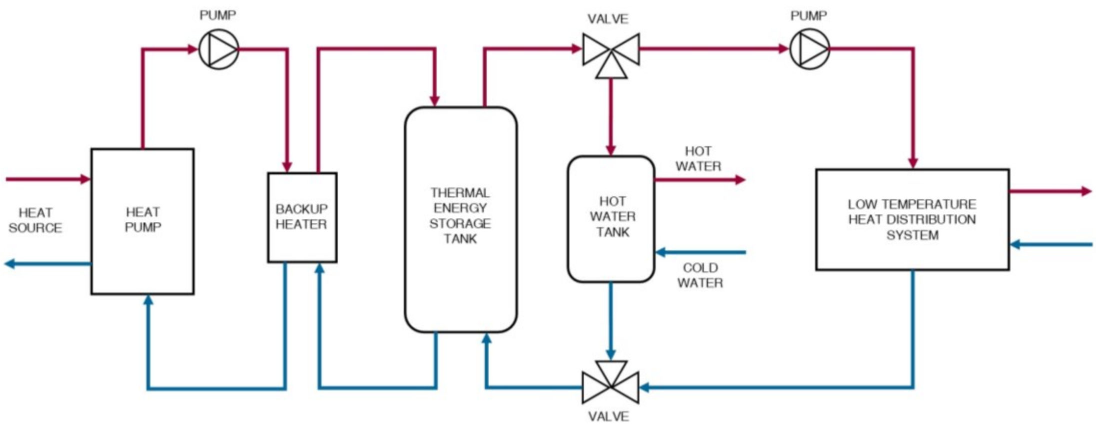

Figure 5.6 Configuration of air source heat pump (ASHP) and backup heater with thermal energy storage (TES) tank

There are various heat pump types; however, ASHP has been selected in the modelling for its wide range of use and less space requirement during installation. Mitsubishi Ecodan PUZ series are selected because of using R32 (low GWP and Ozon Depletion potential) to explore various heating performances (Mitsubishi Electric, 2020). However, the PUHZ series is also investigated to test the impact of using a different refrigerant (R410) on energy performance. In order to select the correct size of the heat pump, three different sizes are explored 8.5kW (PUZ85), 11.2kW (PUZ112), and 14.0kW (PUZ140). COP and capacity data under different outdoor temperature conditions and water outlet temperatures (35 °C, 45 °C, and 55 °C) are presented in Figure 5.7 and Figure 5.8. These figures illustrate that the PUZ series provide higher capacities and COP values under the same flow temperatures. Moreover, the PUZ series has an R32 type of refrigerant which has a lower environmental impact; therefore, the PUZ series are selected for scenario analysis.

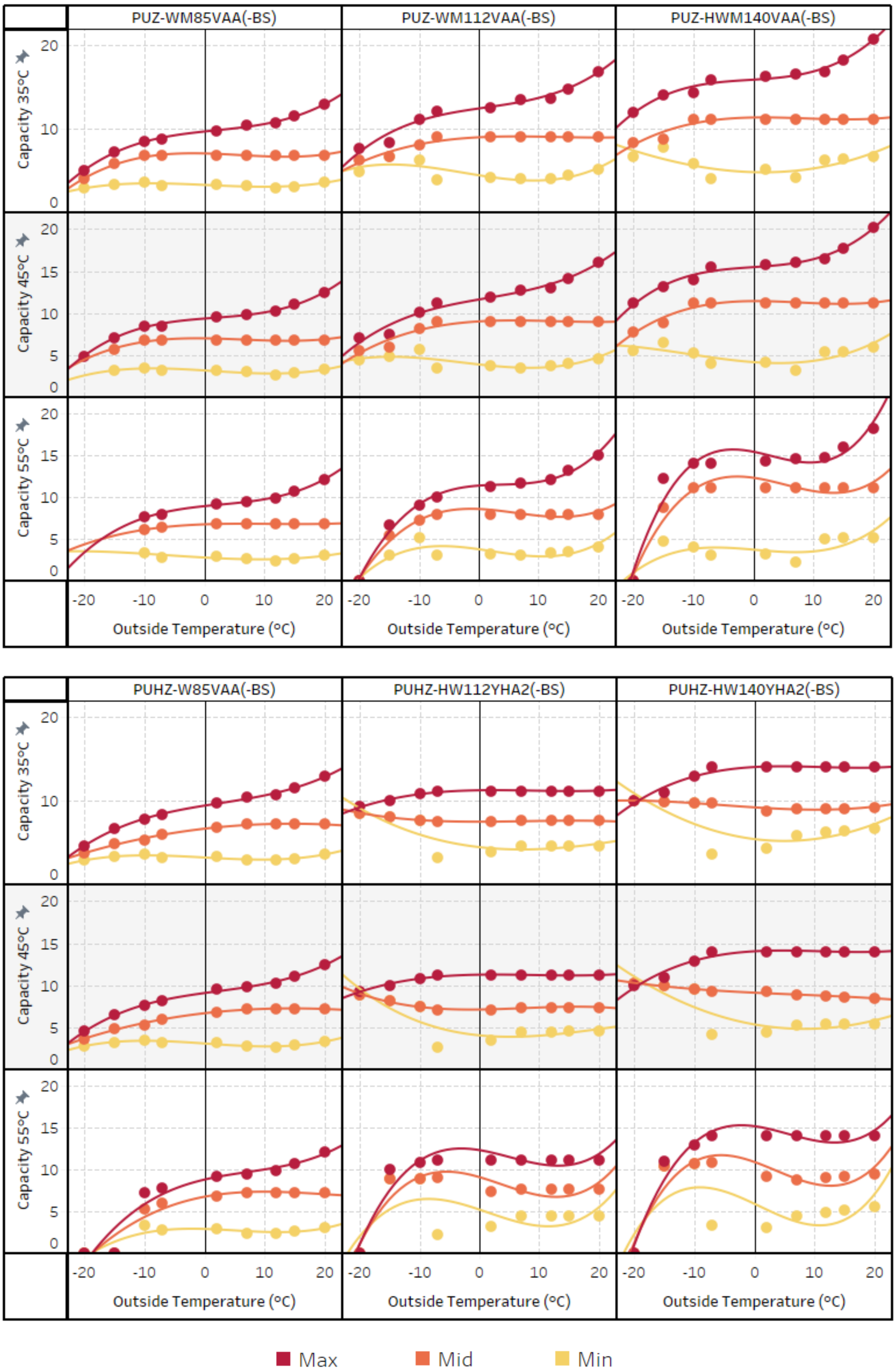

Figure 5.7 Capacity and COP performance of Mitsubishi Ecodan PUZ series heat pumps under different water outlet and outside temperatures (Data source: Mitsubishi Electric, 2020)

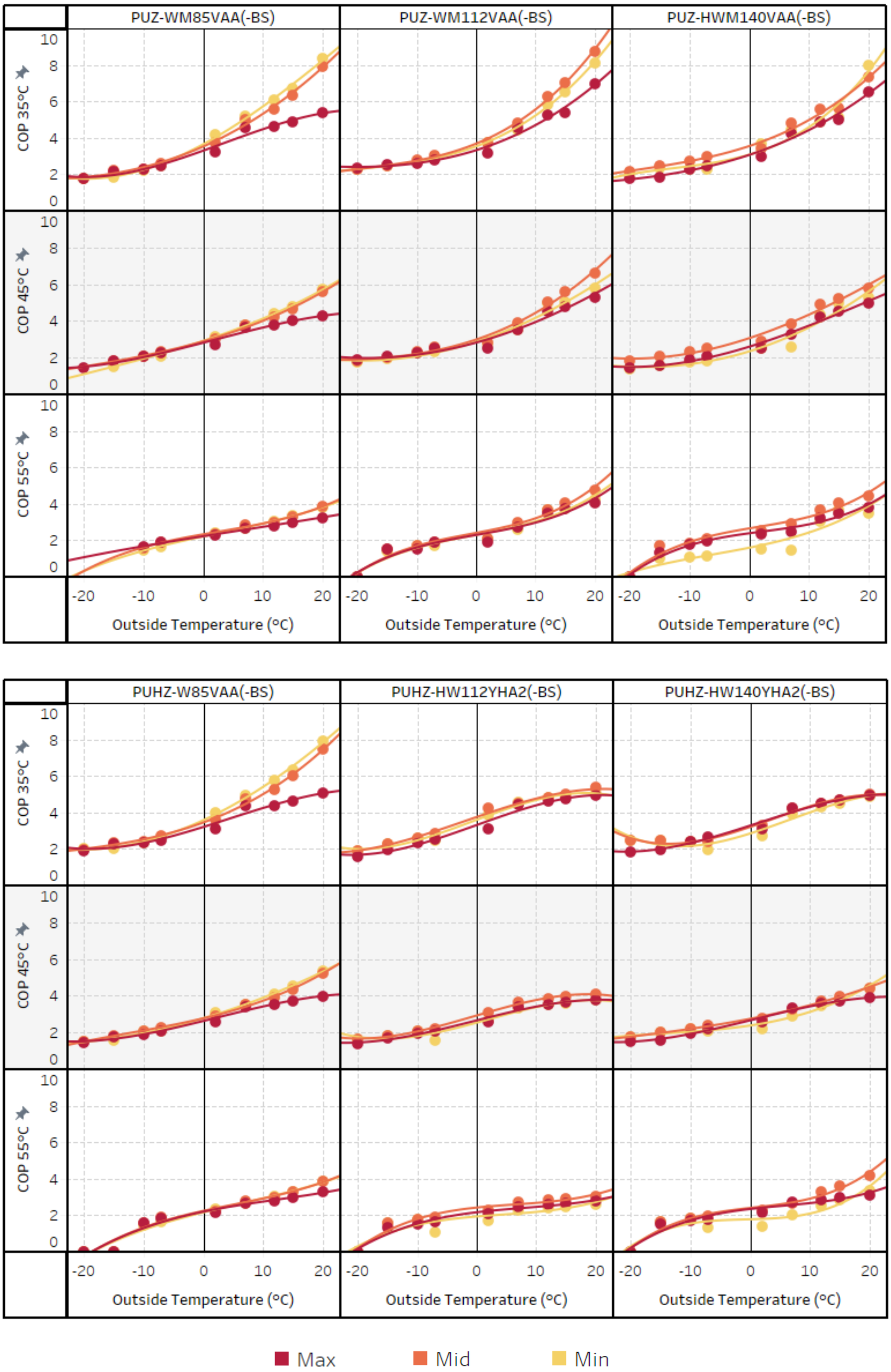

Figure 5.8 Capacity and COP performance of Mitsubishi Ecodan PUHZ series heat pumps under different water outlet and outside temperatures (Data source: Mitsubishi Electric, 2020)

5.2.2. Model Calculation

Losses

The model starts to calculate heat gains and losses to analyse the performance of the dwelling. Fabric heat loss is calculated as in the following Equation 5.1.

$$L_F = \sum (A \times U) \quad (5.1)$$

where L_F is fabric heat loss (W/K), A is the area of component (m^2) and U is the thermal transmittance of the component (W/m^2K).

Thermal bridges are calculated as in the following Equation 5.2.

$$L_{TB} = y \times \sum A_{exp} \quad (5.2)$$

where L_{TB} is losses from thermal bridging (W/K), A_{exp} is the total area of exposed surfaces to the external environment and y is the thermal bridging factor (W/m^2K).

Ventilation heat loss is calculated as in the following Equation 5.3.

$$L_V = 0.33 \times n \times V \quad (5.3)$$

where L_V is ventilation heat loss (W/K), n is air change rate (ach) and V is the volume of heated space (m^3).

Total heat loss is calculated as in the following Equation 5.4.

$$\sum L_{Total} = (L_F + L_{TB} + L_V) \times T_h - T_e \quad (5.4)$$

where L_{Total} is total heat loss (W), T_h is heating setpoint temperature, T_e is external temperature.

Gains

Solar gains are calculated as in the following Equation 5.5.

$$G_S = 0.9 \times A_W \times S \times g \times FF \times Z \quad (5.5)$$

where 0.9 represents typical average transmittance, A_w is the window area (m^2), S is the solar flux (W/m^2), g is the transmittance factor of the glazing at normal incidence, FF is the frame factor (fraction of the glazed area) and Z is the solar access factor.

Internal gains are calculated as in the following Equation 5.6.

$$G_I = A \times f \qquad 5.6$$

where *A* is the gross floor area (m^2) and f is the internal gain factor (W/m^2).

Total gains are calculated as in the following Equation 5.7.

$$\sum G_{Total} = G_S + G_I \qquad 5.7$$

Thermal Mass Calculations

The temperature reduction from setpoint temperature depends on the thermal properties of building materials used in the dwelling calculated as in the following Equations 5.8-5.16**.**

$$HLP = \frac{\sum L_{Total}}{A_{GF}} \qquad 5.8$$

$$TMP = \frac{\sum C \times A}{A_{GF}} \qquad 5.9$$

$$T_{au} = TMP \,/\, (3.6 \times HLP) \qquad 5.10$$

$$a = 1 + T_{au}/15 \qquad 5.11$$

$$T_c = 4 + 0.25 \times T_{au} \qquad 5.12$$

$$\gamma = \sum G_{Total} \,/ \left(\sum L_{Total} \times (T_h - T_e) \right) \qquad 5.13$$

$$\text{if } \gamma > 0 \text{ and } \gamma \neq 1: \quad \eta = \frac{1-\gamma^a}{1-\gamma^{a+1}}$$

$$\text{if } \gamma = 1: \quad \eta = \frac{a}{a+1} \qquad 5.14$$

$$\text{if } \gamma \leq 0 \quad \eta = 1$$

$$T_{sc} = (1 - R) \times (T_h - 2) + R \times (T_e + \eta \times G_{Total} \,/\, L_{Total}) \qquad 5.15$$

$$u = 0.5 \times (T_h - T_{sc}) / T_c \qquad 5.16$$

where HLP is the heat loss parameter (W/m^{2}K), L_{Total} is total heat losses (W/m^{2}K), A_{GF} is the gross floor area of the building (m^2), TMP is the thermal mass parameter (kJ/m^{2}K), C is the specific heat capacity of building materials, A is the area of building materials, T_{au} is a time constant, a is a constant, T_c is a time constant, γ is a constant, G_{Total} is total gains, L_{Total} is total losses, T_h is heating setpoint temperature, T_e is external temperature, η is utilisation factor, T_{sc} is internal temperature without heating, R is the responsiveness of the heating system, u is temperature reduction.

Tank Temperature Calculations

Tank temperature is calculated as in the following Equations 5.17-5.19.

$$\sum D_{DHW} = V_W \times 4.18 \times T \quad 5.17$$

$$H_R = \sum L_{Total} - \sum G_{Total} + \sum D_{DHW} \quad 5.18$$

$$\text{if } T_{TS} > 5+T_e \qquad T_{TE} = T_{TS} - \frac{\sum H_R}{V_T \times 4{,}18} - \frac{\sum H_P}{V_T \times 4{,}18} - L_S$$

$$\text{if } T_{TS} \leq 5+T_e \qquad T_{Ts} = T_e \quad 5.19$$

where D_{DHW} is DHW demand, V_W is the volume of the water (litre), T is required water outlet temperature (°C), H_R is required heat, L_{Total} is total losses (W), G_{Total} is total gains (W), D_{Water} is hot water demand (W), T_{TS} is tank starting temperature, T_e is external temperature, T_{TE} is tank end temperature, H_P is provided heat with heat pump and backup heater, V_T is tank size (litre), L_S is standing loss (°C) of the tank.

Standing loss is calculated as in the following Equations 5.20-5.22.

$$L_S = f_V \times f_T \times f_C \times V_C \quad 5.20$$

$$f_V = (120/V_C)^{\frac{1}{3}} \quad 5.21$$

$$f_C = (0.005 + 0.55/(t+4) \quad 5.22$$

where L_S is the standing loss of the cylinder tank, f_V is the volume factor, f_T is the temperature factor, f_C is the cylinder loss factor, V_C is cylinder tank volume (litre), and t is insulation thickness (mm).

The heating schedule is decided as maximising heat pump operation during off-peak times and avoiding gas boiler usage and minimising heat pump operation during peak times and covering the remaining demand with a backup heater. The model has calculated heat pump and backup heater capacities as in the following Equations 5.23-5.27.

In peak times;

if $C_{MIN} \geq H_R$ $\quad$ $E_P = C_{MIN}$

if $C_{MIN} < H_R$ $\quad$ $E_P = C_{MID}$ $\quad$ 5.23

if $T_E < T_L$ $\quad$ HP => ON $\quad$ 5.24

In off-peak times;

$E_P = C_{MAX}$ $\quad$ 5.25

if $T_E > T_H$ $\quad$ HP => OFF $\quad$ 5.26

At all times;

if $T_E < T_B$ $\quad$ Backup => ON $\quad$ 5.27

where C_{MIN}, C_{MID}, and C_{MAX} are minimum, medium and maximum heat pump capacities, H_R is required heat demand, E_P is provided energy, T_E is the end temperature of the tank, T_L is the lower threshold temperature, T_H is the higher threshold temperature, T_B is the backup temperature.

5.3. Results & Discussion

The scenario names are presented in a structure based on the specifications of the scenarios for simplicity (Figure 5.9). Each section defines the selected option for that scenario so it will be easier to identify scenarios and compare them.

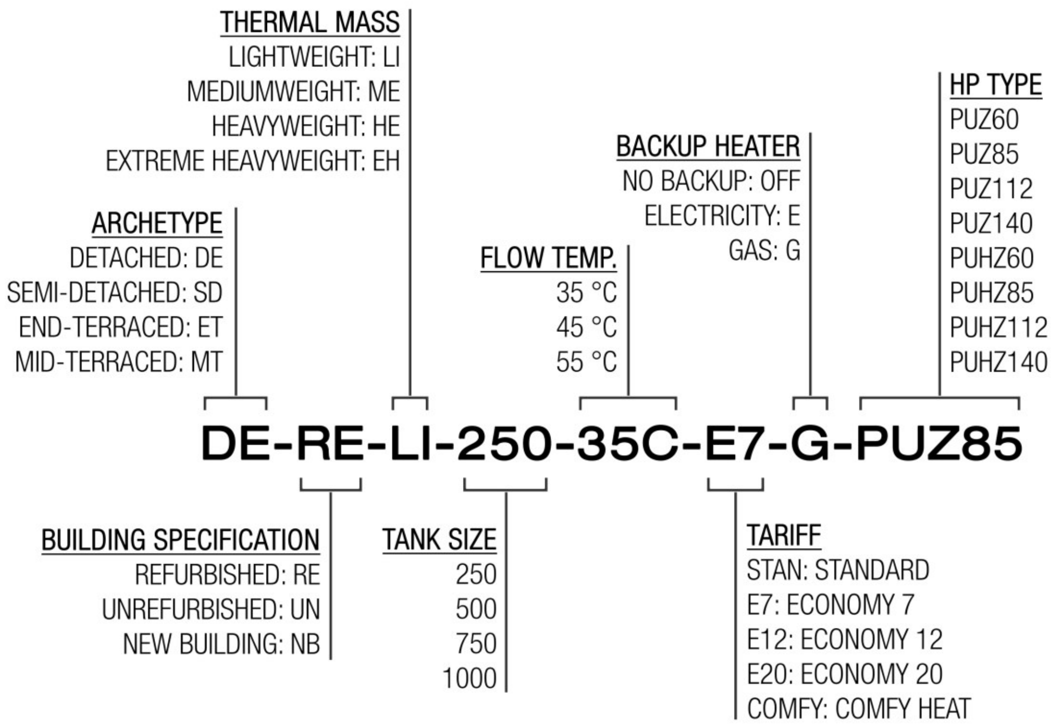

Figure 5.9 Structure of the scenario names

5.3.1. Sensitivity Analysis

The baseline scenario for the model has been identified as 'DE-RE-ME-250-35C-E7-G-PUZ112' to provide results for a refurbished detached house which has a mediumweight thermal mass, 250-litre thermal storage, PUZ112 model heat pump running with 35 °C flow temperature using Economy 7 electricity tariff and a natural gas backup heater (boiler). In order to run a sensitivity analysis, one setting has been changed in each iteration to investigate the impacts (Table 5.5).

Figure 5.10 shows SPF and daily average COP values for the entire year. The baseline scenario has a minimum daily COP of 3.84 and it can reach 7.31 during the summer. This leads to 4.59 SPF which is quite high. This is mainly because Orkney's weather conditions are not extreme and do not go below 3.5 °C during the winter. As heat pump performance is dependent on weather conditions high COP values are achieved under these conditions. PUZ85 type of heat pump has similar results with a slightly higher SPF (4.67); however, PUZ140 has lower SPF (4.29) with a maximum of 5.51 daily COP which is more stable throughout the year. PUHZ series show lower efficiencies than the PUZ series with 4.43, 4.39, and 4.01 SPF for PUHZ85, PUHZ112, and PUHZ140 respectively. Changing the backup heater type to electricity does not have an impact on the baseline scenario. However, lower maximum COP values resulted when no backup heater is in operation even though SPF is the same. Changing the electricity tariff will reduce the SPF slightly in all tariffs except the Comfy Heat tariff. E20 and Standard tariffs create fewer fluctuations in daily COP values because of the high number of off-peak time hours throughout the day. Changing water outlet temperature has a drastic change in daily COP values with 2.95 and 2.28 minimum COP values for 45 °C and 55 °C water outlet temperatures. Maximum values also decreased to 5.41 and 4.20 respectively and result in 3.69 and 2.79 SPF values. The highest impact in SPF values was achieved with lower water outlet temperatures.

Table 5.5 Scenarios for sensitivity analysis (Red cells show the changes made to the baseline scenario after each iteration)

Scenario Name	Building Type	Building Specs	Thermal Mass	Tank Size	Flow Temp	Tariff	Backup Heater	Heat Pump Type
DE-RE-ME-250-35C-E7-G-PUZ112	DE	RE	ME	250	35C	E7	G	PUZ112
DE-RE-ME-250-35C-E7-G-PUZ85	DE	RE	ME	250	35C	E7	G	PUZ85
DE-RE-ME-250-35C-E7-G-PUZ140	DE	RE	ME	250	35C	E7	G	PUZ140
DE-RE-ME-250-35C-E7-G-PUHZ85	DE	RE	ME	250	35C	E7	G	PUHZ85
DE-RE-ME-250-35C-E7-G-PUHZ112	DE	RE	ME	250	35C	E7	G	PUHZ112
DE-RE-ME-250-35C-E7-G-PUHZ140	DE	RE	ME	250	35C	E7	G	PUHZ140
DE-RE-ME-250-35C-E7-OFF-PUZ112	DE	RE	ME	250	35C	E7	OFF	PUZ112
DE-RE-ME-250-35C-E7-E-PUZ112	DE	RE	ME	250	35C	E7	E	PUZ112
DE-RE-ME-250-35C-E12-G-PUZ112	DE	RE	ME	250	35C	E12	G	PUZ112
DE-RE-ME-250-35C-E20-G-PUZ112	DE	RE	ME	250	35C	E20	G	PUZ112
DE-RE-ME-250-35C-COM-G-PUZ112	DE	RE	ME	250	35C	COM	G	PUZ112
DE-RE-ME-250-35C-STAN-G-PUZ112	DE	RE	ME	250	35C	STAN	G	PUZ112
DE-RE-ME-250-45C-E7-G-PUZ112	DE	RE	ME	250	45C	E7	G	PUZ112
DE-RE-ME-250-55C-E7-G-PUZ112	DE	RE	ME	250	55C	E7	G	PUZ112
DE-RE-ME-500-35C-E7-G-PUZ112	DE	RE	ME	500	35C	E7	G	PUZ112
DE-RE-ME-750-35C-E7-G-PUZ112	DE	RE	ME	750	35C	E7	G	PUZ112
DE-RE-ME-1000-35C-E7-G-PUZ112	DE	RE	ME	1000	35C	E7	G	PUZ112
DE-RE-LI-250-35C-E7-G-PUZ112	DE	RE	LI	250	35C	E7	G	PUZ112
DE-RE-HE-250-35C-E7-G-PUZ112	DE	RE	HE	250	35C	E7	G	PUZ112
DE-RE-EH-250-35C-E7-G-PUZ112	DE	RE	EH	250	35C	E7	G	PUZ112
DE-UN-ME-250-35C-E7-G-PUZ112	DE	UN	ME	250	35C	E7	G	PUZ112
DE-NB-ME-250-35C-E7-G-PUZ112	DE	NB	ME	250	35C	E7	G	PUZ112
SD-RE-ME-250-35C-E7-G-PUZ112	SD	RE	ME	250	35C	E7	G	PUZ112
MT-RE-ME-250-35C-E7-G-PUZ112	MT	RE	ME	250	35C	E7	G	PUZ112
ET-RE-ME-250-35C-E7-G-PUZ112	ET	RE	ME	250	35C	E7	G	PUZ112
DE-RE-ME-250-35C-E7-G-PUZ112-T20*	DE	RE	ME	250	35C	E7	G	PUZ112
DE-RE-ME-250-BOILER-ONLY-20	DE	RE	ME	250	-	-	BOILER ONLY	-

*Setpoint temperature is reduced by 1 °C

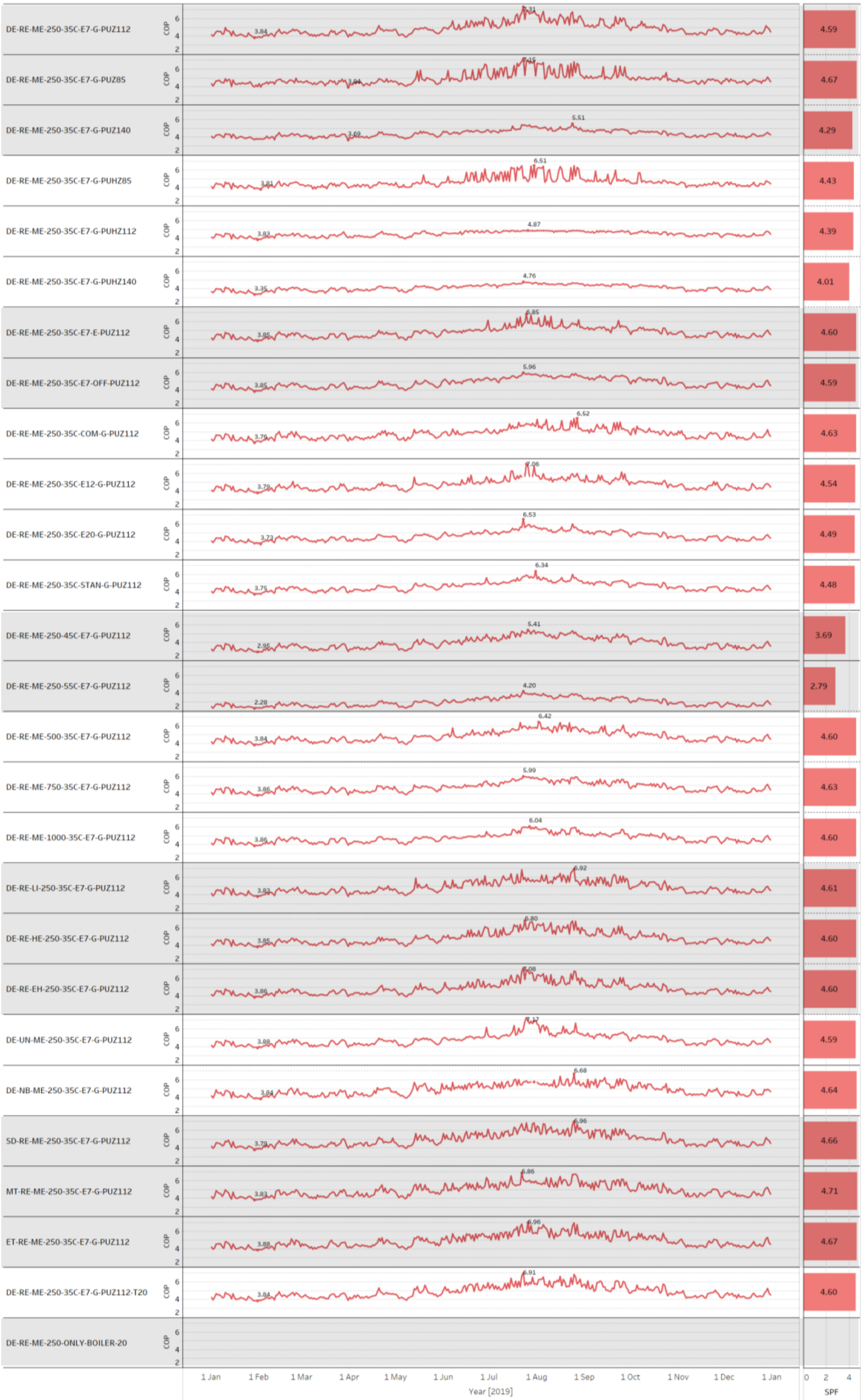

Figure 5.10 SPF and daily COP values for heat pumps in sensitivity analysis scenarios

Changing the tank size does not have much impact on SPF values but offers more stable COP values without fluctuations. Changing thermal mass, archetypes, building specifications or setpoint temperature do not have a significant impact on SPF values; however, they change the amount of energy required; therefore, slight changes in SPF values depend on energy consumption. Changing the archetype to a mid-terraced house, for instance, reduce the amount of energy needed; therefore, a slightly higher SPF value is achieved.

Figure 5.11 illustrates the energy consumption values of sensitivity analysis scenarios for a heat pump and a backup heater during peak and off-peak times. The baseline scenario indicates that the backup heater will dominate the energy input with 9285 kWh energy consumption (8295 kWh peak time and 990 kWh off-peak time). The heat pump will cover the 1780 kWh energy input need (702 kWh peak time and 1078 kWh off-peak time). Increasing the size of the heat pump helps to reduce the consumption of the gas boiler to 8685 kWh; however, it shifts some peak time usage of the backup heater to off-peak time, and peak time electricity consumption also increases to 845 kWh. Reducing the size of the heat pump has a reverse impact.

Changing the backup heater to electricity will decrease the consumption of the backup heater to 6460 kWh as electricity is more efficient than gas whereas no significant improvement was seen in heat pump performance. The noticeable change occurs when the backup heater is not operating so the heat pump will cover the entire demand with only 3446 kWh of electricity.

In terms of different electricity tariffs, the lowest energy consumptions occur in Standard and Economy 20 (E20) tariffs with 6015 kWh and 6553 kWh in total. Scenarios with Economy 12 (E12) and Comfy Heat tariffs perform better than Economy 7 (E7) tariff (9638 kWh and 10,515 kWh respectively) as the number of hours in off-peak time is greater.

Increasing the flow temperature of the heat pump will increase the energy consumption similar to thermal mass. When the thermal mass of the building increases higher energy consumption occurs. However, increasing the thermal storage tank size will have a positive impact. Total energy consumption can be reduced to 6243 kWh with a 1000 litre tank size by reducing boiler consumption and increasing electricity usage during off-peak time.

Changing building types and specifications has various impacts. An unrefurbished building will increase the consumption to 15,145 kWh but a more efficient new building can reduce the consumption to 6968 kWh. Also, the highest consumption occurs in a detached house as in the baseline scenario (11,064 kWh) and is followed by semi-detached, end-terraced and mid-terraced houses with 8781 kWh, 8543 kWh and 7736 kWh respectively. This is mainly because of the differences in the size of the houses and the area of exposed walls.

On the other hand, reducing the setpoint temperature by 1 °C will decrease the consumption to 10,048 kWh which creates a 10% reduction. Finally, turning the heat pump off and covering the demand with the gas boiler will increase energy consumption significantly (18,480 kWh).

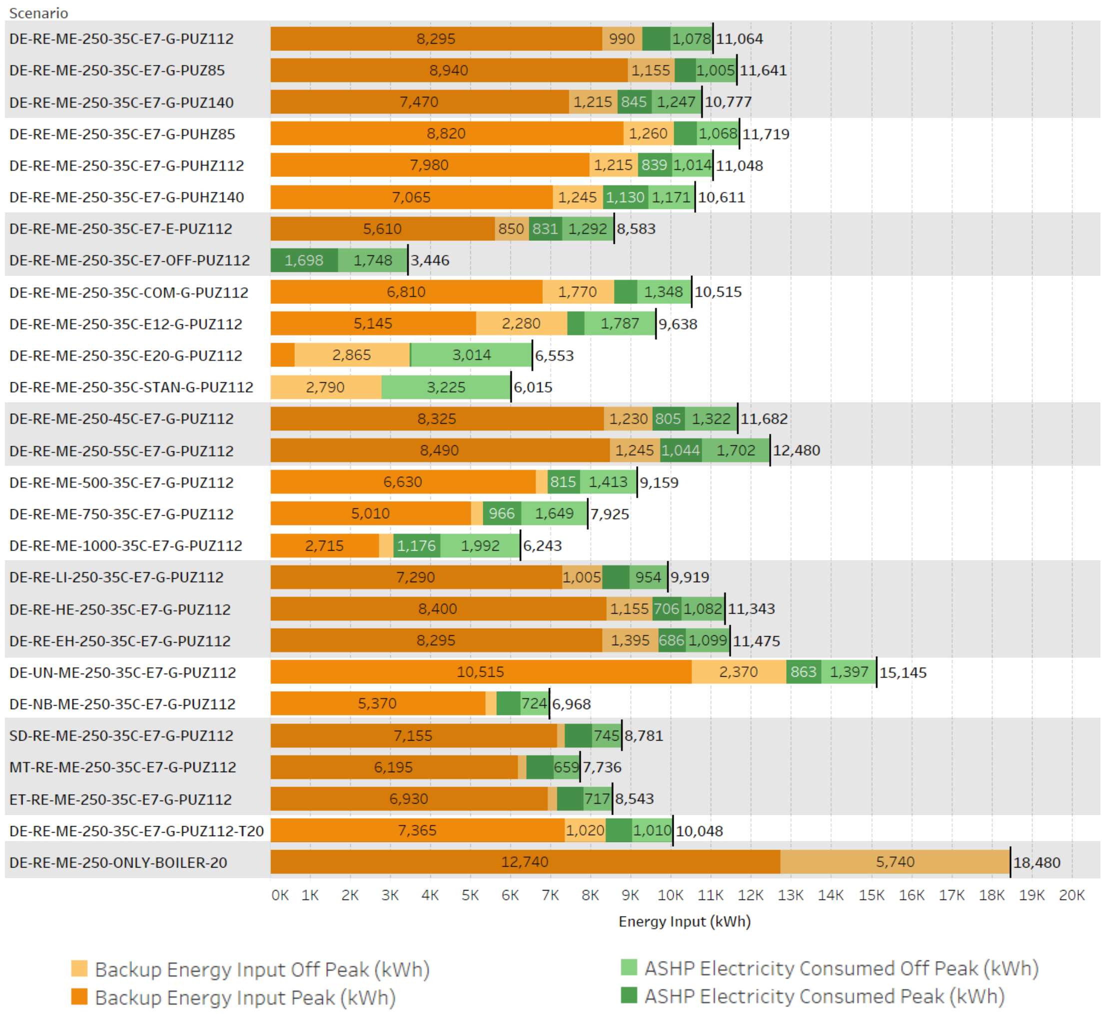

Figure 5.11 Energy input of sensitivity analysis scenarios for heat pump and backup heater during off-peak and peak times

Figure 5.12 shows the amount of energy output produced by the backup heater and heat pumps. It can be seen from the figure that the amount of heat energy needed is around 16,500 kWh for most of the scenarios. The only changes occur when the efficiency of the backup heater and the specification of the house is changed. When the backup heater is changed to electricity or not in operation the amount of heat demand decreases to 16,228 kWh and 15,803 kWh respectively. The unrefurbished building requires the highest demand with 21,965 kWh and the new building requires the lowest demand with 11,185 kWh.

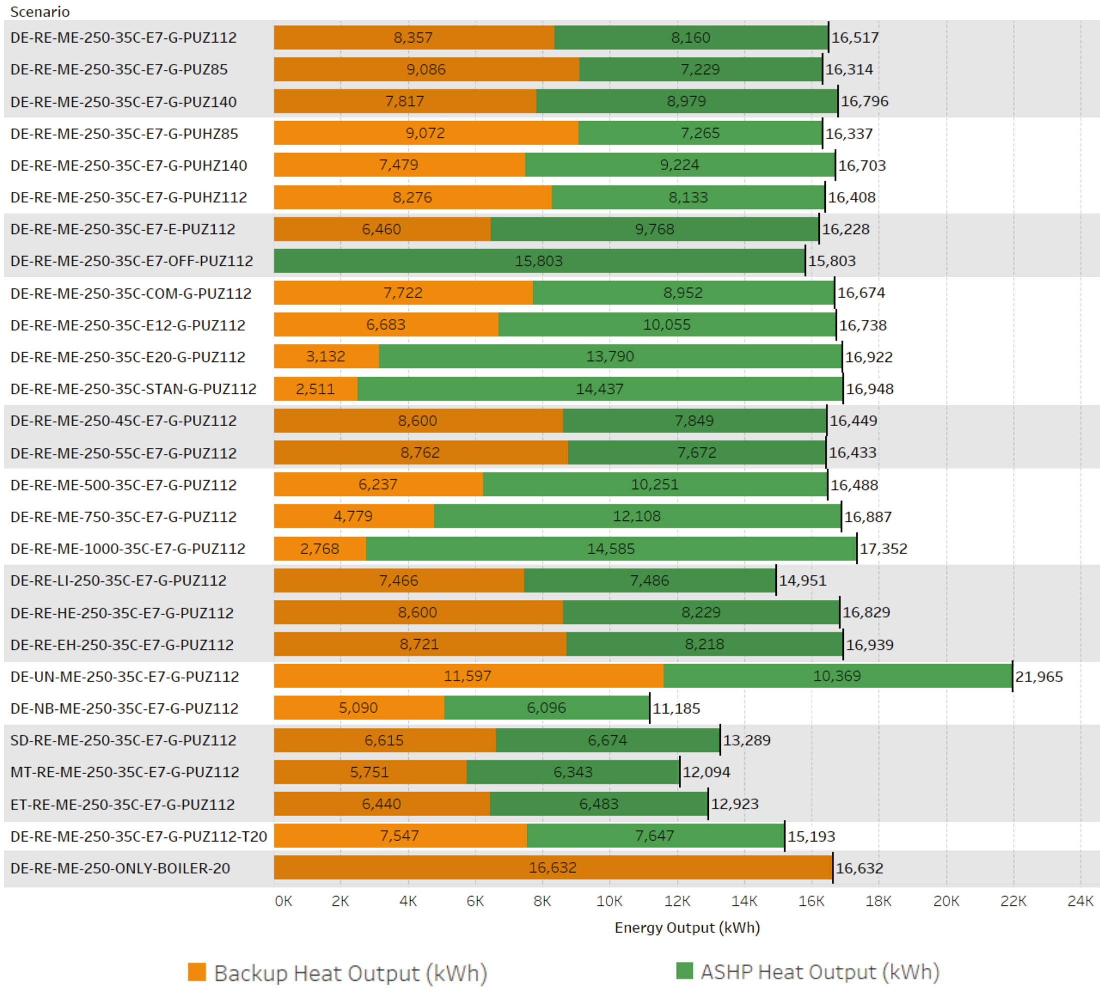

Figure 5.12 Energy output of sensitivity analysis scenarios for heat pump and backup heater during off-peak and peak times

The highest cost occurs when the backup heater type is changed to electricity (Figure 5.13). The cost is reaching £2049 because the backup heater is changed to electric heater with 100% efficiency which is far lower than the heat pump, so peak time electricity input increases by 5610 kWh. Therefore, when the backup heater is turned off the heat pump provides the entire demand, and the cost reduces to £598. This scenario performs the best outcome with the lowest energy input and cost.

In terms of energy consumption, Standard and E20 tariffs have the lowest energy consumption; however, they have the highest cost among other tariffs (£793 and £720 respectively). This is mainly because of the higher electricity prices in these tariffs. Comfy Heat and E12 tariffs perform better than E7 tariff with a cost of £639 and £627 respectively even though they have a lower number of hours in off-peak time.

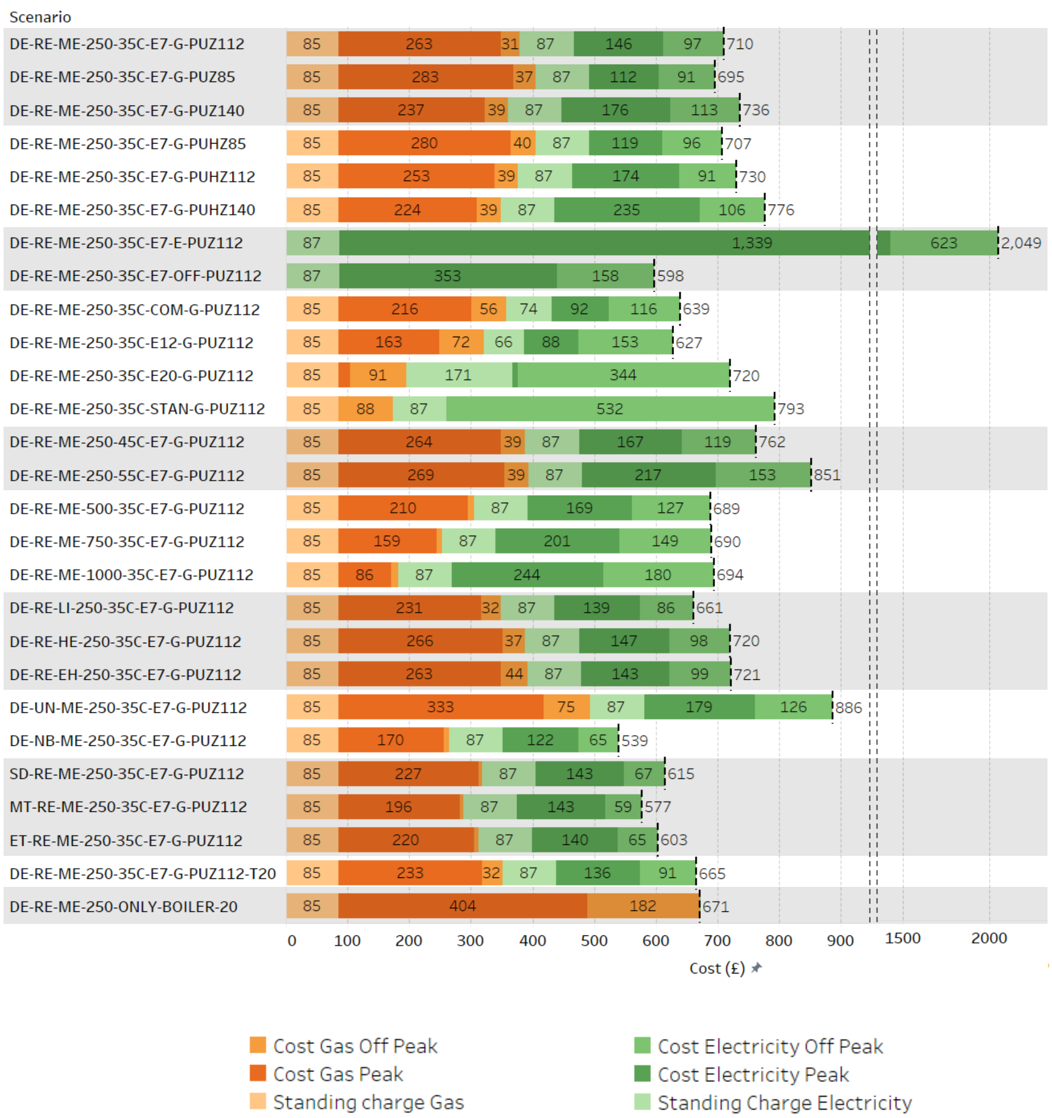

Figure 5.13 Heating cost of sensitivity analysis scenarios for heat pump and backup heater during off-peak and peak times

Increasing the flow temperature of the heat pump creates higher costs as it reduces the COP. Scenarios with 45 °C and 55 °C flow temperatures have a cost of £762 and £851 respectively. Similar to energy consumption figures, changing thermal mass does not have a significant impact on the cost. Also, changing tank size does not have an impact on the total cost; however, the contribution changes significantly. The contribution of the gas boiler reduces to 44%, 37% and 26% in scenarios with 500L, 750L and 1000L tank sizes respectively. So, increasing the tank size helps to reduce natural gas consumption without increasing the heating cost.

Changing building types and specifications has various impacts similar to energy consumption values. Reducing the internal set-point temperature by 1 °C can reduce the cost to £665. Finally, the scenario with turning the heat pump off and covering the demand with the gas boiler has a slightly lower cost than the baseline scenario (£671). It is also important to see that, this reduction can also be achieved by reducing the set-point temperature by 1 °C so the importance of human behaviour is also important.

The model provides hourly heat pump electric power outputs, so the operation of the heat pump is compared with electricity prices to investigate the operation of heat pumps. Figure 5.14 illustrates hourly heat pump load and electricity prices for the coldest winter workday and holiday by different tariffs and house specifications. During the off-peak time, the heat pump tries to run at maximum capacity so the buffer tank could also be charged; however, in peak times, it tries to minimise the electricity load by using a buffer tank and running at minimum capacity if necessary. If the minimum capacity is not enough to cover the space heating demand, then the heat pump runs at medium capacity. In all tariffs, the heat pump run in optimised operation; however, unrefurbished houses require more loads during peak times especially if the peak time period is very long. E7 tariff, for instance, performs better in the new building category with 4-time minimum operation during peak time; however, it increases to 9-times minimum operation in the refurbished category. In the unrefurbished category, it even creates medium capacity runs 4-times and minimum capacity 4-times. Comfy Heat tariff has similar off-peak time hours to the E7 tariff, but the spread of the off-peak hours is better. Therefore, medium capacity heat pump loads occur less. As the peak time period increases the energy efficiency of the house becomes more important. When the number of off-peak time hours increases (E12 and E20) peak time operation minimizes. These results illustrate that the operation of the heat pump is optimised and works correctly to continue scenario optimisation analysis.

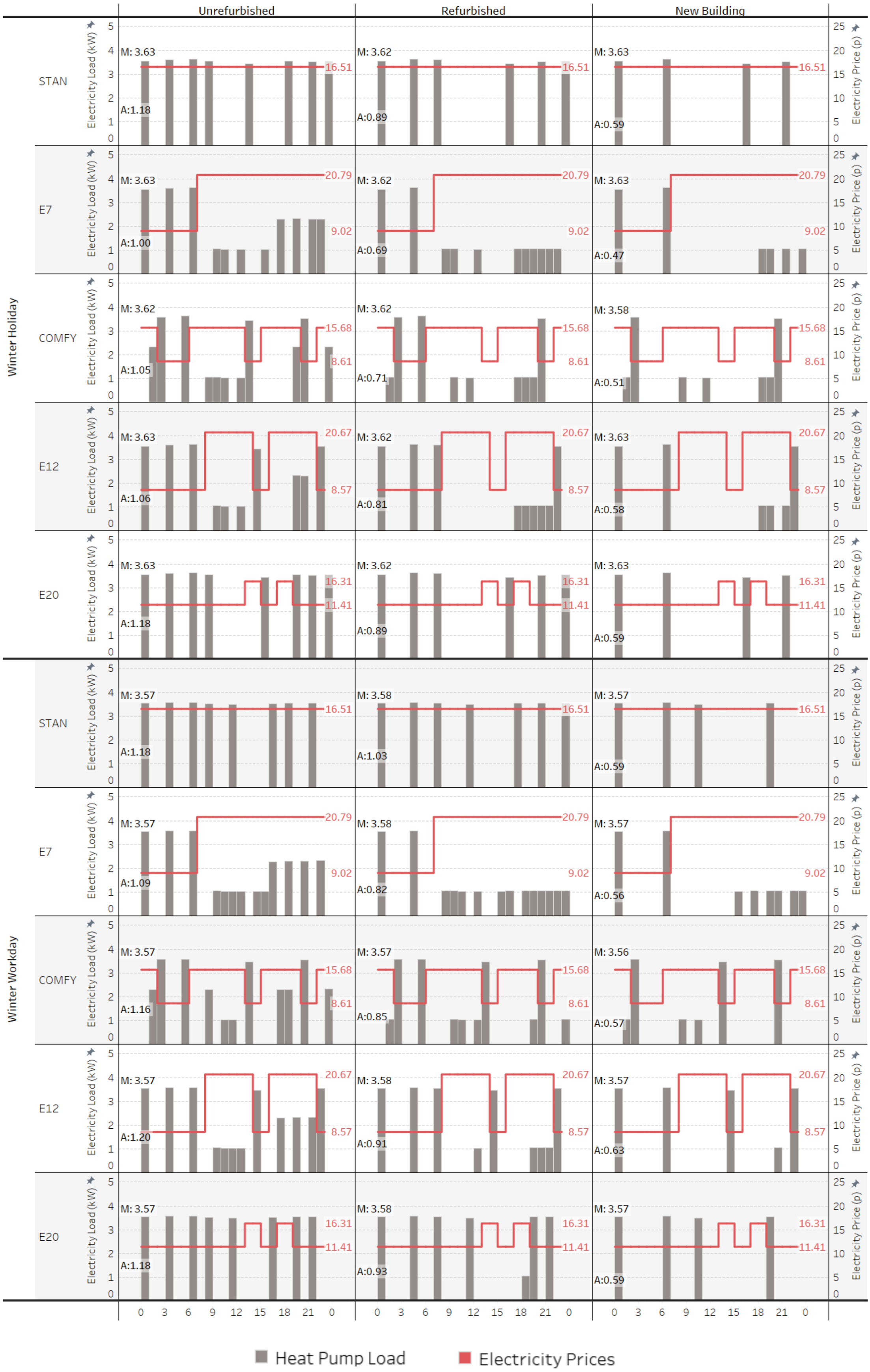

Figure 5.14 Hourly heat pump electricity load and electricity prices by different tariffs (M: Maximum, A: Average)

5.3.2. Scenario Optimisation Analysis

A refurbished detached house with a mediumweight thermal mass construction material and PUZ112 heat pump type with 35 °C flow temperature is selected as the baseline scenario. As the water flow runs in low temperatures, the stored water will be heated to 60 °C one hour once a week to avoid legionnaires' disease based on HSE (2000) guidance. Five types of tariffs (Standard, E7, Comfy Heat, E12, and E20) and four tank sizes (250L, 500L, 750L, and 1000L) are compared with two different settings (Gas boiler as a backup heater and no backup heater) for the optimisation. Figure 5.15 and Figure 5.16 show SPF and daily average COP values for optimisation scenarios. When the gas boiler is in operation as a backup heater, Standard and E20 tariffs show the lowest SPF values with 4.45 on average. The highest SPF is achieved with 250L tank size with 4.48 and 4.49 in both tariffs respectively. The highest SPF among all scenarios is achieved with 4.63 in E7 tariff with 750L tank size and Comfy Heat tariff with 250L tank size. Overall, smaller tank sizes achieve higher SPF with higher maximum COP values. When tank sizes have increased the fluctuations in daily COP values and SPF reduces. A similar trend occurs when the backup heater is not in operation. The highest SPF values are achieved with 250L tank sizes; however, the decrease in SPF values in larger tank sizes is around only 0.4% on average.

Figure 5.17 illustrates the energy input for optimisation scenarios for the heat pump and boiler. When the gas boiler is used as a backup heater, Standard tariff results show the lowest energy consumption values because the heat pump is running at full capacity assuming that there is no peak or off-peak time tariff, so the gas boiler usage is minimised. The boiler is only running when the tank size is 250L. Even though the consumption figure is 6015 kWh with a 250L tank size, energy input values occur as 3794 kWh, 3879 kWh, and 3973 kWh for larger tank sizes respectively. 250L tank size is not enough to replace the gas boiler in the Standard tariff. E20 tariff results show similar but slightly higher results than the Standard tariff. The consumption increases to 6553 kWh and 4333 kWh with 250L and 500L tank sizes; however, when the tank sizes increased the consumption figures are decreasing in the E20 tariff. So, increasing the tank size has a positive impact on this tariff.

The highest consumption occurs in the E7 tariff with 250L tan size (11,064 kWh). This is mainly because the low number of off-peak hours leads to natural gas usage during peak time and decreases electricity usage to 16% of total energy consumption. As the number of off-peak hours is not enough to utilize maximum heat pump usage, the alternative option would be to increase tank sizes. Higher tank sizes help to decrease energy consumption to 9159 kWh, 7925 kWh, and 6243 kWh with 500L, 750L and 1000L tank sizes respectively. Higher tank sizes offer higher electricity usage in off-peak times and help to reduce natural gas usage. Even though the share of electricity in total energy consumption is 16% in 250L tank size, this could be increased to 24%, 33%, and 51% with higher tank sizes respectively.

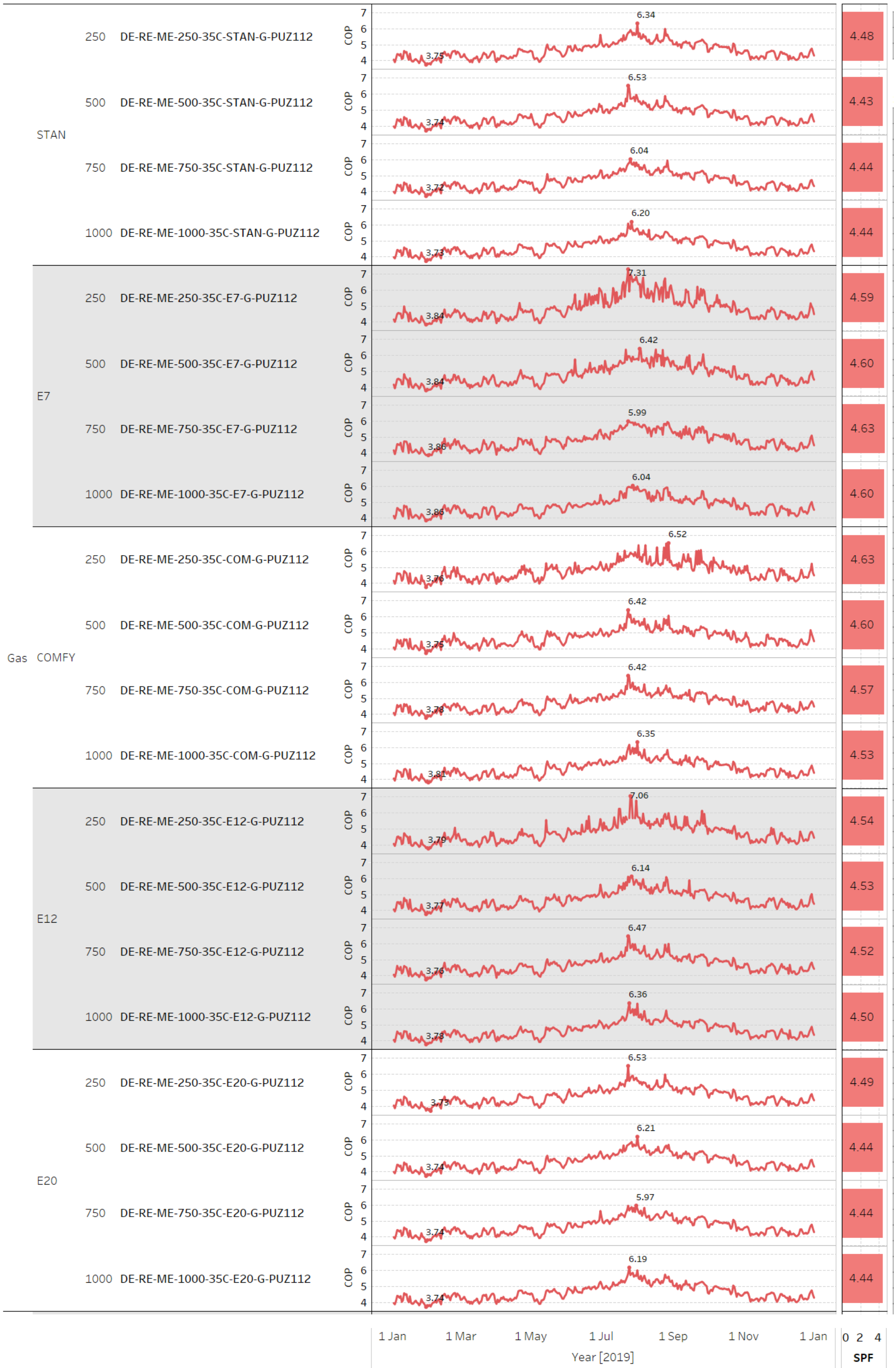

Figure 5.15 SPF and daily COP values for heat pumps in hybrid scenarios

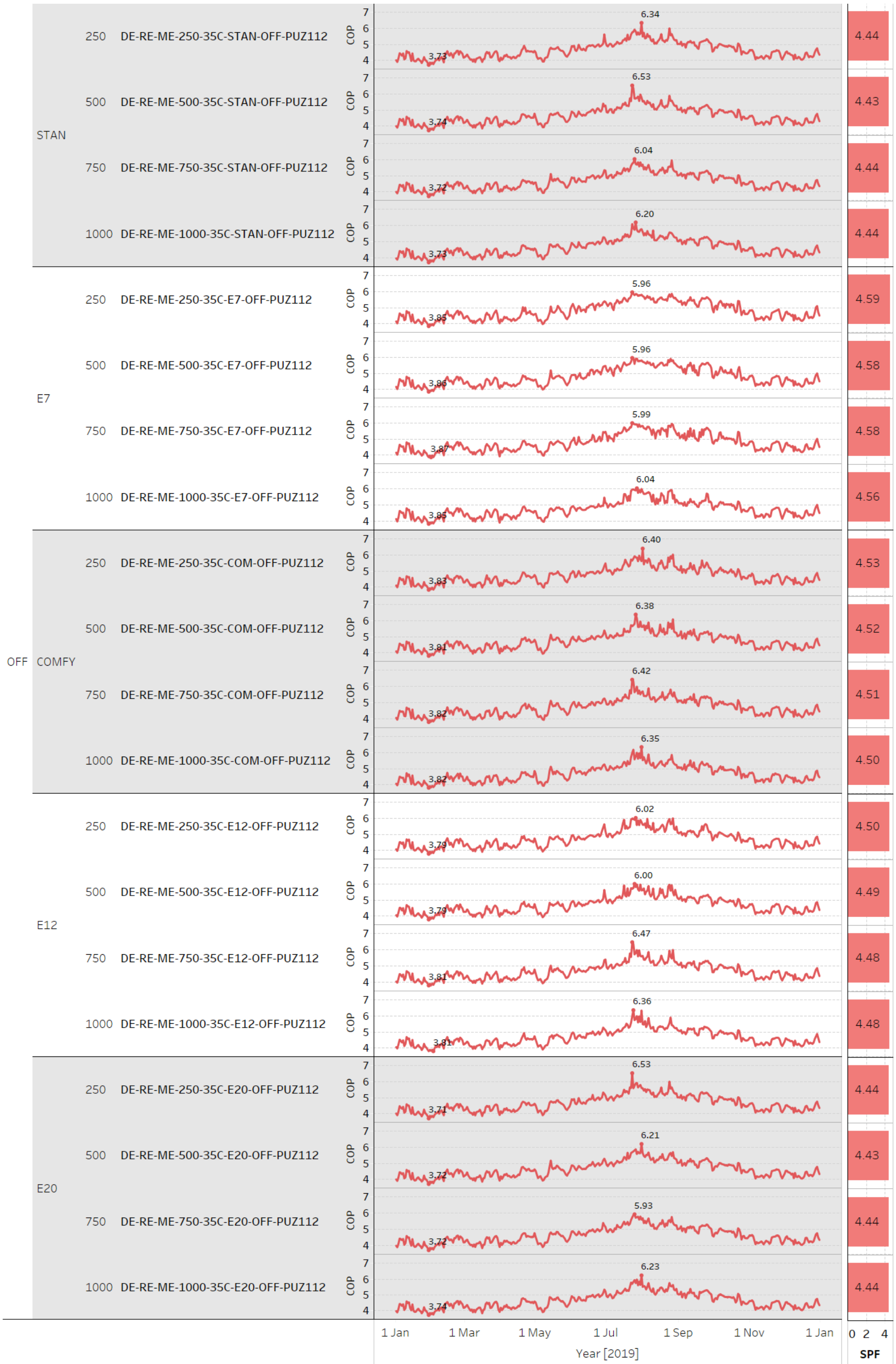

Figure 5.16 SPF and daily COP values for heat pumps when the backup heater is not operating

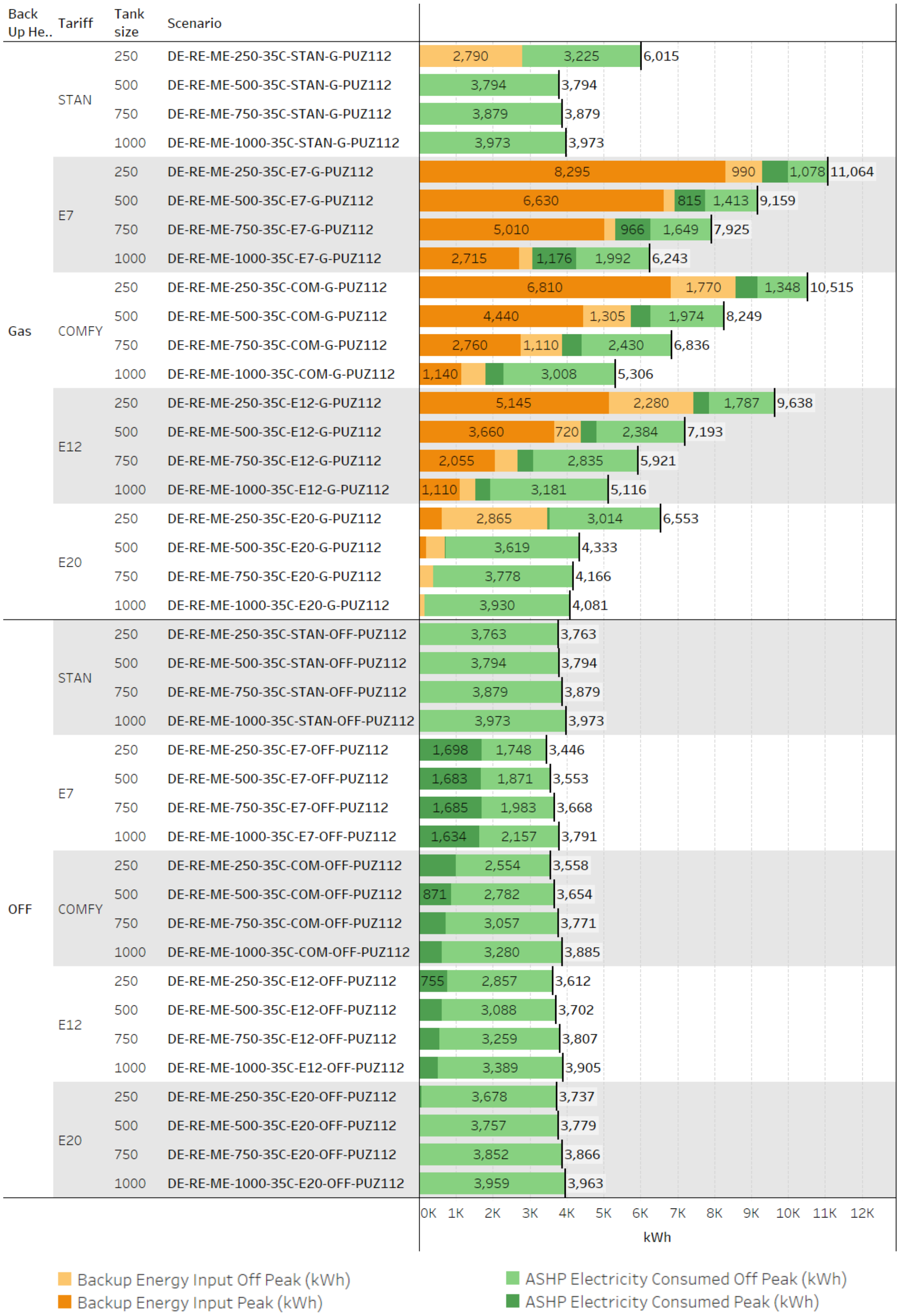

Figure 5.17 Energy input of backup scenario analysis for heat pump and backup heater during off-peak and peak times

Comfy Heat and E12 tariffs have 12% and 25% lower results than E7 tariff on average. When the number of off-peak hours increases energy consumption reduces because of a higher heat pump fraction in energy generation. This reduction is greater in higher tank sizes; however, the trend in natural gas usage is similar. When tank sizes are increased, energy consumption reduces. E12 tariff with a 1000L tank size can reduce the consumption to 5116 kWh which is 25% higher than the lowest energy consumption in all scenarios. This is relatively small when it is compared with 9638 kWh which occurs with a 250L tank size.

When the backup heater is not in operation all energy demand is provided by the heat pump. Energy consumption figures are very similar in all scenarios ranging between 3446 kWh and 3763 kWh with a 250L tank size. When the tank size increases energy consumption could reach 3791-3973 kWh, but the difference is still small when compared with the backup heater operation. Even though the total energy consumption values are similar, the fraction of peak and off-peak times changes for E7, Comfy Heat and E12 tariffs. The peak time usages in E7 tariff are 49%, 47%, 46%, and 43% for 250L, 500L, 750L, and 1000L tank sizes. However, these numbers reduce to 28%, 24%, 19%, and 16% for Comfy Heat tariff, and 21%, 17%, 14%, and 13% for E12 tariff. These differences could result in higher heating costs because of higher peak time tariffs but this will be covered in the next section.

Figure 5.18 shows the amount of energy produced by both the heat pump and gas boiler. Space heating demand for scenarios with the backup heater is around 16,500-17,500 kWh depending on the size of the tank and tariff. The lowest amount of delivered energy is achieved with the E7 tariff with 250L and 500L tank sizes (16,517 kWh and 16,488 kWh respectively). Higher tank sizes require higher energy output; therefore, delivered energy increases to 16,887 kWh and 17,352 kWh with higher tank sizes.

Comfy Heat and E12 tariffs have similar results to E7 with only around a 1% difference in total delivered heat in all tank sizes, but gas boiler usage varies significantly. Natural gas share in delivered heat with 250L tank size is 51% in E7 tariff and decreases to 46% and 40% for Comfy Heat and E12 tariffs. Similar reductions occur for higher tank sizes as well. Standard and E20 tariffs have the lowest energy delivered by the gas boiler (2511 kWh and 3132 kWh respectively) with 250L tank sizes. This is mainly because of high off-peak hours in the E20 tariff and no peak/off-peak hours difference in the Standard tariff.

When the backup heater is not operating all delivered heat is provided by the heat pump. All tank sizes except 250L in Standard tariff have the same delivered energy figures with backup heater scenarios. In other scenarios for all tariffs and tank sizes the amount of total delivered heat is expected to reduce slightly. The highest reduction occurs in the E7 tariff with 250L tank size with a 5% reduction.

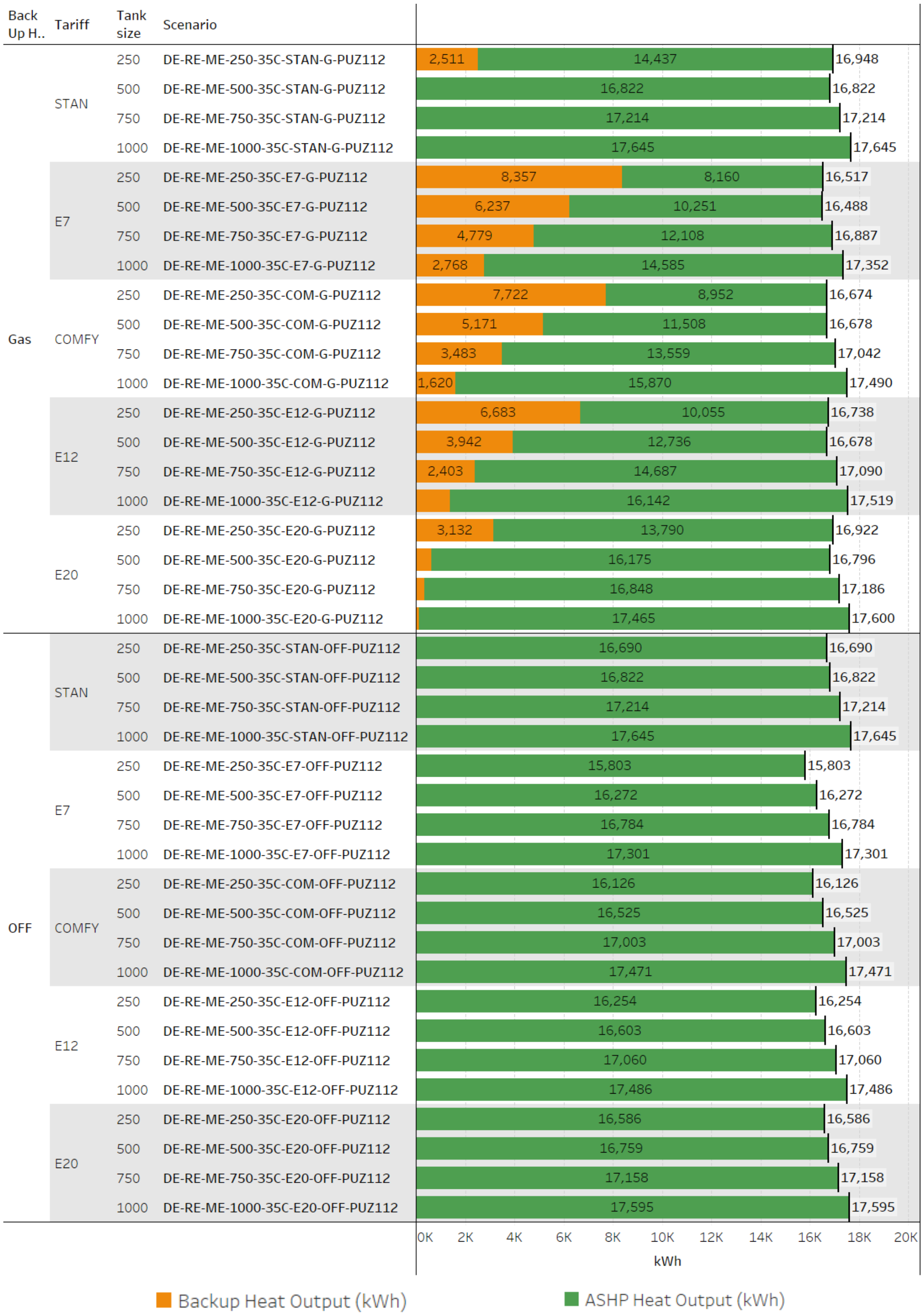

Figure 5.18 Energy output of backup scenario analysis for heat pump and backup heater during off-peak and peak times

Figure 5.19 illustrates the total heating cost results for both heating technologies during peak and off-peak times. Even though there is no differentiation between off-peak and peak time costs for natural gas, the results are presented in the same format as electricity. This approach helps to understand the optimisation of the scenario by reducing gas usage and maximising electricity in off-peak time.

When the backup heater is in operation, the Standard tariff has the highest cost with £792.9, £798.5, £812.5, and £828.1 with 250L, 500L, 750L, and 1000L tank sizes respectively. Increasing the tank creates higher heating costs as there is no off-peak time strategy in this tariff. E20 tariff expects an average 14% reduction in total heating cost. However, the highest standing charge occurs in this tariff with £171.2 followed by £87.1, £86.8, £74.1, and £65.6 in E7, Standard, Comfy Heat and E12 tariffs respectively. Therefore, the reduction in the total cost is limited in the E20 tariff. Another reason for the high heating cost is that even though, the 20 hours of off-peak rate is very competitive, the highest electricity off-peak rate among other tariffs also exists in this tariff.

E7 tariff shows around 15% lower results than the Standard tariff. The cost of the scenario with a 250L tank size reduces to £709.7. Electricity peak time cost dominates off-peak time results with £145.9 and £97.2 respectively. A similar trend occurs for larger tank sizes; however, the electricity share increases from 53% with 250L tank size to 44%, 37%, and 26% with larger tank sizes. Even though the reduction of total heating cost is not significant when the tank size increases, the contribution of the heat pump increases from 47% to 74%.

Comfy Heat tariff has an average of 37% lower results than the Standard tariff, but the lowest reduction occurs in the E12 tariff with around 39% in all scenarios. Off-peak time electricity cost dominates peak time results, and the difference is greater with larger tank size. Peak time electricity share in total electricity cost is 23% in both tariffs with 1000L tank size. Although half of the cost in scenarios with 250L tank size comes from natural gas, this contribution reduces to 25% with 1000L tank size.

When the backup heater is not in operation, heating costs in all scenarios reduce. The main reason for that is there is no standing charge for the gas boiler in this setting, so it creates a benefit. The high efficiency of the heat pump could eliminate increases coming from electricity costs depending on different electricity rates in different tariffs. The lowest reductions occur in Standard, E7, and E20 tariffs with an average of 12%, 14%, and 16% decreases. The highest reduction can be achieved with the Comfy Heat tariff with a 31% reduction followed by the E12 tariff with 26%. The total cost of a heating bill can be achieved as £450 with the Comfy Heat tariff. The weather conditions and having no extreme conditions provide higher COP values which could compete with gas prices and make standalone operation financially feasible.

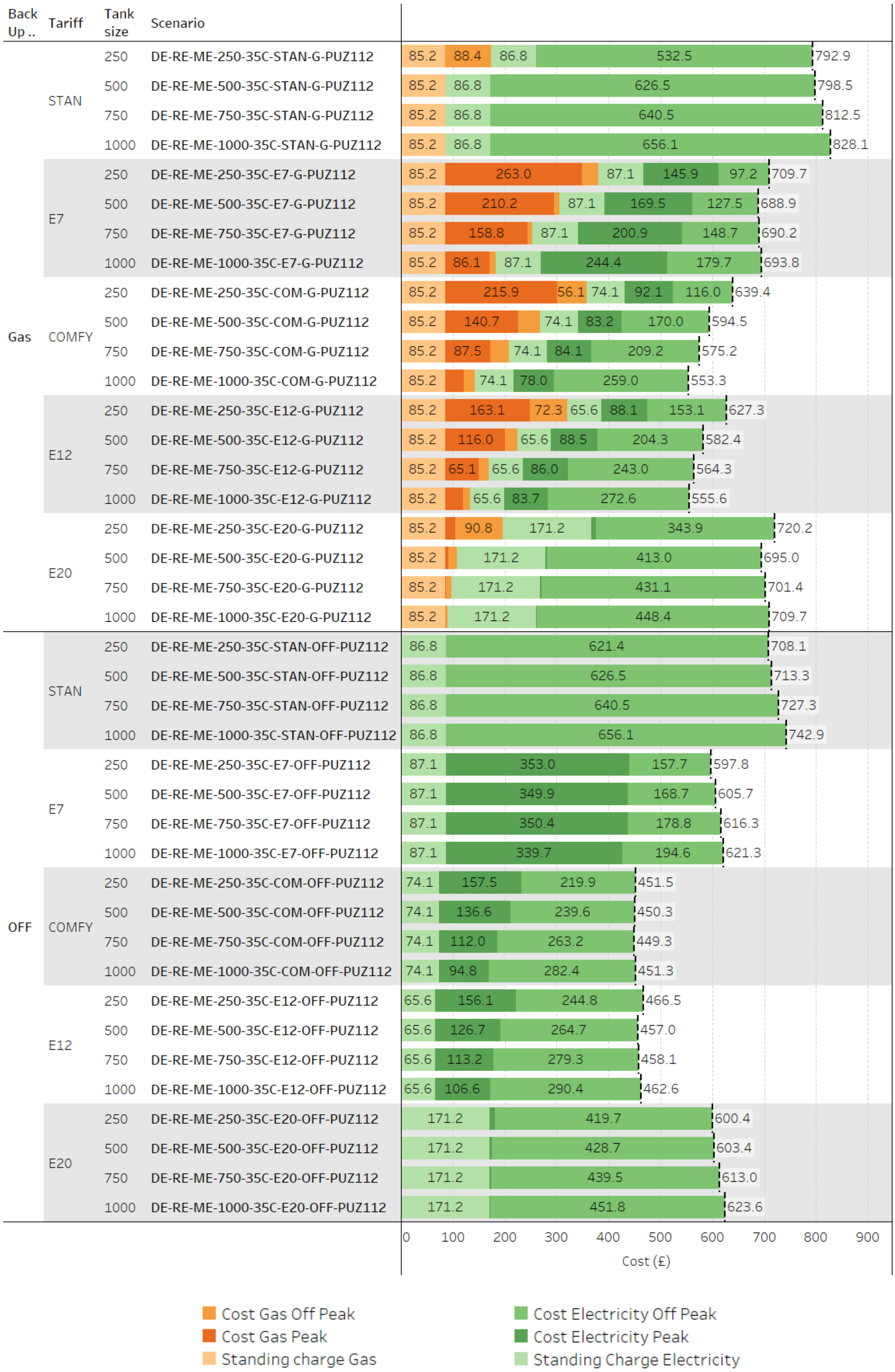

Figure 5.19 Heating cost of backup scenario analysis for heat pump and backup heater during off-peak and peak times

5.3.3. Heat Pump Sizing

The previous section analysed the optimisation of scenarios in terms of electricity tariffs, tank sizes and backup heater; however, heat pump sizes are not investigated. Therefore, this section will focus on heat pump sizing. The model investigates three sizes of heat pumps; 8.5 kW (PUZ85), 11.2 kW (PUZ112), and 14.0 kW (PUZ140).

Figure 5.20-Figure 5.21 shows SPF and average daily COP values for Comfy Heat and E12 tariffs for the entire year. Only these two tariffs are selected mainly because the optimum results have been collected from these tariffs in the previous section; therefore, Standard, E7 and E20 tariffs are not analysed. When the backup heater is in operation the highest SPF is achieved by the PUZ112 model with an average of 4.55 SPF which is 1% higher than PUZ85 (4.51 SPF on average). However, PUZ85 performs slightly better only in Comfy Heat tariff with 250L tank size. PUZ140 has the lowest SPF with an average of 4.25 which is 6.5% lower than PUZ112. When the backup heater is not operating the highest SPF is achieved by PUZ85 and PUZ112 with 4.50 SPF. PUZ85 performs better than PUZ112 in smaller tanks with higher SPF values whereas the latter outperforms with higher tank sizes. PUZ140 performs 6% lower with an average of 4.22 SPF in both tariffs.

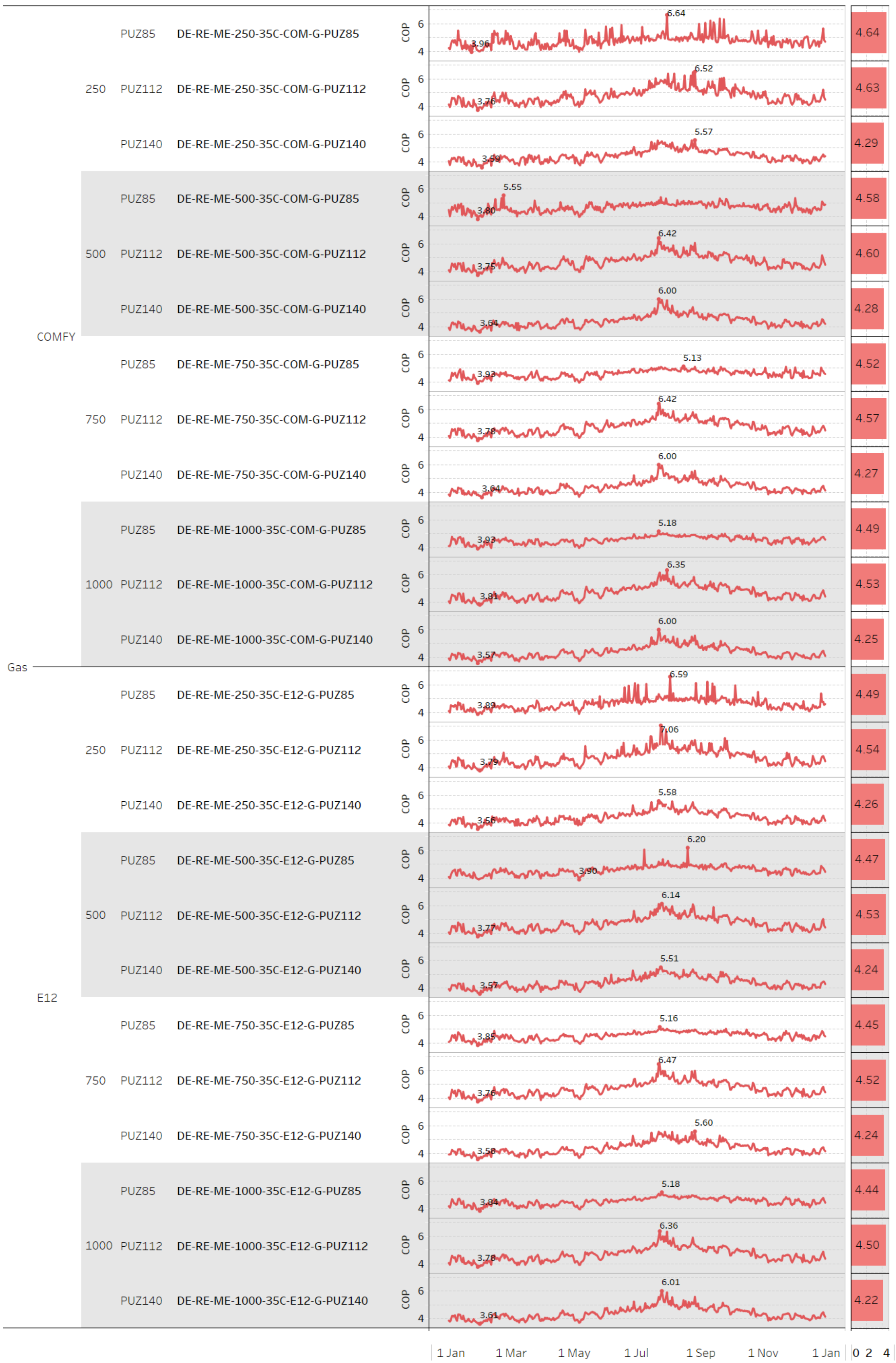

Figure 5.20 SPF and daily COP values for heat pumps when backup heater is operating

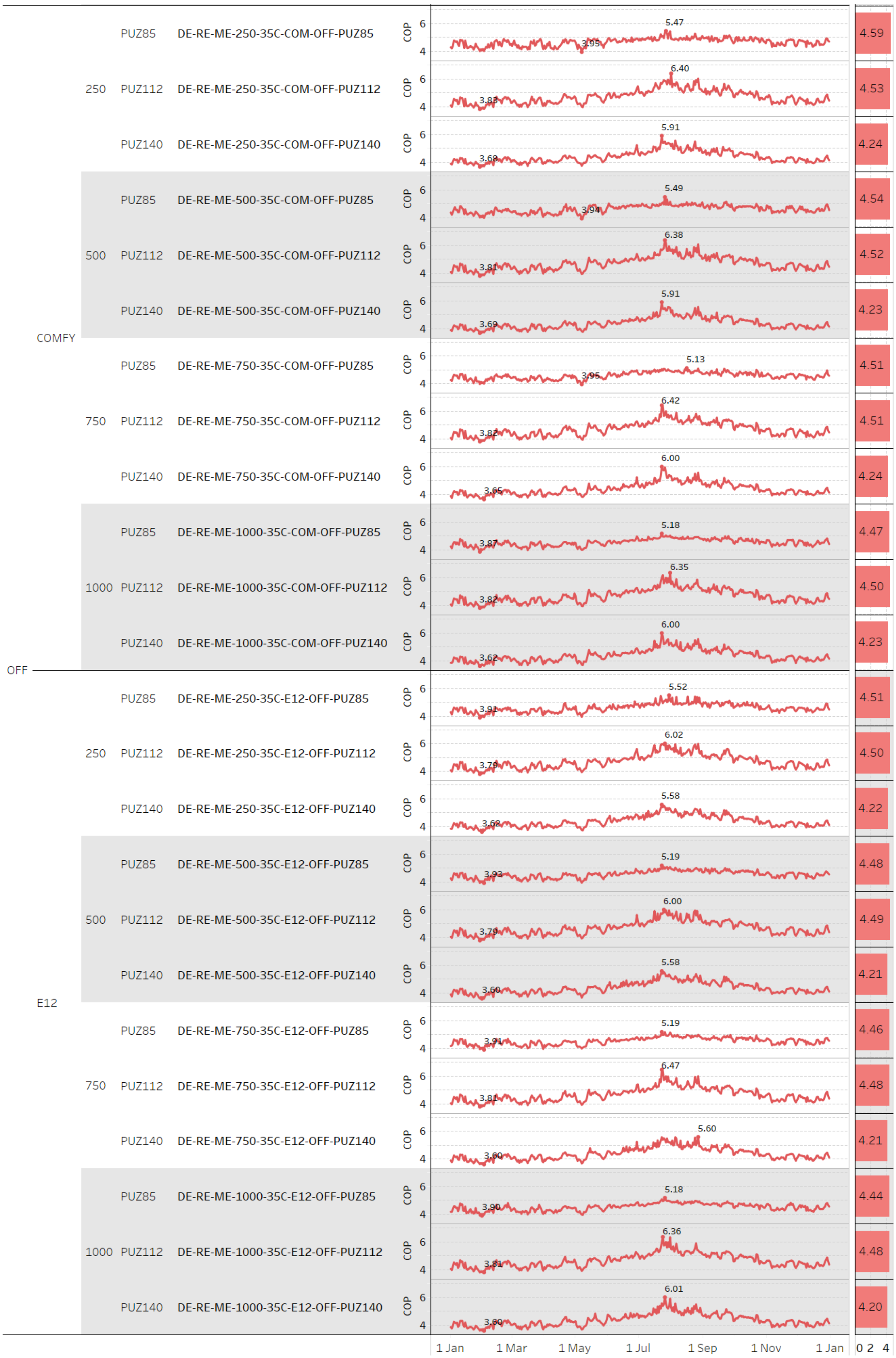

Figure 5.21 SPF and daily COP values for heat pumps when backup heater is not operating

Figure 5.22 illustrates energy input data for scenarios for Comfy Heat and E12 tariffs with different tank and heat pump sizes. Scenarios with backup heaters in both tariffs show that larger heat pump sizes consume more energy as expected and help to reduce natural gas usage; therefore, total energy consumption reduces. Total energy consumptions of Comfy Heat tariff with 250L tank sizes are 11,298 kWh, 10,515 kWh, and 9750 kWh with PUZ85, PUZ112, and PUZ140 heat pump types respectively. The largest heat pump size helps to reduce energy consumption by 14% in total. A similar trend occurs for larger tank sizes; however, the reduction in the largest tank size is only 4%.

E12 tariff results show similarities to the Comfy Heat tariff; however, the reduction is around 10% in all tank sizes except 1000L. As there are more off-peak hours in this tariff smaller heat pumps produce more energy than the Comfy Heat tariff; therefore, the performance of smaller sizes is relatively better in E12. This also creates another difference occurring in 1000L tank size. Increasing the heat pump size does not have a positive impact on the 1000L tank size in the E12 tariff. The reason for this behaviour is that the E12 tariff has 10 hours of continuous off-peak hours during the night; so only 2 hours of off-peak time occurs during the day; therefore, long period of peak hours tries to minimize the heat pump operation during the day as a strategy, and larger heat pumps also become insufficient. The solution to this issue would be the homogenous distribution of off-peak hours throughout the day.

When the backup heater is not in operation, the lowest energy consumption occurs with the smallest heat pump (PUZ85) in both tariffs as expected. PUZ112 has only 3% higher results with 250L tank size and the difference becomes smaller with larger tank sizes, and it performs even better with 1000L tank size. PUZ140 performs the worst with the highest energy consumption figures which is 9% on average. This behaviour occurs in both tariffs.

Figure 5.23 shows the energy provided by both the heat pump and the gas boiler. There is a linear correlation between energy output and heat pump and tank sizes. In Comfy Heat tariff, the lowest provided energy (16,466 kWh with backup heater and 15,840 kWh without backup heater) is achieved with the smallest tank size (250L) and heat pump (PUZ85); and the highest (17,565 kWh with backup heater and 17,551 kWh without the backup heater) with the largest tank size (1000L)and heat pump (PUZ140). E12 results show a similar trend with and without the backup heater in all scenarios.

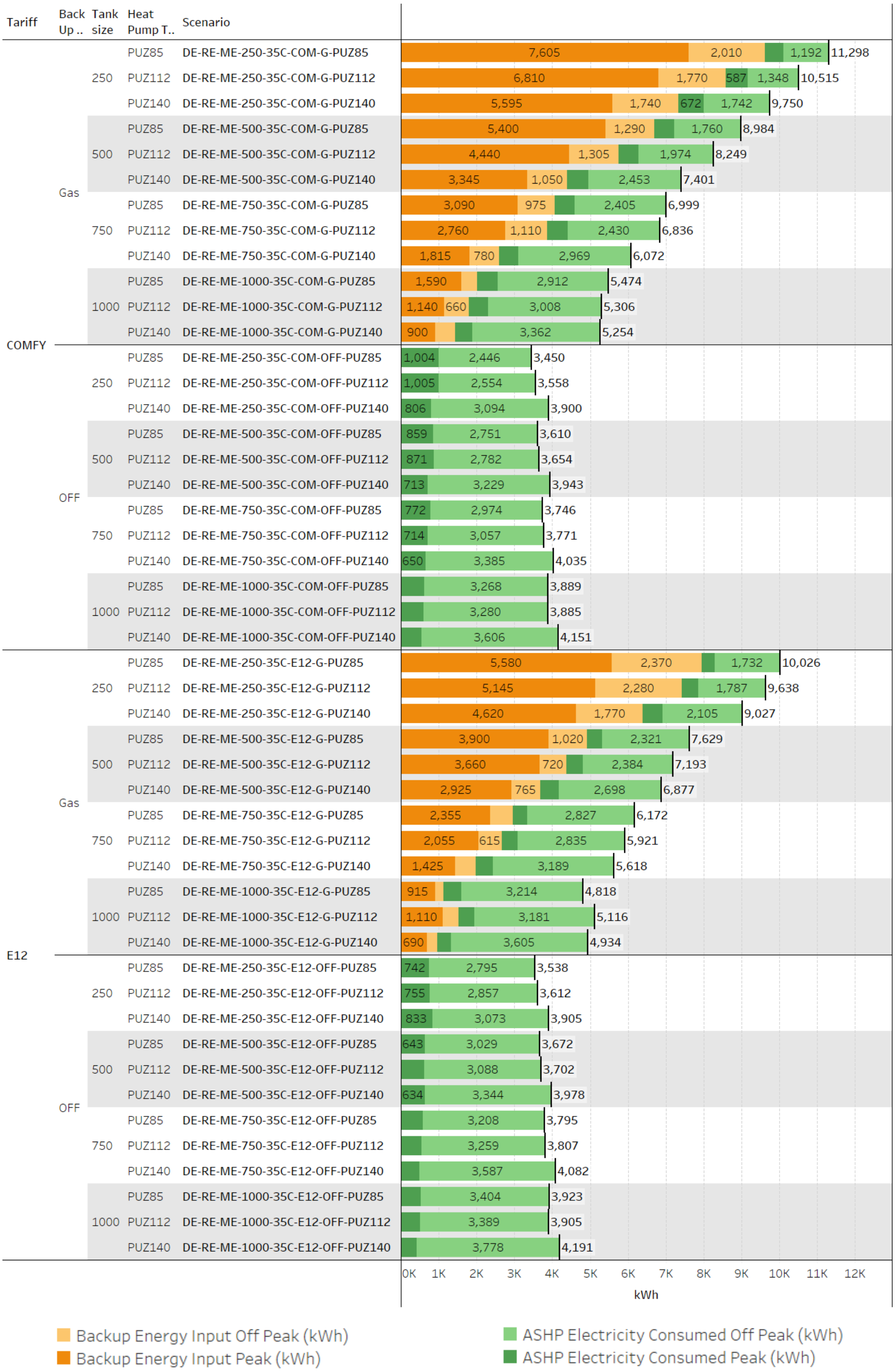

Figure 5.22 Energy input of heat pump sizing scenarios during off-peak and peak times

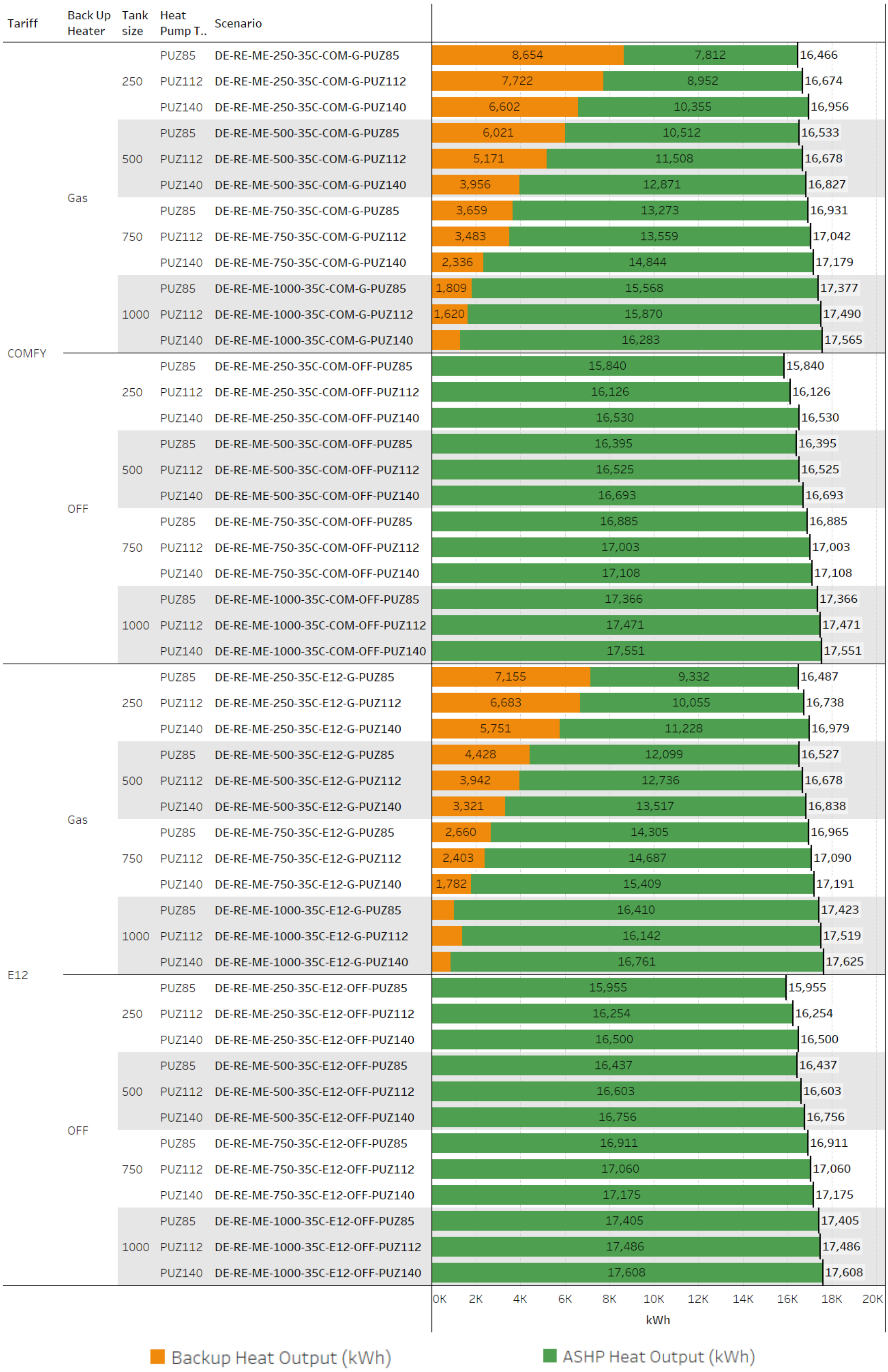

Figure 5.23 Energy output of heat pump sizing scenarios during off-peak and peak times

Figure 5.24 illustrates the cost of heating for scenarios with Comfy Heat and E12 tariffs. When the backup heater is in operation, the lowest cost is achieved with PUZ112 in both tariffs; however, the difference is relatively small which is around 1%. The lowest cost occurs with 1000L tank size with £553.3 and £555.6 for Comfy Heat and E12 tariffs respectively. The highest cost is achieved with PUZ140 in 250L tank size with £647.2 and £643.5 for both tariffs respectively.

As the aim of optimisation is reducing peak time heat pump usage, focusing on only the total cost may not be sufficient. Even though, larger heat pump sizes produce more heat and help to reduce natural gas use, peak time heat pump use differs with tank size. In Comfy Heat tariff, peak time heat pump usage increases with 250L tank size from £77.0 to £92.1 and £105.4 when heat pump size is increased. PUZ140 with 500L tank size and PUZ112 with 750L also show slightly higher results than PUZ85; however, the remaining tank sizes show lower peak time heating cost results when heat pump size increases. In the E12 tariff, only 1000L tank size performs better in terms of lower peak time heat pump usage when the size increases. The peak time heating cost for PUZ85 is £99.0 and reduces to £83.7 and £76.3 with PUZ112 and PUZ140 respectively. However, in all other tank sizes increasing heat pump size increases peak time heating cost.

When the backup heater is not in operation, the lowest heating cost is achieved with PUZ85 in 250L and 500L tank sizes in Comfy Heat tariff and only 250L tank size in E12 tariff. PUZ112 achieves the lowest heating cost in all other scenarios and performs better. In the same categories, larger heat pump sizes have lower peak time heating costs than PUZ85; however, PUZ140 has the highest total cost in all scenarios.

Even though scenarios with different tariffs, tank and heat pump sizes perform differently, PUZ112 performs better than the remaining heat pump types in terms of the heating cost. This is valid for whether the backup heater is in operation or not. However, it is also important to keep in mind that energy consumption performance differs from heating cost when the backup heater is in operation. The lowest energy consumption is achieved with the largest heat pump size. When the backup heater is not in operation; however, both smaller heat pump sizes perform better. Therefore, the 11.2 kW size heat pump (PUZ112) performs better than other heat pump sizes overall.

The summary of the results is illustrated in Figure 5.25 and Figure 5.26 with optimised scenario results of Comfy Heat and Economy12 tariff sorted by the lowest heating cost. The results show that standalone heat pump system performs better than hybrid applications. Moreover, Comfy Heat tariff performs better than E12 tariff in standalone system with 750L and 500L tank sizes. However, in hybrid applications, there is no outperforming tariff whereas high tank sizes provides lower heating costs.

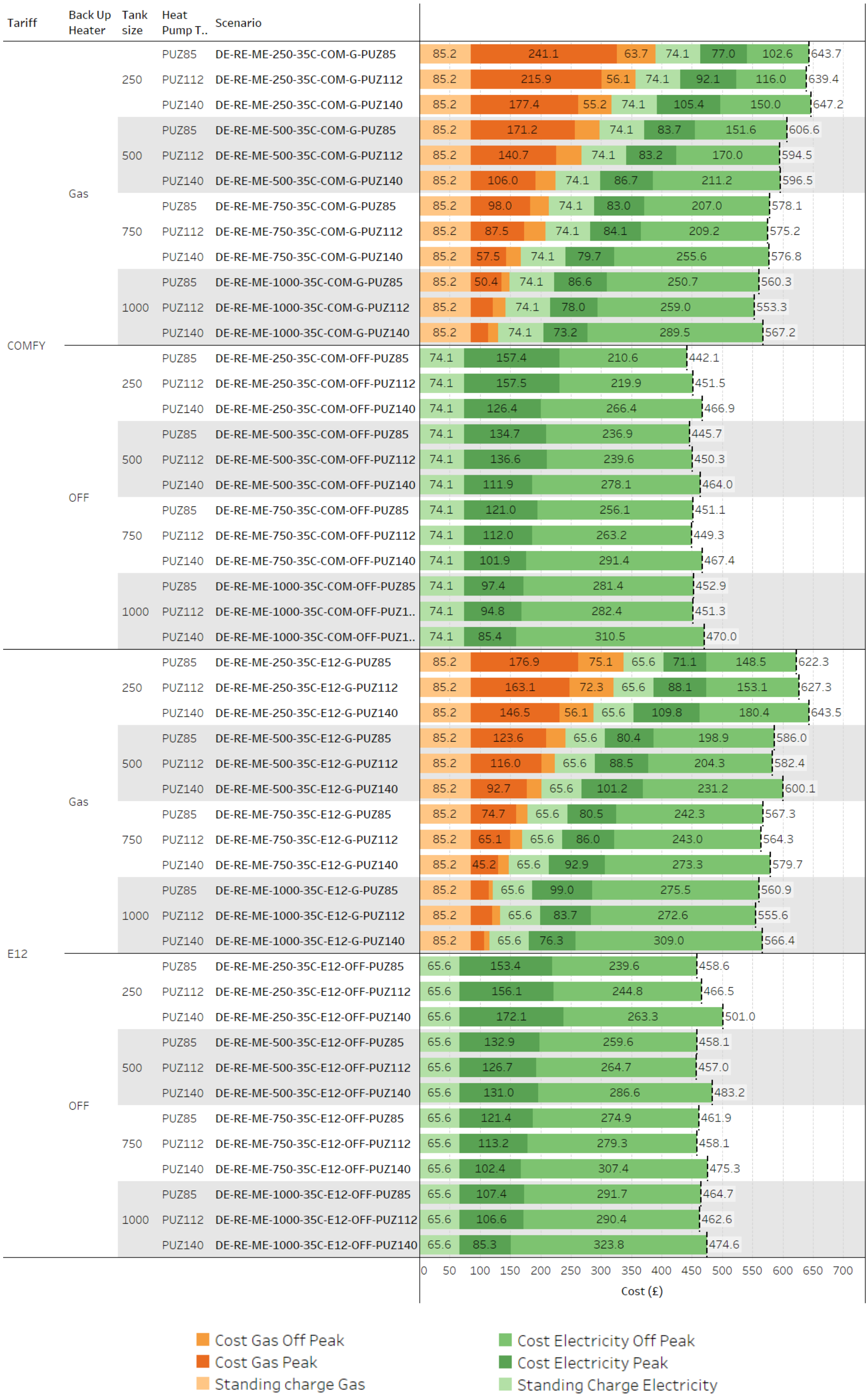

Figure 5.24 Heating cost of heat pump sizing scenarios during off-peak and peak times

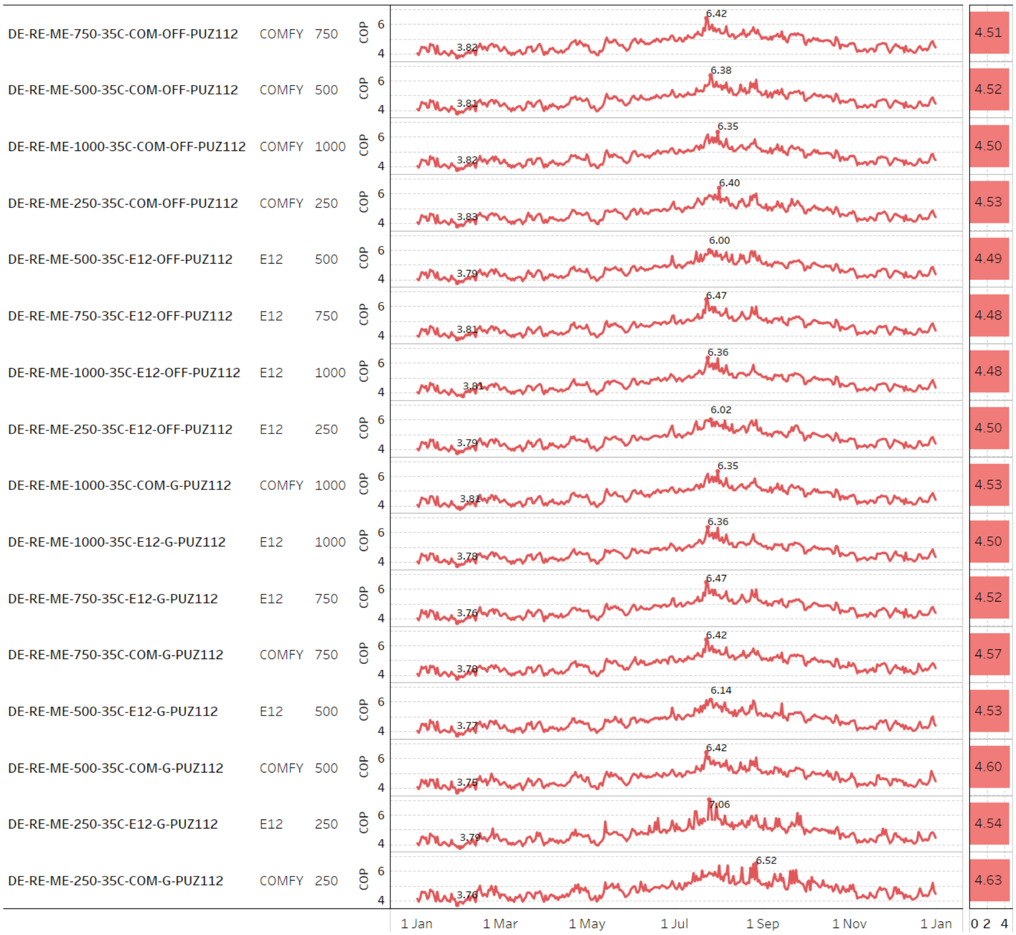

Figure 5.25 Optimised SPF and daily average COP values for Comfy Heat and E12 tariffs sorted by the lowest total heating cost

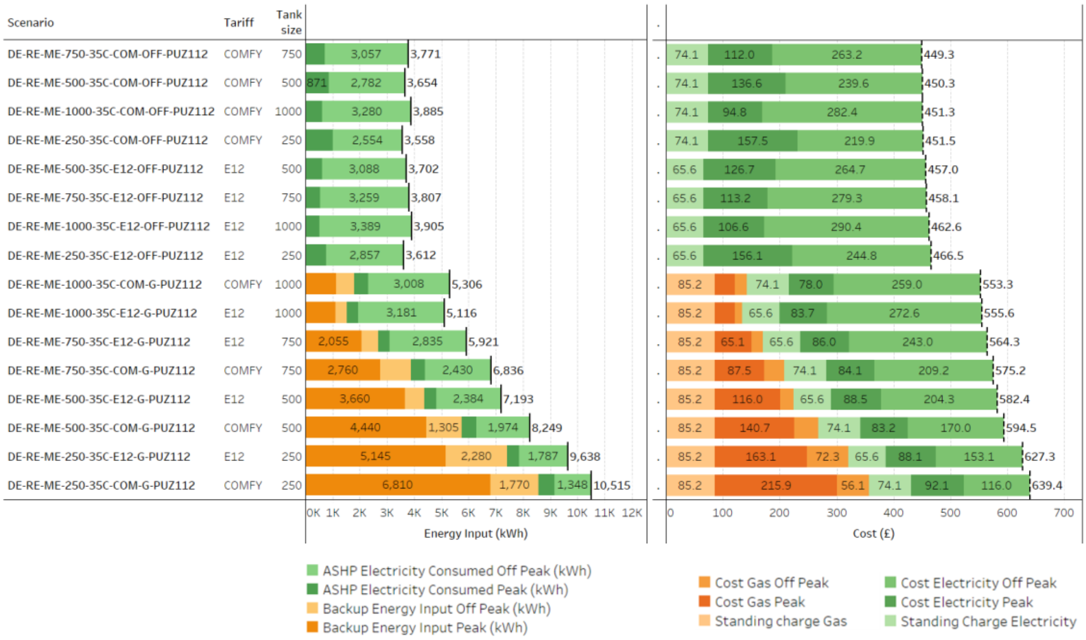

Figure 5.26 Optimised energy input and heating cost for Comfy Heat and E12 tariffs sorted by the lowest total heating cost

5.4. Data Quality and Limitations

This study has optimised the heat pump operation to reduce energy demand and heating costs; however, it has several limitations as followed:

- The model is a steady-state model which does not analyse dynamic calculations. Therefore, thermal mass calculations are only considered for storing heat capacities but not time-shifting capabilities. High thermal mass construction materials could help to store heat during the off-peak time and use it in peak times; however, this impact is not considered.
- Heat pump field trials show differences between estimated and real heat pump performance. This could be mainly relevant to poor heat pump installations, inaccurate system design and sizing or occupancy behaviour. 58% of consumers find heat pumps as a complex technology (Nesta & BIT, 2022b); therefore, a discrepancy in the optimised operation of heat pumps could be seen in real life. In order to avoid this issue, a consumer understanding and awareness study could be conducted for further studies.
- Climatic conditions are changing due to climate change impact, so weather data used for the baseline scenario will be different for future scenarios. It requires climate change modelling which requires a more detailed analysis of weather conditions; therefore, this impact is not covered in this study due to simplicity.

5.5. Conclusions

This chapter has focused on energy modelling and explored energy consumption and heating cost results of different building archetypes (detached, semi-detached, end-terraced, and mid-terraced) in Orkney. The aim of this section is to optimise heat pump operation in these archetypes by scenario analysis with different building specifications (unrefurbished, refurbished, new building), electricity tariffs (Standard, Economy7, Comfy Heat, Economy12, Economy20), thermal energy storage tank sizes (250L, 500L, 750L, 1000L), heat pump sizes (8.5 kW, 11.2 kW, 14.0 kW), flow temperatures (35 °C, 45 °C, 55 °C) and backup heater settings (gas boiler as a backup heater, no backup heater).

In the hybrid operation (air source heat pump coupled with a natural gas boiler), Comfy Heat and E12 tariffs outperform the remaining tariffs in heating cost, even though Standard and E20 tariffs have the lowest energy consumption values. The latter tariffs have the highest number of off-peak hours, so energy consumption reduces with higher heat pump operations. However, electricity prices in these categories are also higher than Comfy Heat and E12 tariffs so they don’t create financial benefits.

When the heat pump operation is optimised the amount of energy input in the baseline scenario could be reduced by 13% in the hybrid operation (from 11,064 kWh in the baseline scenario to 9638 kWh). However, this reduction could reach 68% when the heat pump operates in standalone mode (from 11,064 kWh in the baseline scenario to 3558 kWh). On the other hand, a similar reduction which is around 12% can be seen in heating costs under hybrid operation (from £709.7 in the baseline scenario to £627.3). This reduction could reach 36% in standalone operation (from £709.7 in the baseline scenario to £451.5). It is important to remind that these reductions are compared with the baseline scenario which has a hybrid heat pump operation. When the optimised heat pump operation results are compared with the standalone gas boiler energy input reductions reach 81% (from 18480 kWh in the standalone gas boiler scenario to 3558 kWh). Heating costs could be reduced by 33% (from £671.0 in the standalone gas boiler scenario to £451.5). The reduction in energy input is greater when compared with the gas boiler due to higher heat pump efficiencies; however, the reduction in heating costs is relatively small due to lower gas prices.

Thermal energy storage tanks require additional space in houses; however, when a gas boiler is in operation as a backup heater, they provide significant reductions, especially in energy consumption. As gas prices are significantly lower than electricity, storing energy in peak times with a gas boiler comes with cost benefits. Moreover, continuous off-peak time in some tariffs (E12, E20, etc.) also helps to store energy provided by the heat pump during off-peak times with thermal energy storage tanks.

Thermal energy storage tanks help to reduce natural gas usage significantly and also heating costs. However, optimised scenario results show that scenarios with standalone heat pumps have lower energy consumption and energy cost results than hybrid operations (Figure 5.26). The main reason is that consumers need to pay a standing charge for gas boilers during the entire year even though they use the boiler standalone or as a backup. This standing charge reaches £85.2 for a year which is nearly the same as the difference between standalone and hybrid operation heating costs. So, high-performing heat pumps with optimised operation do not require a gas boiler as a backup heater.

Comfy Heat tariff performs better than the E12 tariff in all tank sizes, and 500L and 750L tank sizes are the best performers. When the backup heater is in operation the lowest values are achieved with higher tank sizes in both tariffs. Buffer tanks create significant energy reductions in relevant tariffs (E7, Comfy Heat and E12 tariffs have both peak and off-peak times throughout the day so energy reductions can be seen). Heating costs also benefit from higher tank size even though it is not as much as energy reductions.

Scenario optimisation analysis is conducted for Orkney; therefore, weather and solar data for this location are used in the model. Orkney does not have extreme weather conditions and outside temperatures do not drop lower than 3.5 °C. As the efficiency of heat pumps is dependent on weather conditions, the minimum COP values remain higher than 3.75 in optimised scenarios (Figure 5.25). As electricity prices are around 2.5 times higher than gas prices in off-peak times and 5 times higher in peak times, higher COP values are required to compensate for these prices. The optimised scenarios successfully compensate for these prices with high COP values; therefore, scenarios with standalone heat pumps perform better than hybrid scenarios.

This chapter assessed the operation of an air source heat pump in a standalone or hybrid setting with a buffer tank to optimise the heating performance. The best-performing electricity tariffs are investigated to aim for reductions in heating costs to decrease the negative consequences of the high fuel poverty level and more end-user engagement in Orkney. The lowest energy consumption and heating costs are desired for a more compelling environment not only for the demand but also for the supply side of the system. The optimisation analysis is conducted only for a detached refurbished house for simplicity because the optimised operation of the heat pump is replicable for other house archetypes and specifications. The novel element in this research is to be able to investigate variable heat pump operation with a thermal energy storage tank for different house archetypes and climatic conditions in Orkney. Evaluating different electricity tariffs also provides an outlook for end-users. Energy modelling results for these archetypes are investigated in the integrated chapter (Chapter 6) for a more holistic approach together with environmental and economic outcomes.

Chapter 6

Integrated Approach: Orkney as a Case Study

6.1. Introduction

This chapter will introduce the integrated approach explained in the methodology section. Chapter 4 investigates the environmental impacts of heat pumps and gas boilers for the UK residential sector through a life cycle assessment (LCA) analysis. Chapter 5 analyses the optimisation of an air source heat pump operation by energy systems modelling (ESM) and scenario analysis in Orkney. In this section integration of individual methods of LCA and ESM has been utilised to investigate energy, environmental and economic results for Orkney as a case study. A building stock model (BSM) has been developed to evaluate both the individual house archetype level and island level results for Orkney. The economic model analyses the life cycle cost analysis of an air source heat pump and discounted savings when the existing conventional heating systems are replaced with. Financing options with existing governmental supports are evaluated to provide an outlook for end-users. Hourly electricity load results are calculated with a diffusion model to analyse the maximum peak loads of variable heat pump operation in the electricity system of Orkney. The first step of this integrated method is to understand the condition of the housing stock and calculate the number of archetypes based on these conditions. Then, existing heating and fuel types have been explored to compare energy, environmental, and economic savings with the current situation. The final step is to calculate these savings at individual house archetypes level and island level in Orkney.

This chapter extends the analysis presented in a published journal paper (Sevindik & Spataru, 2023).

6.2. Methodology

6.2.1. Building Stock Modelling (BSM)

Energy Performance Certificates (EPC) assess the energy efficiency of a building and include information about recommended improvements; therefore, using EPC information could help to understand the housing stock condition (BEIS, 2021g). An EPC shows the current and potential energy rating of a property named as Standard Assessment Procedure (SAP). The overall EPC rating is comprised of walls, roof, floor, windows, hot water, lighting and heating efficiencies, and has 7 bands ranging from A-G with a certain amount of SAP points out of 100 points as maximum.

EPCs provided by Scottish Government Statistics (2021) have been used to explore Orkney housing stock in terms of archetype, age and efficiency. Orkney has 11,228 dwellings and the majority of them are Detached houses with 59.8% of the total followed by Semi-detached, Terraced and Flats with 22.1%, 11.1 % and 6.9% (Figure 6.1). EPC dataset has 1740 dwellings representing 15% of the total housing stock but the share of Detached houses in this dataset is around 75% which is greater than real data. The number of terraced houses and flats is limited in this dataset, so these archetypes are underrepresented in this dataset. Therefore, the EPC dataset has been used for archetype characteristics and specifications but for the number of house archetypes Scottish Government Statistics (2017) are used (Figure 6.1).

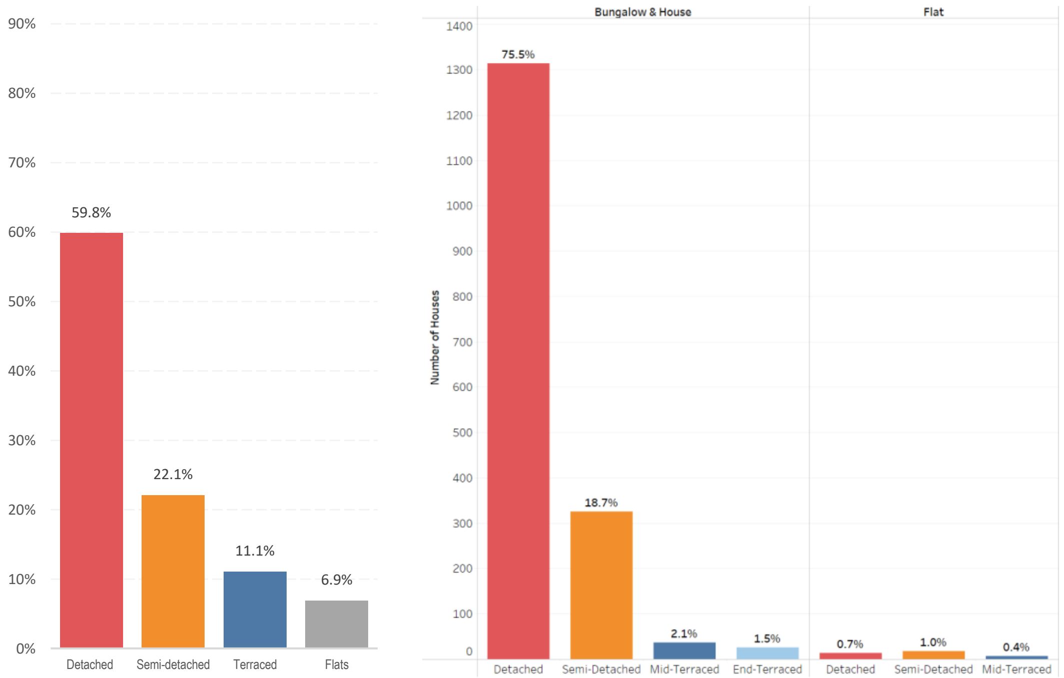

Figure 6.1 House archetypes by Scottish Government Statistics (2017) (left), and EPC data (Scottish Government Statistics, 2021) (right).

The majority of the houses in Orkney are detached houses with a mean gross floor area of 118 m² (Figure 6.2). Only 7.4% of this archetype has an EPC rating of A or B; however, C-D-E-F bands have been distributed evenly between 23-18%. Semi-detached houses have higher B-C-D band ratings and account for 85% of the total. The mean gross floor area is 80.5 m² for this archetype stock. Terraced houses have mainly B-C-D rating bands with a 73 m² mean floor area. Flats are not considered in this study as it is the smallest category among the number of houses, and the EPC dataset does not have enough sample to analyse this archetype.

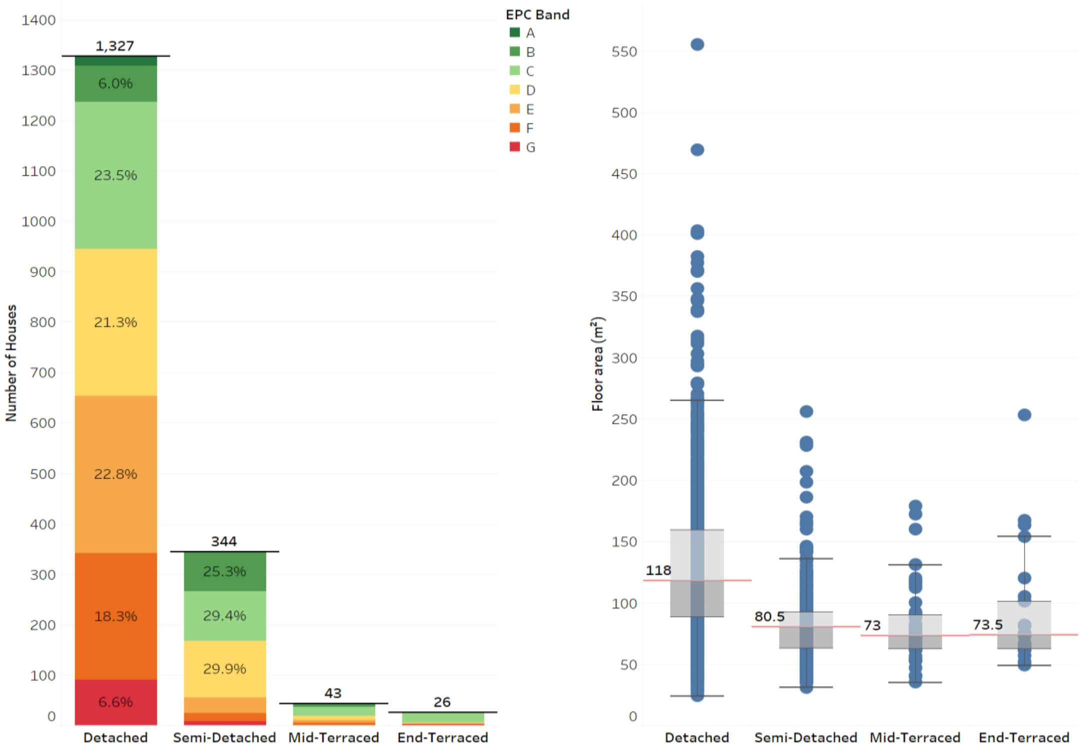

Figure 6.2 EPC ratings (left) and gross floor area (right) of house archetypes

Figure 6.3 illustrates the age bands of the housing stock by EPC ratings and the results show that half of the building stock is built before 1975 and only 6% has an EPC rating of A or B or C. However, this reaches 37% with the houses built after 1975. One-fifth of the housing stock does not have age information in the dataset; however, 82% of this category has a rating of A or B or C. So, it can be assumed that the majority of these categories comprise either new buildings built with higher energy efficiency standards or well-refurbished houses in the existing housing stock.

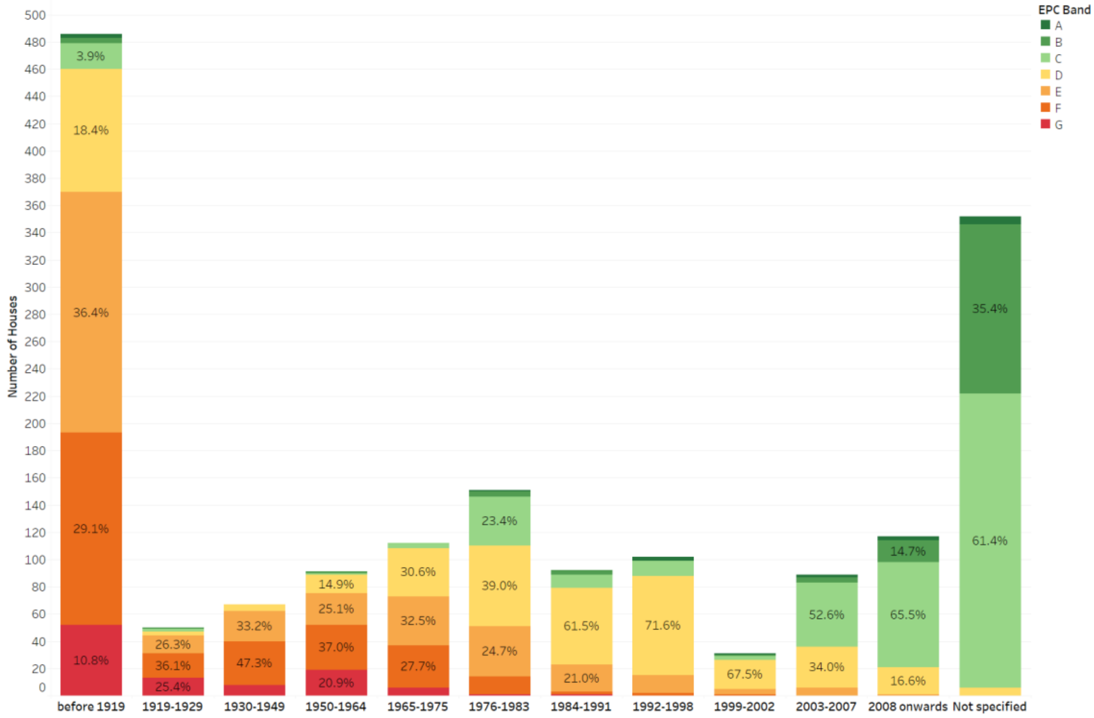

Figure 6.3 EPC ratings of house archetypes by construction age band

To present house archetypes' conditions energy efficiency of the houses needs to be investigated. Energy system modelling conducted in this study calculates energy demand and supply; therefore, understanding the heat loss in the houses is very crucial to investigate energy efficiency. In order to explore heat losses in the houses, energy modelling results are explored. Results for four different archetypes (Detached, Semi-detached, End-terraced, Mid-terraced) with three different specifications (Unrefurbished, Refurbished, New building) are illustrated in Figure 6.4 to investigate the total heat energy loss calculated by the energy model. The results show that Fabric Heat Loss (FHL) is the main cause of losses in each scenario with an overall 80.2% of the total. However, the share of the impact varies depending on archetypes and especially with building specifications. FHL is responsible for 85.2% of total losses in unrefurbished houses followed by Ventilation Heat Loss (VHL) accounts for 14.8%. The share of FHL reduces to an average of 79.6% and 71.6% in refurbished houses and new buildings. The highest FHL contribution occurs in Detached houses with an average of 81.3% and is followed by End-terraced, Semi-detached and Mid-terraced houses with 80.9%, 79.6% and 78.0% respectively. The results indicate that FHL is the main cause of losses in all scenarios so the breakdown of FHL is investigated to understand the contribution of individual construction components.

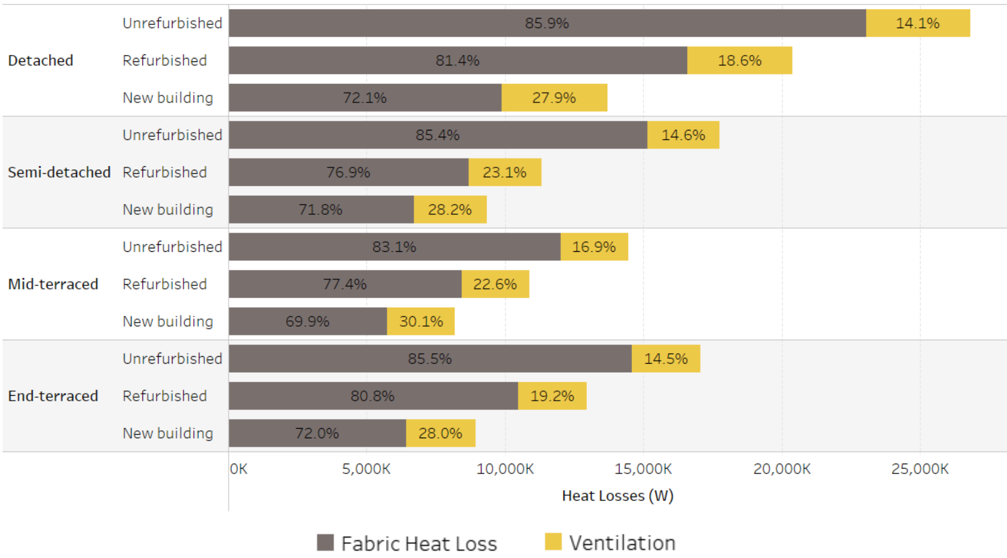

Figure 6.4 Breakdown of heat energy loss in the energy model

The results of the FHL breakdown show that walls are the main contributors to FHL overall with 51.9% followed by windows, floor and roof with 26.9%, 13.3% and 7.9 respectively (Figure 6.5). However, windows contribute more in a Mid-terraced new building because the area of the exposed wall is smaller and the wall is highly insulated. The contributions are varies depending on the house specification. The impact of walls and floor reduces when the house becomes more insulated in other words the impact of windows increases. These contributions are calculated for different archetypes and specifications because EPCs evaluate the energy efficiency of individual construction components so understanding the impact of these components and their weightings will be crucial.

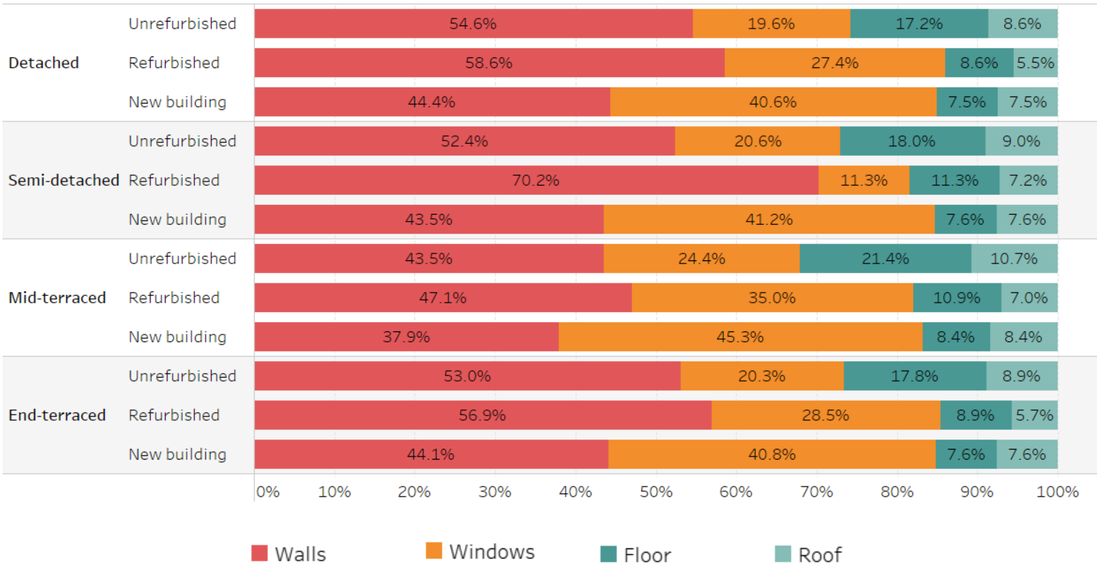

Figure 6.5 Contribution of construction components to fabric heat loss

Some elements of the EPC calculated by SAP are directly linked to the heating demand such as walls, roof, floor and windows efficiencies; therefore, these categories are investigated to understand the heat loss condition in the housing stock. The dataset has five efficiency categories as '*Very poor*', '*Poor*', '*Average*', '*Good*', and '*Very good*'. These categories are represented with numeric values (1, 2, 3, 4 and 5 respectively) to calculate the overall efficiency score of the housing stock. The average efficiencies of individual construction elements (walls, roof, floor and windows) are calculated and illustrated into three categories based on their scores (1.0-3.5, 3.5-4.5, 4.5-5.0) to represent '*Unrefurbished*', '*Refurbished*' and '*New building*' categories used in energy modelling. However, the impact of individual construction elements varies in different archetypes and building specifications; therefore, while calculating the overall efficiency score of the house, the weight of the construction element has been altered based on the results illustrated in Figure 6.5.

In light of these calculations, Figure 6.6 shows the energy efficiency categories based on their scores of individual construction components and overall results by different archetypes. The results illustrate that the majority of the Detached houses are categorised as unrefurbished with 55.8% of the total housing stock followed by the refurbished and new building categories with 25.4% and 18.8% respectively. The most efficient construction parts are the roof and walls in this archetype with 64.5% and 55.1% respectively. The floor is the least efficient category in all archetypes and the highest contribution occurs in Detached and Mid-Terraced archetypes with 66.2% and 51.4%.

Semi-Detached houses have more efficient building stock than Detached houses with less unrefurbished housing stock of only 28.8%. Refurbished and new building categories accounts for 36.3% and 34.9% of the total stock in this archetype. The mid-terraced category has very similar numbers for refurbished and new building categories with 27.9% for each respectively. Unrefurbished housing stock accounts for 44.2% of this archetype. End-Terraced houses have the highest number of new building category with 53.8%. Refurbished and unrefurbished categories account for 23.1% each.

After identifying the housing stock condition, the current heating situation of Orkney is explored. The main heating type in Orkney is electric heaters with 45.2% of the total housing stock (Figure 6.7). It is followed by oil boilers and heat pumps with 36.7% and 9.0%. The remaining is provided by wood, coal and LPG boilers. In refurbished houses electric heater is the main heating type with 15.8%; however, oil is the dominant fuel type in unrefurbished ones with 20.6%. The majority of heat pumps are used in the new building category with an overall 7.7% and it is the main heating type in this category.

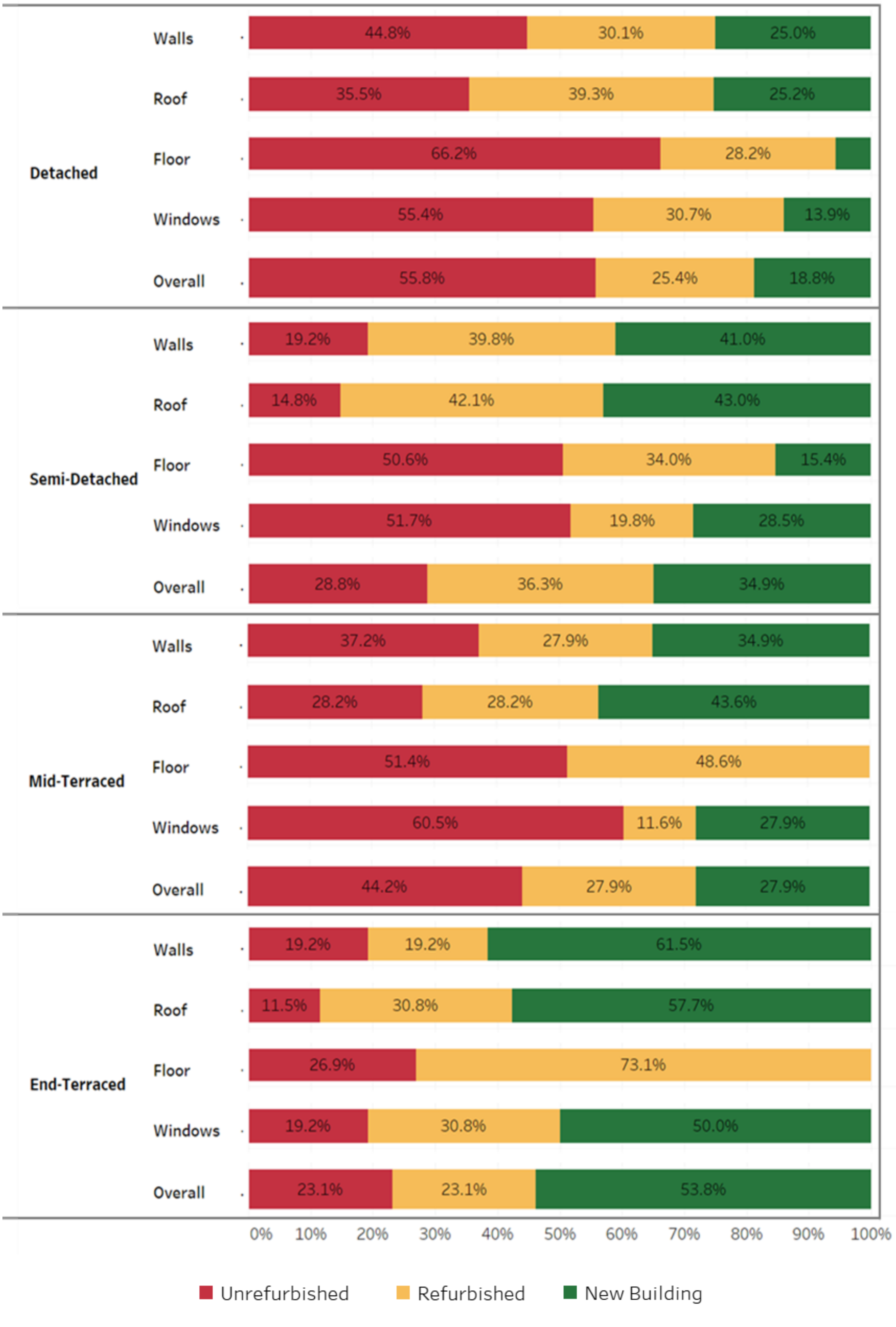

Figure 6.6 Energy efficiency scores for wall, roof, floor, windows and overall, by house archetypes

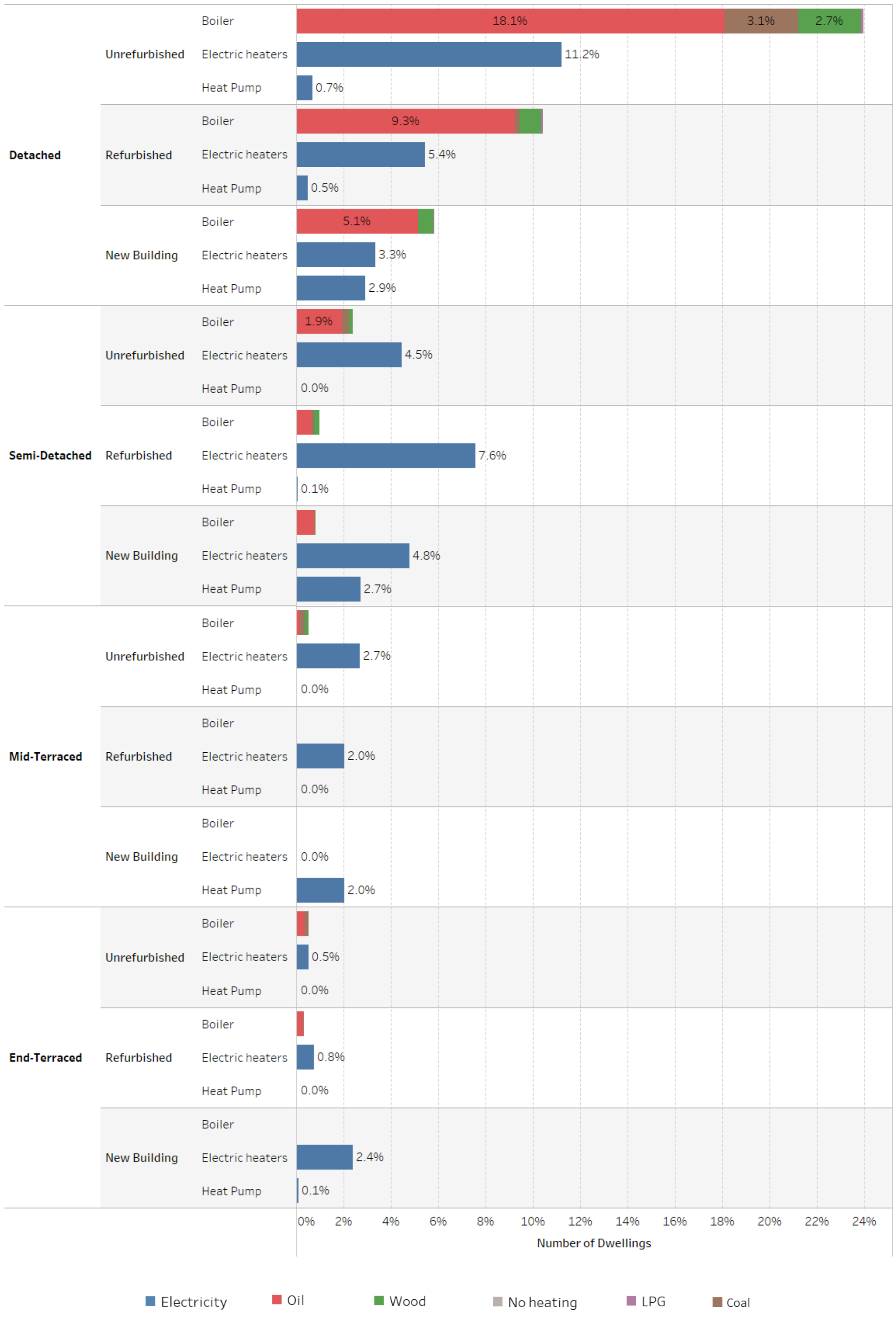

Figure 6.7 Proportion of main heating fuel type and the total number of heaters

6.2.2. Integrated Approach

In the previous section, housing stock condition is analysed by archetypes and their specifications to understand their energy efficiency performance. The integrated approach aims to identify energy, environmental and economic savings for individual archetypes and the total for Orkney. Therefore, the objectives of the integrated approach are;

- to identify individual and total energy savings by comparing current energy demand and supply with the heat pump uptake scenario,
- to analyse the life cycle assessment of an air source heat pump utilised in Orkney
- to compare the environmental results of the current situation with future scenarios,
- to investigate GHG emission savings of Orkney for the current situation and future scenarios with heat pump uptake scenario,
- to analyse individual and total cost savings for the current fuel types and future scenarios,
- to investigate life cycle cost analysis for end-users to identify the optimum financial structure for heat pump uptake scenario,
- to identify hourly electricity consumption results for individual archetypes and the Orkney electricity system.

In this section, the integration of life cycle assessment and energy systems modelling has been utilised. First of all, individual energy, environmental and economic results of different archetypes are calculated. Then, cumulative results for Orkney are calculated by multiplying the individual results by the number of archetypes and heating types for the baseline model. Finally, a scenario analysis is conducted to compare overall results for the current situation with future scenarios to analyse energy, environmental and cost savings. In this section, only an air source heat pump is considered for the analysis for simplicity similar to the energy systems modelling chapter. In this section, two scenarios have been developed for the year 2050.

Baseline: It represents the current situation at Orkney. The number of heat pumps deployed in the islands is around 1050 representing one-tenth of total dwellings. The majority of the houses are in the unrefurbished category using electric heaters and oil boilers.

Circular Economy (CE) scenario: Circular principles through reducing energy and material demand, and prioritising reuse and recycle options are implemented. High technology development and high consumer engagement are supported by policies; therefore, more efficient houses and low carbon technologies expect a reduction in energy demand. Uptake of heat pumps reaches 100% to achieve UK's Net Zero target.

Resource Efficiency (RE) scenario: Implementation of circular principles is supported but not using full potential. A reduction in energy demand is expected but this decrease is lower than the CE scenario. Energy efficiency improvement applications are limited.

Figure 6.8 illustrates the number of dwellings modelled for baseline and future scenarios. In the baseline scenario, majority of the dwellings were categorised as unrefurbished houses (5279) and followed by refurbished and new building categories (3151 and 2797 respectively). The main heating type is electricity (electric heaters and heat pumps combined) followed by oil. RE and CE scenarios expect an increase of around 2000 in the total number of dwellings (from 11,227 in the baseline model to 13,313 in the year 2050) in line with the historical trend.

RE scenario assumes that 75% of fossil fuel heating technologies will be replaced with heat pumps. Energy efficiency improvement measures are taken for 75% of unrefurbished and 25% of refurbished houses. Half of the new dwellings constructed until 2050 are assumed to be in the new building category and the remaining are in the refurbished category all of which use heat pumps for space heating.

CE scenario assumes more ambitious numbers to achieve UK's Net Zero target. All of the heating technologies will be replaced by heat pumps in this scenario. The majority of the new dwellings (75%) constructed until 2050 will be in the new building category and the remaining will be in the refurbished category. CE scenario assumes higher energy efficiency improvement measures taken with 100% heat pump uptake.

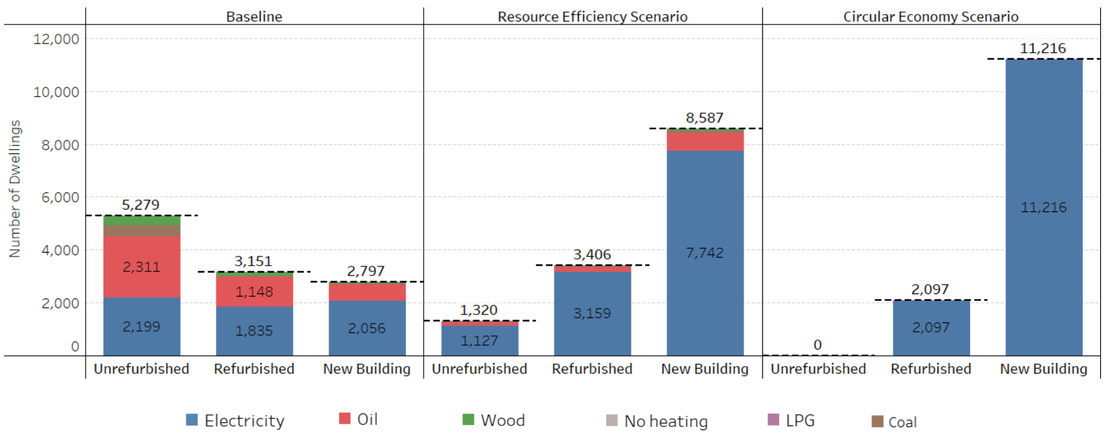

Figure 6.8 Number of dwellings and fuel types by house archetypes and specifications for baseline and future scenarios

6.2.3. Life Cycle Cost (LCC) Analysis

The energy model has developed further to include financial aspects of heat pump uptake scenarios. Existing heating fuel types (oil, coal, LPG, wood, electricity), fuel prices, investments costs, discount rate and lending rate information are included in the model to calculate savings coming from the transition to heat pumps. Different financing alternatives including support from the government (BUS/HES) are also investigated at both the archetype level and the island level. In this section life cycle cost analysis of a heat pump is calculated based on baseline model results. Then, results for Circular Economy (CE) and Resource Efficiency (RE) scenarios are analysed for future results.

The cost of installing heating measures is analysed by Delta-EE (2018) for different heating types including heat pumps. An existing report of Carbon Trust (2020) investigates the overview of heat pump retrofit in London through 15 case studies and CO_2 savings and cost analysis. Nesta and BIT have several economic and social studies on heat pumps about reducing the cost of heat pumps, increasing end-user awareness and policy review (Nesta & BIT, 2022a, 2022b, 2022c). In line with these studies and market research upfront cost of an air source heat pump (ASHP) is assumed as £9250, £10,250 and £12,000 for 8.5 kW, 11 kW and 14 kW sizes of heat pumps (Table 6.1) (these costs include buffer tank costs as it was investigated in energy model). The upfront cost is assumed as £9250 for houses in the new building category, and £10,250 for the remaining house specifications except for unrefurbished detached houses. As detached houses have higher demands than remaining archetypes £12,000 upfront cost is assumed for a larger size of a heat pump. Future cost reductions for heat pumps are expected by DECC (2016a) for a mass market scenario; therefore, 10% and 20% cost reductions are assumed for RE and CE scenarios. Average lending rates and discount rates for a 15-years period are decided from market research and quotes from providers.

Table 6.1 Summary of assumptions for life cycle cost analysis and future scenarios (Data sources: (Nesta, 2022)[1], (Nesta & BIT, 2022b)[2], (Nesta & BIT, 2022c)[3], (BEIS, 2021a)[4], (Carbon Trust, 2020)[5], (Delta-EE, 2018)[6], (DECC, 2016a)[7], (Freeman et al., 2017)[8], (BEIS, 2021c)[9], (HES, 2022)[10]

	Baseline	**Resource Efficiency (RE)**	**Circular Economy (CE)**	**References**
Upfront Cost (8.5 kW)	£9,250	£8,325	£7,400	[1,2,3,4,5,6,7]
Upfront Cost (11 kW)	£10,250	£9,225	£8,200	
Upfront Cost (14 kW)	£12,000	£10,800	£9,600	
Upfront Cost Change	0%	-10%	-20%	[7]
Lending Rate	3.0%	2.8%	2.5%	
Discount Rate	3.5%			[8]
Period	15 years			
BUS	£5,000			[9]
HES	£7,500			[10]

The Boiler Upgrade Scheme (BUS) replaces Renewable Heat Incentive (RHI) and provides a grant of £5000 for the upfront cost of an ASHP (BEIS, 2021c). Similar to this support Scottish Government provides a loan for energy efficiency measures and renewable heating systems including cashback payments (HES, 2022). The government can provide a £2500 interest-free loan and £7500 cashback (£10,000 in total) for an ASHP installation. The unrefurbished detached house is the only category which has more than £10,000 upfront cost so the interest-free loan is not limited to £2500 in this study for simplicity. These support measures are also included in life cycle cost calculations. The results are expressed in discounted costs at an annual rate of 3.5% (Freeman et al., 2017).

Data for fuel prices of energy sources used in Orkney has been collected from previous studies and quotes from suppliers. BEIS (2020e) provides historical data for fuel prices and future trends. National Infrastructure Commission (NIC, 2018) researched the current fuel prices for the year 2050. With the help of these reports and market research from suppliers, the fuel prices for the baseline scenario, RE scenario and CE scenario are used as provided in Figure 6.9. Fossil fuel prices are expected to increase in the future with carbon taxes, and electricity prices to decrease (Energy Brainpool, 2022). Unprecedented events such as the COVID-19 pandemic or events between Ukraine and Russia create instability in fuel prices and the impacts of these are not included in this study as it is very difficult to assess these conditions. Therefore, this study considers that the pre-pandemic trends continue.

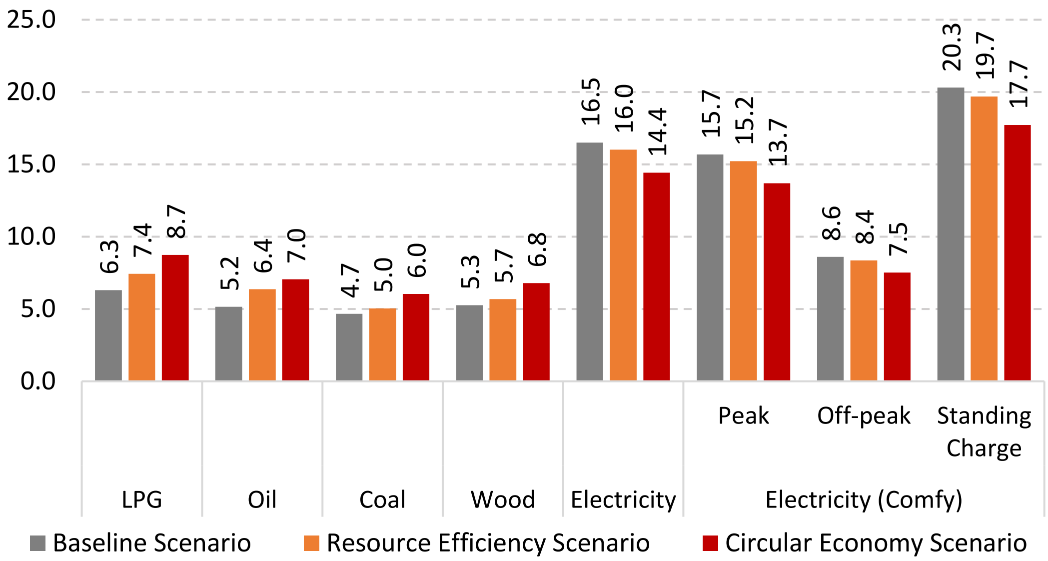

Figure 6.9 Fuel prices for baseline and future scenarios (Data sources: BEIS, 2020e; Energy Brainpool, 2022; NEP, 2022; NIC, 2018)

Specification and energy efficiency improvement conditions of construction elements in house archetypes are illustrated in Figure 6.10. The majority of the houses require external wall insulation when needed which is around 45% of the total housing stock. Cavity wall insulation accounts for 30% and internal insulation for 3% respectively. 22% of the housing stock does not have any specified construction type whereas they are classified under the new building category, so they do not require any wall insulation. The dominant potential insulation type is cavity insulation only in refurbished detached houses. The majority of the houses have double-glazed windows which accounts for 54% of the total housing stock. Most of these windows are in refurbished houses. Unrefurbished houses mainly have single-glazed windows, but double-glazed windows also exist in this category. High-performance windows only exist in the new building category, so they do not require any efficiency improvements. In terms of roof insulation, loft insulation is the dominant potential insulation type; however, 11% of houses require flat roof insulation. Underfloor insulation is the only option for the floor category and the majority of refurbished houses and all unrefurbished ones require floor insulation.

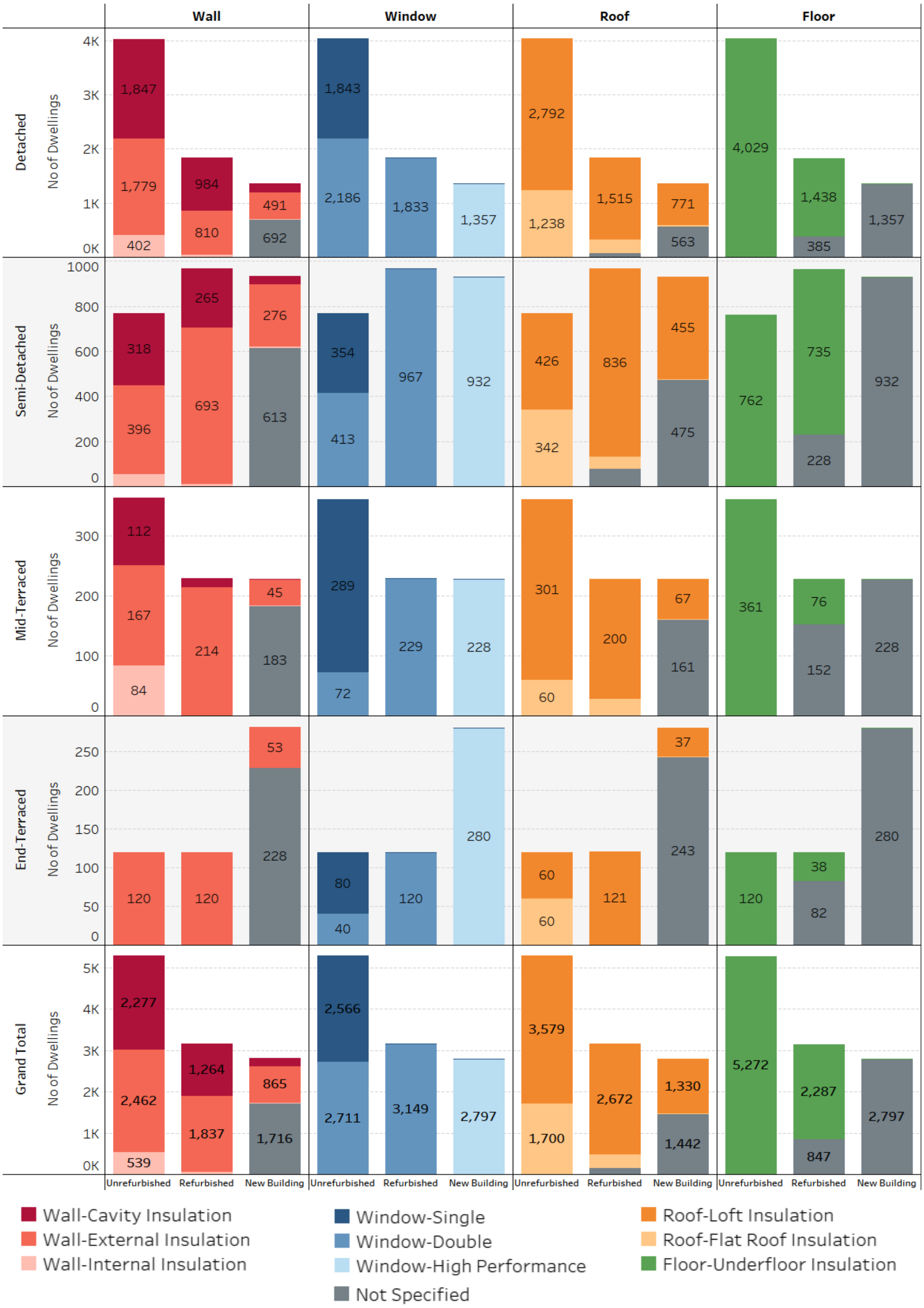

Figure 6.10 Types and specifications of construction elements (wall, window, roof, floor) in house archetypes and number of houses required energy efficiency requirement

Figure 6.11 illustrates the cost of efficiency improvement steps for each construction element by house archetypes. While deciding on the insulation type, the dominant construction element is selected from the previous figure (Figure 6.10). The highest installation cost occurs in unrefurbished detached houses with £22,100 followed by semi-detached and end-terraced houses with £16,325 and £15,525 respectively. Mid-terraced houses require less wall insulation area; therefore, the total cost is relatively low (£9425) when compared with other archetypes. External wall insulation is the major contributor to the costs in all archetypes except mid-terraced houses. Replacing windows dominates the wall insulation in mid-terraced houses as they have less wall area exposed to outside conditions. Refurbished houses were assumed to have wall insulation previously and have better window conditions than unrefurbished houses. However, as the new building category has ambitious insulation targets a secondary glazing layer to the windows is assumed. These efficiency improvement costs are included in the life cycle cost analysis for a broader perspective on the housing stock condition.

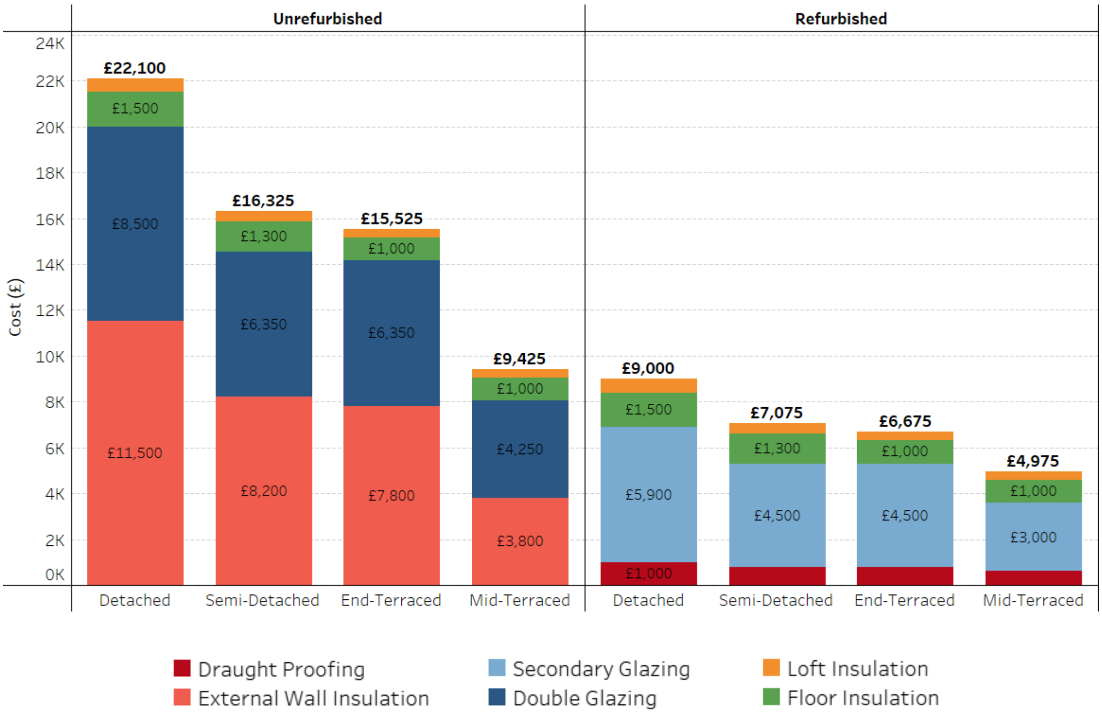

Figure 6.11 Breakdown of energy efficiency improvement costs by house archetypes and specifications (Data sources: CCC, 2019b; Delta-EE, 2018)

6.2.4. Heat Pump Diffusion Model

A previously developed heat pump diffusion model (Kreuder & Spataru, 2015) quantifying the impact of installing air source heat pumps on the electrical load curves at the dwelling and UK levels has been integrated into this research. The methodology of the previous model assumes that heat pumps have a constant operation; however, the energy model has a variable operation pattern. Therefore, variable load curves are used for the analysis, but constant operation curves are also used as a reference to compare the results. The energy model has developed further to provide hourly heat pump electricity loads so an electricity load profile study is conducted to investigate the Orkney grid level.

Dwelling heating needs and electrical heat pump power values have been transferred from the energy model. Data for Orkney electricity system load has been taken from Scottish and Southern Electricity Networks (2021). Average household level hourly electricity load structures have been taken from a study conducted by Intertek (2012) for various types of household settings including with/without electricity heating. Heating-related loads have been taken from the total values so the impact on dwelling and grid level load curves are calculated. The loads are calculated for the coldest winter workday and holiday to investigate.

6.3. Results & Discussion

6.3.1. Energy Savings

Current energy results (supply and demand) and proposed scenarios are calculated for individual archetypes and overall Orkney. Figure 6.12 shows that unrefurbished houses have the highest demand as expected. Moreover, Detached houses have the highest demand among archetypes with an average of 16,591 kWh because of the larger gross floor area and exposed walls to outside conditions. However, it also varies depending on the building specifications. The highest demand occurs in an unrefurbished Detached house with 21,774 kWh. This could be reduced to 16,525 kWh if the building is refurbished or to 11,473 kWh if the house has more strict energy efficiency measures. The proposed energy supply with an air source heat pump (ASHP) is also presented in Figure 6.12.

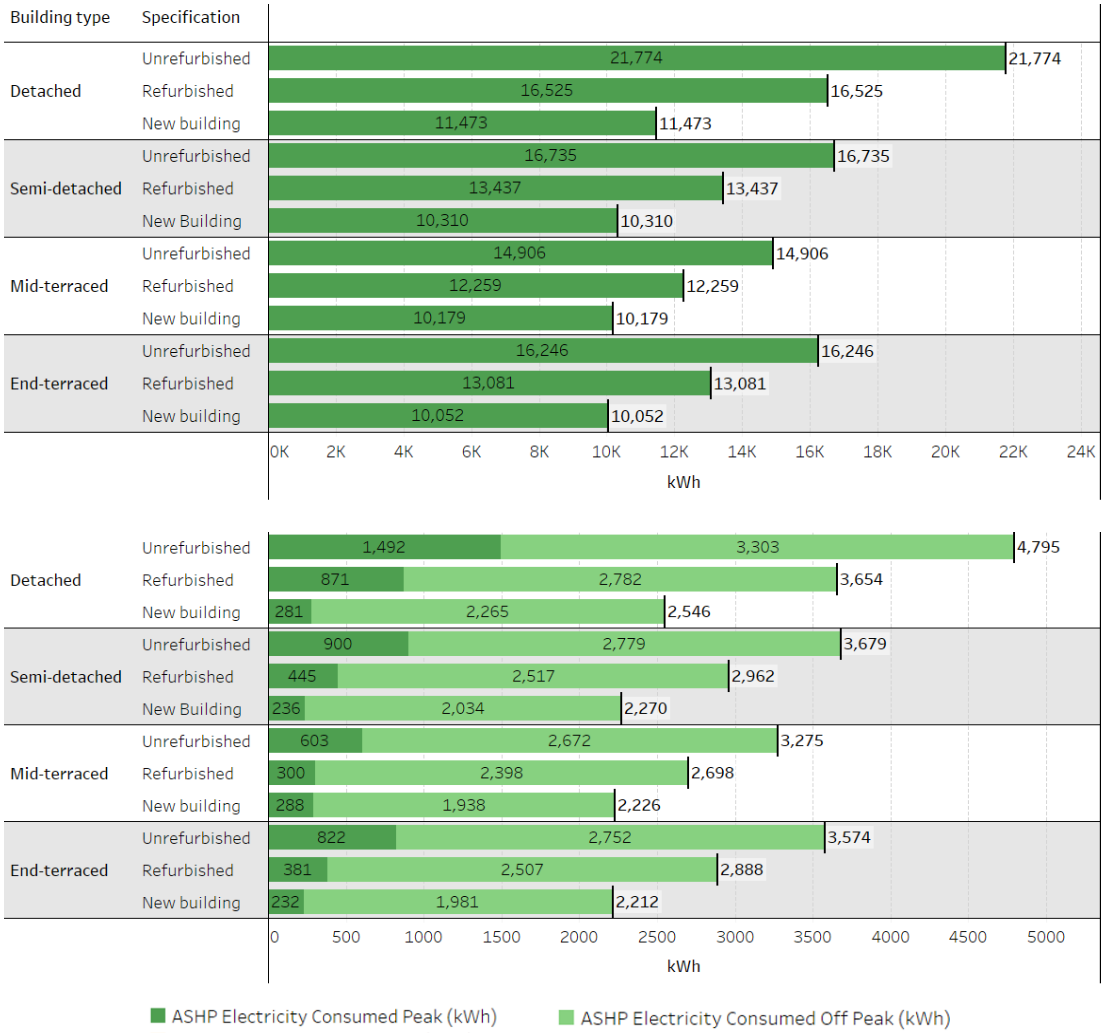

Figure 6.12 Energy demand results (above) and proposed energy supply (below) by house archetypes for heat pump uptake scenarios

The demand figures and main heating fuel type results in the EPC dataset are integrated with building stock modelling to illustrate overall results for Orkney (Figure 6.13). Overall domestic demand occurs at 186.4 GWh whereas supply stands at 192.0 GWh. While calculating the demand 2.65 is used as an average SPF value for current heat pumps as the field trial shows (Lowe et al., 2017). The majority of supply is currently provided by electricity and oil with 84.2 GWh and 83.3 GWh respectively. However, heat pump model scenario results show that supply could be reduced to 67.0 GWh with the RE scenario by replacing the majority of the electric heaters and oil boilers with ASHPs. The supply could even be reduced to 34.4 GWh if all heating types are changed to ASHPs with the CE scenario. It is also important to remind that the energy efficiency of housing stock also plays an important role because unrefurbished houses require higher supply values. Therefore, RE and CE scenarios consider energy efficiency measures taken at different rates explained in the methodology section.

RE results show that if energy efficiency improvement measures are taken, energy demand will decrease to 173.6 GWh and supply will be reduced to 67.0 GWh. This accounts for a 7% decrease in demand and a 65% decrease in supply respectively. The demand figures also include the new housing stock by 2050 which is around 19% of the existing houses; however, energy efficiency improvements still help to decrease the total demand.

CE scenario results show that more strict efficiency standards could provide a 16% reduction in demand even though the total number of dwellings is increased. Higher energy efficiency improvement measures create less energy demand for the entire housing stock. Energy supply is expected to decrease to 34.4 GWh by replacing all heating technologies with ASHPs. The main reason for a higher reduction in energy supply is heat pumps are significantly more efficient than other heating technologies; therefore, the reduction in supply is significantly higher than demand in the CE scenario.

Energy efficiency improvement measures could provide significant reductions in not only the demand side but also the supply side of the system. However, increasing the efficiency level of a house from unrefurbished to new building category could require significant capital costs because the new building category has more strict standards than the refurbished house category. The financial analysis of energy efficiency improvements is investigated in section 6.3.3.

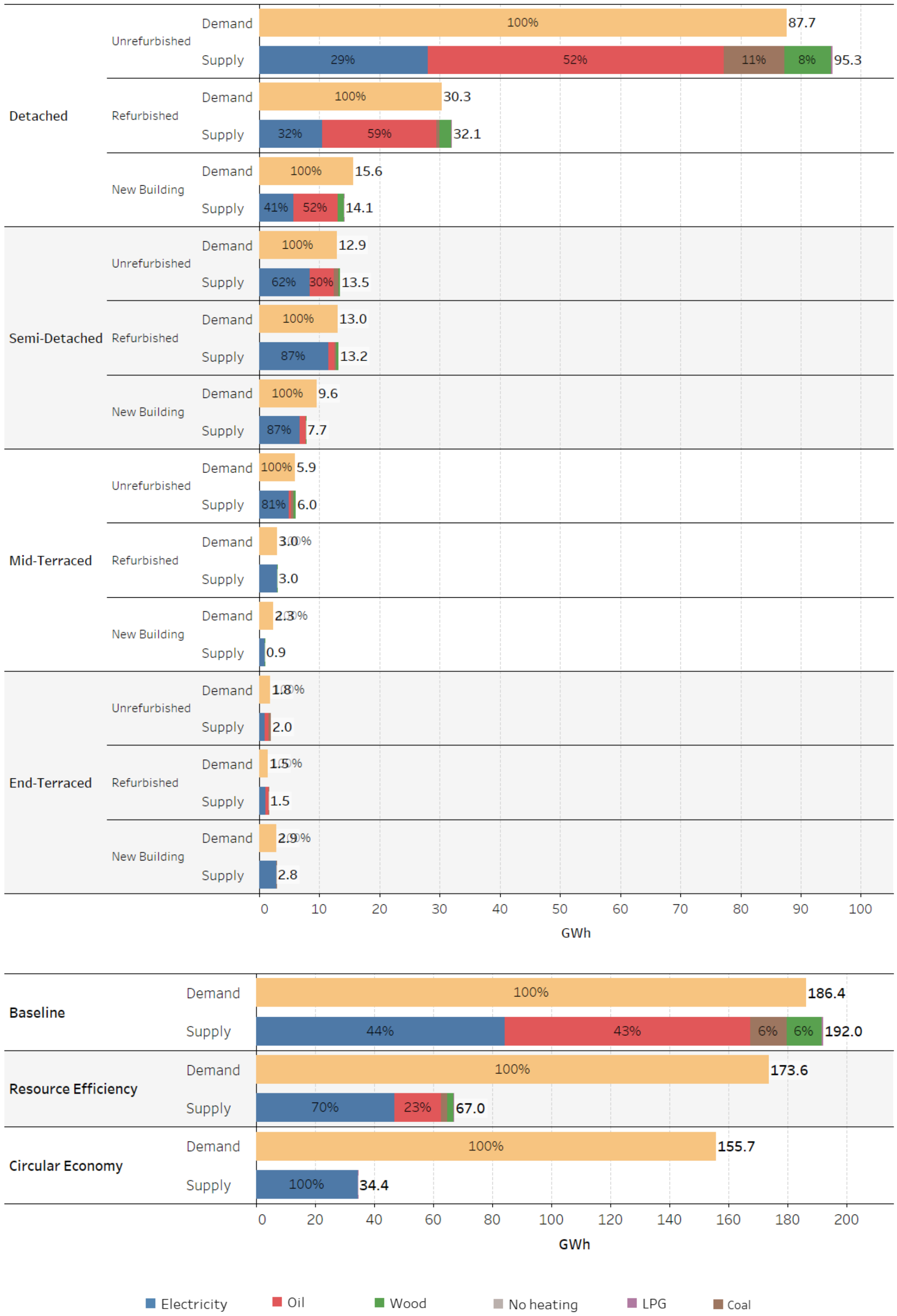

Figure 6.13 Comparison of energy demand and supply for house archetypes with heat pump uptake scenarios by fuel type

6.3.2. Environmental Savings

Life cycle assessment (LCA) results of an ASHP for the UK are calculated in Chapter 4, so in this section, these results are revised for Orkney by changing the transport location to Orkney and the electricity supply mix. Currently, Orkney produces renewable energy from wind and tidal more than its demand; therefore, the electricity mix in Orkney comprises 100% renewable energy sources. Electricity demand varies based on archetypes and their specifications; therefore, environmental results for these individual archetypes are calculated (Figure 6.14). Results show that there is a significant reduction in most categories when it is compared with the results for the UK. The main reason for that is the change in the use phase. In UK results, the use phase was dominating the remaining categories, however, the amount of electricity used for the heat pump throughout the lifetime (20 years) is reduced because of higher efficiencies (2.8 SPF used for the UK study and the average optimized SPF modelled for archetypes in Orkney is 4.5). Moreover, electricity is produced mainly from wind energy; therefore, the negative consequences are decreased.

The highest reduction occurs in the IR[3] category with a nearly 99% decrease. The main contributor to this category is electricity from nuclear therefore renewable electricity helps to reduce this impact. Other highest reductions occur in ALO, TE and NLT categories with 98%, 98% and 96% respectively. The reduction in ALO and TE categories is relevant to electricity produced from biomass which exists in the UK electricity mix but not in Orkney. NLT category is relevant to the fossil fuels that exist in the UK electricity mix.

The lowest changes occur in FE and ME categories with a 9% and 14% reduction. The main processes that contribute to these categories are the manufacturing and disposal of scrap metals so as there are no changes in these phases the results remain similar and only the use phase creates these differences. ULO and MD categories also have 19% and 34% lower results mainly because of the differences in the electricity mix.

The CC category results decreased from 44,320 kgCO_2e to 5621 kgCO_2e on average. Even though the average value is very low when compared with the UK figure, results vary based on the archetype and building specification. It can reach 6284 kgCO_2e if the building is an unrefurbished detached house or decrease to 5295 kgCO_2e if it is a new semi-detached house. The new buildings category shows 14%, 5%, 7% and 9% lower results for detached, semi-detached, end-terraced and mid-terraced archetypes respectively.

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[3] **CC** (Climate Change), **OD** (Ozone Depletion), **TA** (Terrestrial Acidification), **FEU** (Freshwater Eutrophication), **MEU** (Marine Eutrophication), **HT** (Human Toxicity), **POF** (Photochemical Oxidant Formation), **PMF** (Particulate Matter Formation), **TE** (Terrestrial Ecotoxicity), **FE** (Freshwater Ecotoxicity), **ME** (Marine Ecotoxicity), **IR** (Ionising Radiation), **ALO** (Agricultural Land Occupation), **ULO** (Urban Land Occupation), **NLT** (National Land Transformation), **WD** (Water Depletion), **MD** (Metal Depletion), **FD** (Fossil Depletion).

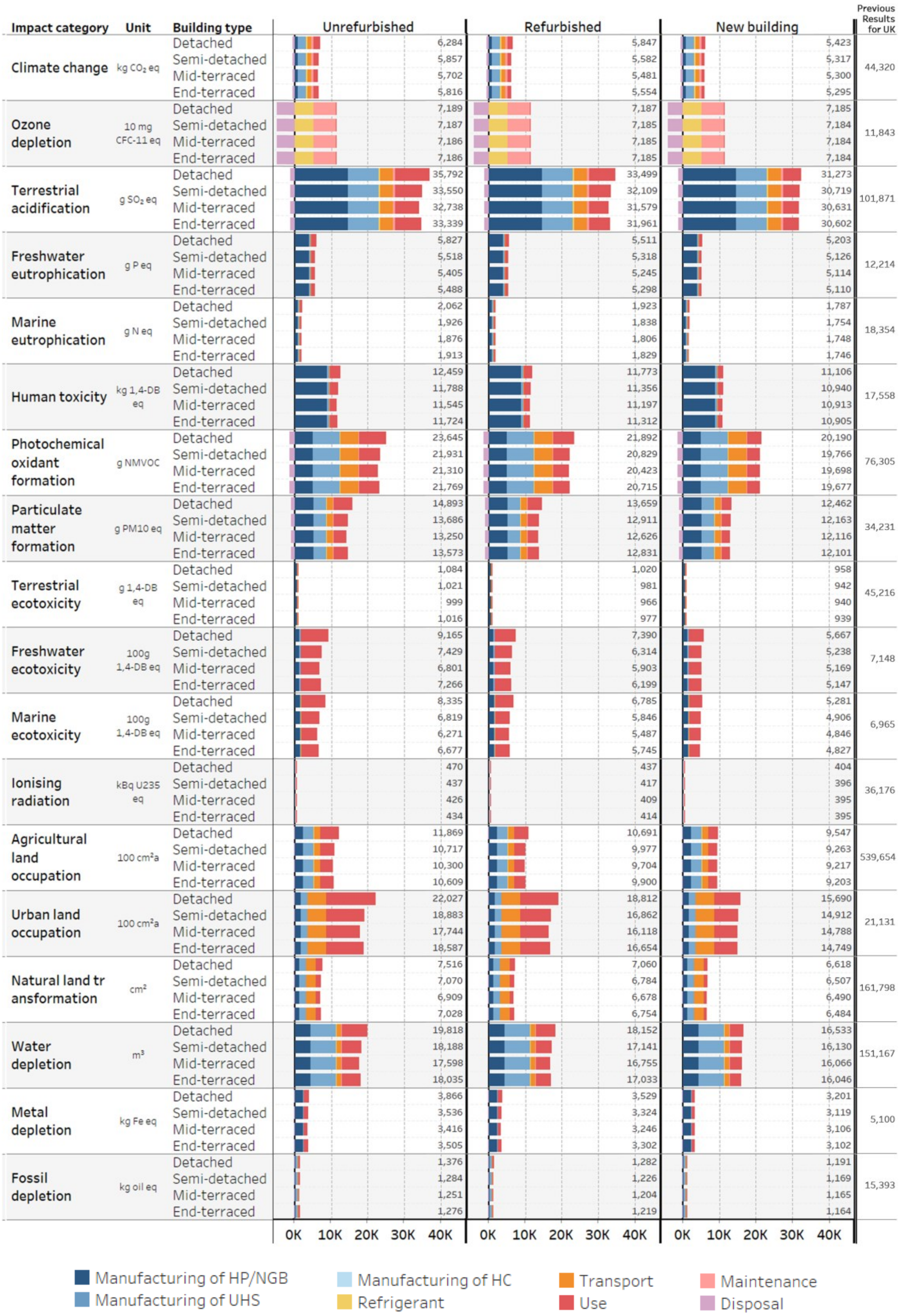

Figure 6.14 Lifecycle environmental impacts of heat pump uptake scenarios by house archetypes

The differences in results exist also in other categories by different house archetypes and specifications. Detached houses have the highest results among archetypes. Semi-detached, mid-terraced and end-terraced houses have 6%, 7% and 6% lower results than the detached houses on average respectively. Similarly, the unrefurbished category has the highest results among building specifications. Refurbished and new building categories have 6% and 12% lower results on average respectively. This difference is mainly because of different use phase requirements; however, some impact categories are more sensitive to this change. The highest changes in one impact category exist in FE, ME and ULO categories. The differences between an unrefurbished detached house and a new building end-terrace house could be as high as 78% in FE, 73% in ME and 49% in ULO category. These results emphasize that not only the environmental impacts of different space heating technologies are important but also the house archetypes and specifications. A refurbished house and a new building category have 5% and 10% lower results than an unrefurbished one in the CC category. The highest change occurs in the FE category with a 16% and 30% reduction in refurbished and new building categories. ME category shows similar reductions with 15% and 29% for the same building specifications. ULO category also shows reductions of around 11% and 22% with energy efficiency improvements.

House archetypes and their specifications create different electricity demands and heat pump size requirements. This study compares the life cycle impacts of different archetypes by differentiating the electricity use; however, one size heat pump is used in the study. This is mainly because the data is limited to the amount of materials used for different sizes of heat pumps; therefore, only one size of heat pump is used. In the UK study, the use phase dominates most of the categories, so the importance of the manufacturing phase remains limited; however, when heat pumps are deployed with renewable electricity, similar to the Orkney case study, the importance of the manufacturing phase increases. Therefore, this limitation exists in this part of the study.

The results of LCA are integrated with building stock modelling and cumulative results for Orkney have been calculated. The baseline scenario represents the existing heat pump numbers currently, and future scenarios show the results based on the heat pump uptake numbers illustrated in Figure 6.8. Results show that currently 5517 tCO_2e is released from heat pumps and this number could reach 59,684 tCO_2e and 72,404 tCO_2e with RE and CE scenarios. (Figure 6.15). CE scenario shows the highest results with around 12 times greater than the baseline scenario as it aims to replace all existing heating systems with heat pumps. RE scenario also shows higher results but it is around 10 times greater than the baseline overall. These results are showing the cumulative environmental impacts and are more relevant when it is compared with the existing systems. As this study did not cover the life cycle assessment of other fossil fuel heated systems, one category is chosen to be compared. In order to understand the environmental CO_2e emission savings that occurred during the use phase, the CC category is selected to compare the emissions of fuels used in scenarios.

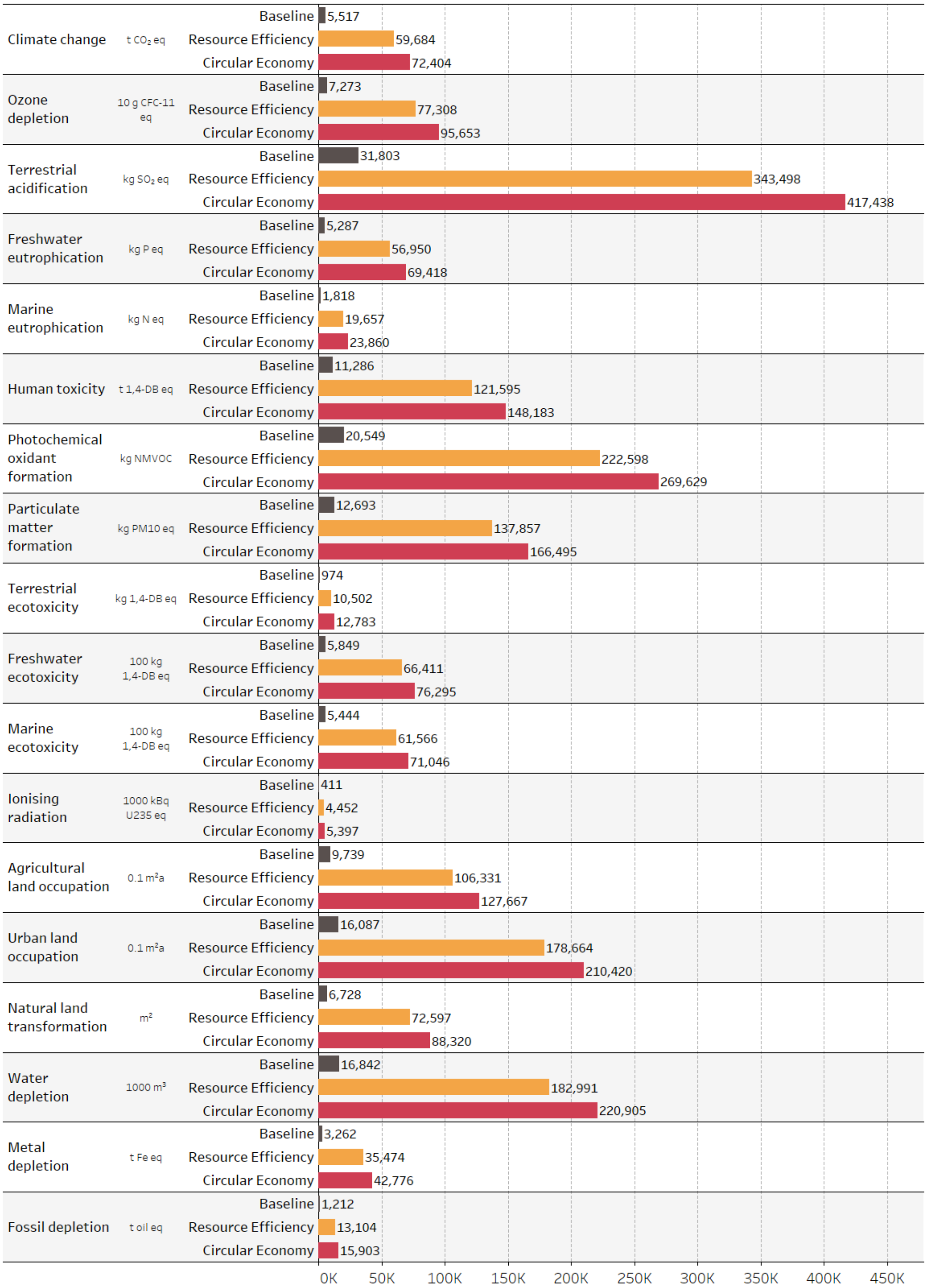

Figure 6.15 Cumulative lifecycle environmental impacts of heat pump uptake scenario for Orkney

Figure 6.16 illustrates the breakdown of CO_2e emissions for the baseline scenario by archetypes contributed by fuel types and total emissions for future scenarios. As the dominant house archetype is detached houses the majority of the emissions (around 85%) come from this group. Oil is responsible for 77% of total emissions (20,552 tCO_2e) followed by coal with 16% (4248 tCO_2e) and electricity with 6% (1612 tCO_2e) in the baseline scenario. Wood and LPG account for only 1% (269 tCO_2e) of total emissions. RE and CE scenarios reduce total emissions by 78% and 98% respectively. RE scenario expects an 81% reduction in fossil fuel emissions and a 44% reduction in electricity emissions. CE scenario replaces all heating technologies with heat pumps, so the emissions are 659 tCO_2e coming from electricity which is very low when compared with the RE scenario. This reduction accounts for an 11.25% average annual mitigation rate. Even though the number of houses is higher in the future with around 2000 more new dwellings ambitious energy efficiency improvement targets also help to reduce both demand and emissions. UK's Net Zero target is ambitious and requires ambitious steps including not only a shift in the heating system but also a shift in energy efficiency measures.

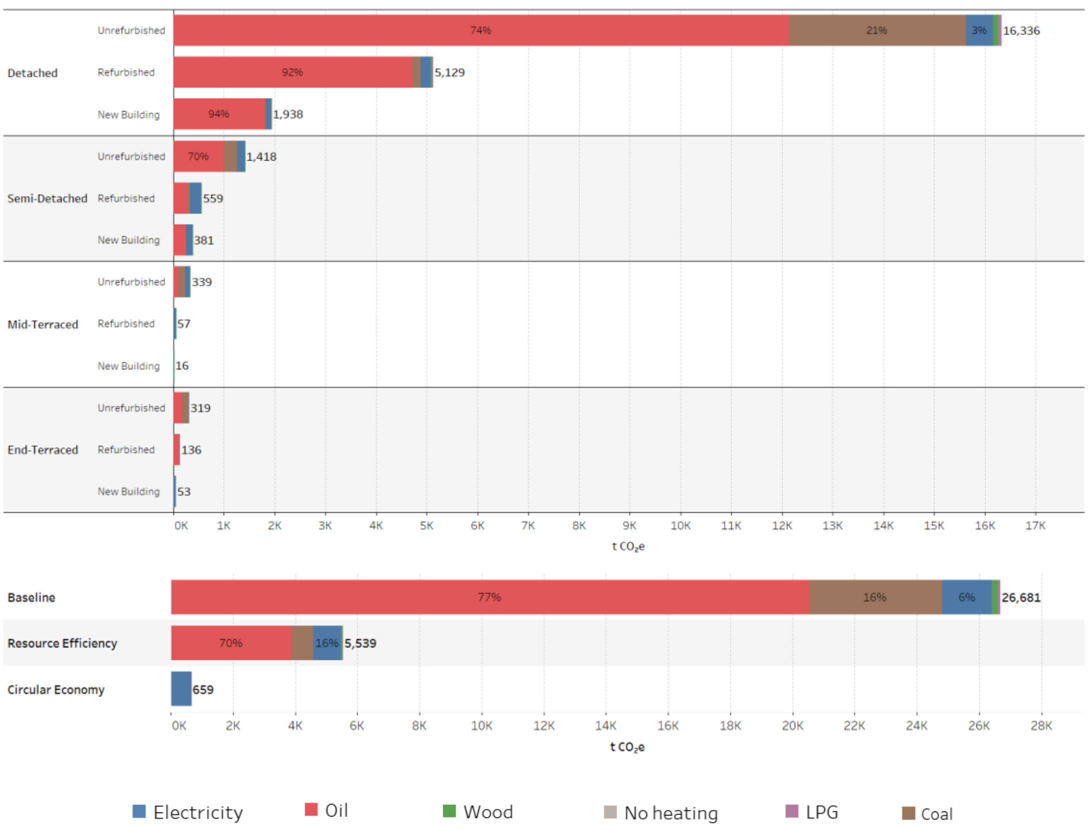

Figure 6.16 Comparison of current and heat pump uptake scenario CO_2e for house archetypes contributed by fuel type

6.3.3. Cost Savings

Energy modelling results illustrated that Comfy Heat and E12 tariffs have the optimum heating cost results; therefore, the heating cost of house archetypes and specifications for the Comfy Heat tariff is presented in Figure 6.17. E12 results are very similar to Comfy Heat tariffs so it is omitted for simplicity. Detached houses have the highest heating cost with an average of £452 heating cost. Mid-terraced houses have 25% less heating cost on average followed by end-terraced and semi-detached houses with 21% and 19% respectively. The main reason for this difference is that the demand varies based on gross floor areas and house archetypes.

House specification is also a significant factor to reduce heating costs. An unrefurbished detached house's energy cost could be as high as £592.4 for the entire year. 48% of this cost comes from off-peak time electricity usage and 39% comes from peak time usage. 13% is the standing charge which is the same for all house archetypes. When the energy efficiency of the house is improved to the refurbished category the total heating cost could be reduced to £450.3, and £313.1 with the new building category. The major reason for this reduction is that not only the heating demand reduces with the help of energy efficiency improvement measures but also it can help to shift the majority of the energy usage to off-peak time; therefore, the share of peak time usage decreases to 30% and 14% in refurbished and new building categories. Similar trends occur for the remaining house archetypes and the lowest heating cost occurs in a new building category end-terraced house with £281.

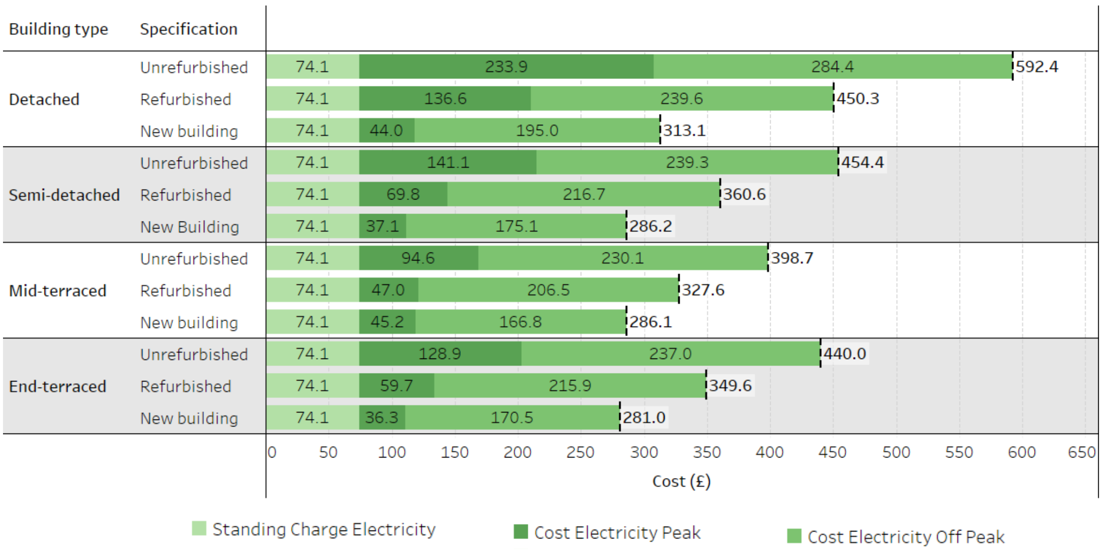

Figure 6.17 Heating energy cost for heat pump uptake scenarios by house archetypes from Comfy Heat tariff

Individual heating costs for house archetypes with different specifications are calculated to integrate with building stock modelling so cumulative heating cost results for the Orkney level could be analysed. Figure 6.18 shows cumulative heating costs for the entire island by different house archetypes for the baseline model and results for future scenarios. The total heating cost on the island is around £23.0 million and the majority of it comes from detached houses.

Electricity is responsible for 76% of the total heating cost followed by oil, coal and wood with 19%, 3% and 3% respectively. As the number of heat pumps is limited in the baseline scenario electricity is used by electric heaters which are not as efficient as heat pumps. Therefore, even though 44% of the energy demand is provided by electricity, the heating cost share peaks at 76% of the total cost.

RE scenario could help to reduce heating cost results to £8.4 million via replacing 75% of the heating technologies with heat pumps and energy efficiency improvement measures. The share of fossil fuels is reduced to 12% of the total heating cost in this scenario. However, the CE scenario offers more reduction with more ambitious heat pump uptake and energy efficiency improvement targets in line with UK's Net Zero target. Even though only 25% of the heating technologies are not replaced in the RE scenario, replacing this stock could help to reduce the heating cost to £3.7 million which is less than half of the RE scenario. The main reason for this reduction is that the CE scenario not only offers to replace fossil fuels but also an ambitious energy efficiency improvement scenario so there will be no unrefurbished houses left and the majority of the houses are in the new building category.

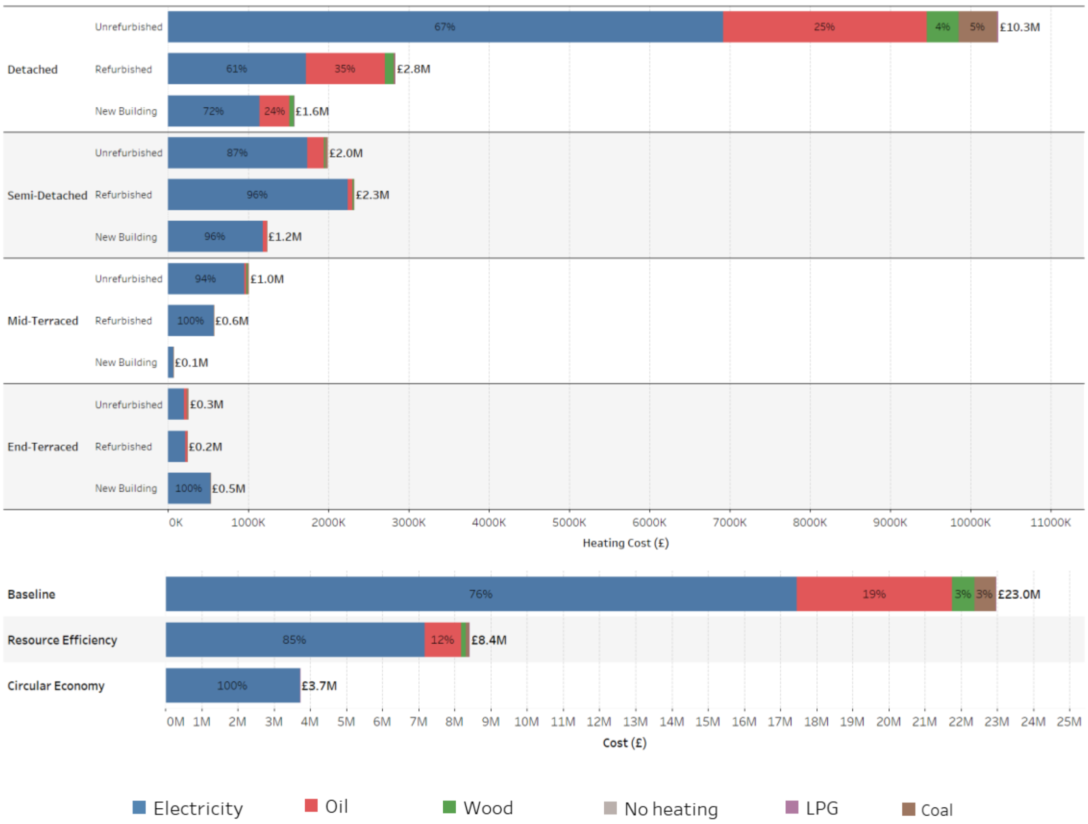

Figure 6.18 Heating energy cost of baseline model by archetypes and specifications and future scenarios

Previous figures show the heating cost of heat pumps and the cost saving of replacing existing heating technologies with heat pumps. The next part of this section focuses on the life cycle cost of heat pumps and financial alternatives. Figure 6.19 shows different financial options for a refurbished detached house; self-financed, financed, financed with Boiler Upgrade Scheme (BUS) grant, interest-free financed with Home Energy Scotland (HES) cashback and interest-free financed with HES cashback including energy efficiency improvement (EEI) costs. The results are illustrated in discounted costs of 3.5% for a 15-year period. Figure 6.19 only shows the results for a refurbished detached house for simplicity so different archetypes are investigated in Figure 6.20 and Figure 6.21.

Self-financed and financed options are not economically viable in the baseline scenario for end-users for all fuel types except electric heaters. Replacing oil boilers with heat pumps creates -£4525 and -£4164 savings for self-financed and financed scenarios respectively. Coal and wood have similar results around -£3300 and -£3400. LPG has better results than previous ones whereas still performs negative with -£2094 and -£1732 for self-financed and financed options respectively.

Grants and cashback provided by governments help to reduce upfront costs so heat pumps become an economic option for end-users. BUS grant offers a £5000 grant for homes in UK and Wales, and HES provides £7500 cashback and an interest-free loan for the remaining costs for Scottish homes. In these scenarios, the highest outcome occurs in LPG boilers with £6045 and £3091 with HES and BUS grants respectively. Coal and Wood have lower results around £4500 for HES and £1500 for BUS grant. The oil boiler has £3613 for HES and only £659 for BUS grants.

Energy efficiency improvement measures are beneficial for reducing energy demand so reducing heating costs increase savings. However, installation costs of energy efficiency measures are significant especially for unrefurbished houses (illustrated in Figure 6.11). A refurbished detached house requires £9000 for more ambitious energy efficiency improvements; therefore, EEI measures become economically viable for only LPG with £1480 in life cycle costs. The remaining fuel types, (oil, coal and wood) show negative results with -£951, -£12 and -£86 respectively.

Replacing electric heater with heat pumps always show positive results for all financial options as electricity prices are higher than fossil fuels which create higher potential fuel cost savings. The results could be as high as £24,129 with the HES grant whereas self-financing is also significantly high (£15,991) when compared with other fuel types.

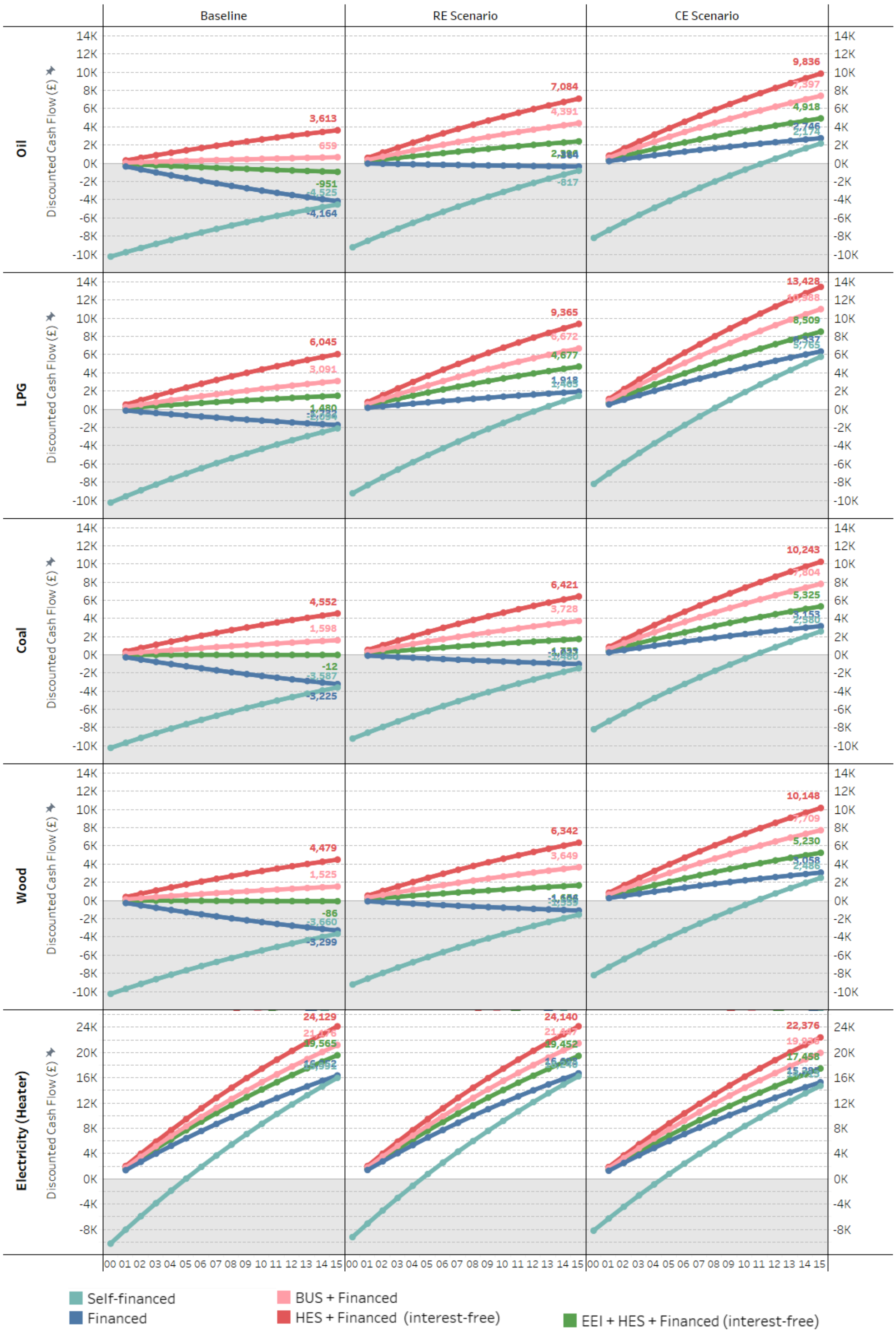

Figure 6.19 Cumulative lifetime costs of replacing heating technologies with heat pumps and different financial options for future scenarios (BUS: Boiler Upgrade Scheme Grant, HES: Home Energy Scotland Cashback, EEI: Energy Efficiency Improvement Cost)

Current electric prices are higher than remaining fuels; however, it is expected to have an increase in fossil fuel prices with carbon pricing. Electricity prices are also expected to decrease with a reduction in technology prices so future scenarios are created to investigate financing options. Future scenario results show that changes in fuel prices increase the financial benefits. HES grant savings could reach £7084 in the RE scenario and £9836 in the CE scenario for oil. Coal and wood also show similar trends to oil, but the highest benefits occur with LPG among fossil fuels. Savings from LPG could reach £13,428 in the CE scenario. Self-financed and financed options are still negative for oil, coal and wood fuel types in the RE scenario; however, they also become positive in the CE scenario. Only a reduction occurs in electric heaters because electricity prices are expected to decrease in the future. Therefore, consumers using electric heaters should replace their heating system in the baseline scenario to achieve the highest potential savings.

Figure 6.20 illustrates the breakdown of total undiscounted costs by house archetypes and different scenarios with interest-free financed option coupled with HES grant. Labels appearing above/below the bars show the discounted total savings. Only three fuel types (oil, coal and electricity for heaters) are investigated for simplicity as they are the major heating technologies in Orkney. Unrefurbished detached houses have £4097 discounted cumulative savings for oil in the baseline scenario. The main contributor to this saving is the base case potential fuel cost saving which is £18,726. HES grant also provides £7500 so total savings become positive. Project and electricity costs are around £12,000 and £8889 which changes based on house archetypes and specifications.

Total discounted savings are greater in coal and electric heaters with £5334 and £31,131 in an unrefurbished house in the baseline scenario. However, total discounted savings are expected to reduce in refurbished and new building categories mainly because of the reduction in base case potential fuel cost savings. Even though the upfront cost of heat pump installation and electricity cost reduces because of the reduction in energy demand, potential savings from base case fuel costs expects higher reductions; therefore, total discounted savings reduces. Refurbished detached houses are expected to have a 12%, 15% and 22% reduction in discounted savings for oil, coal and electricity. This reduction reaches 36%, 39% and 46% in the new building category respectively.

Other house archetypes have similar trends; however, they expect more reductions in savings based on their energy consumption. Semi-detached and end-terraced houses are expected to have a 30%, 28% and 21% reduction in oil, coal and electricity in refurbished houses. Higher reductions are expected in the new building category with 42%, 41% and 39% respectively. Mid-terraced houses show slightly lower results than other archetypes.

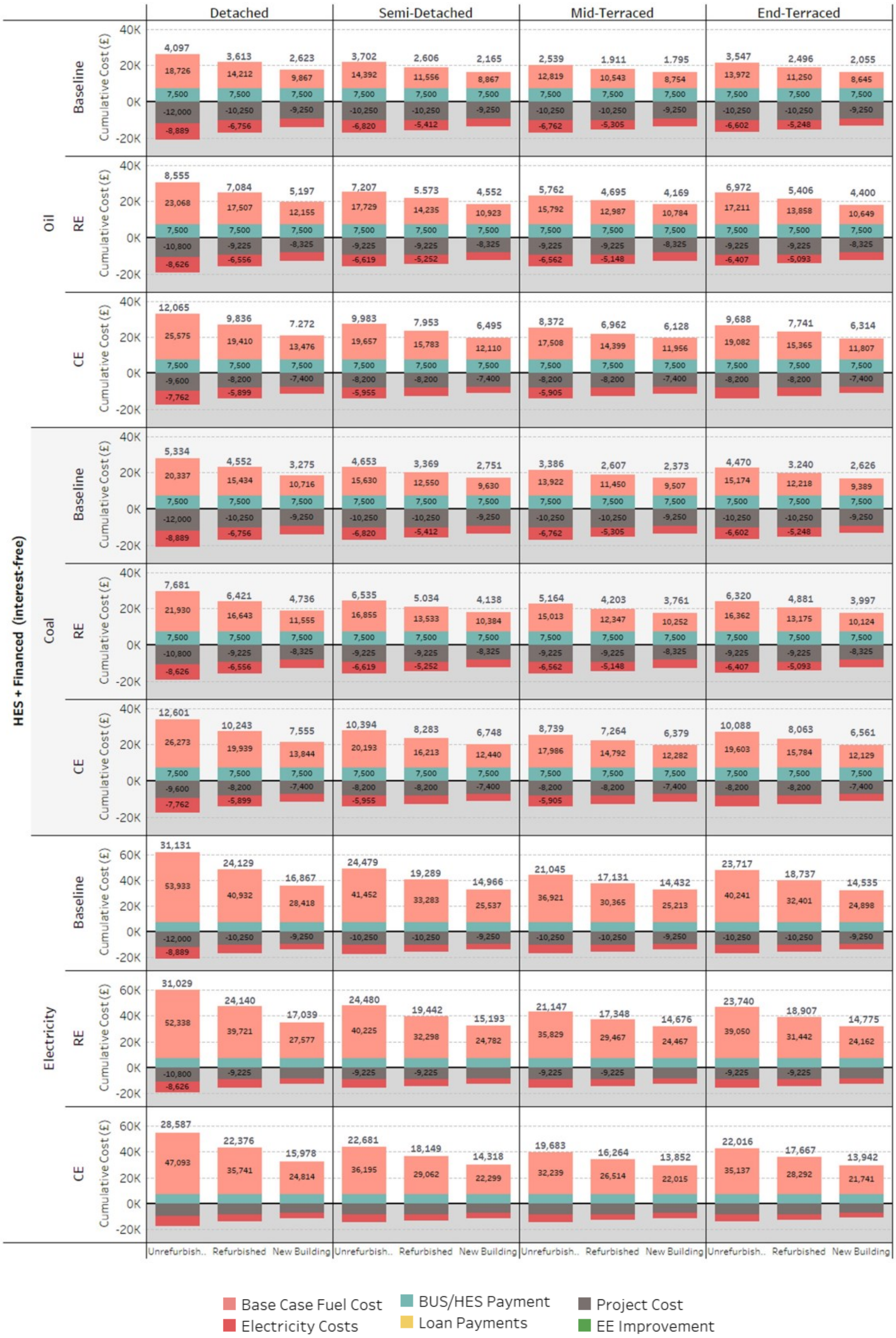

Figure 6.20 Undiscounted cost distribution of replacing heating technologies with heat pumps and future scenarios for interest-free financed option coupled with HES grant (Labels above/below the bars show total discounted savings)

Future scenario results show that total discounted savings could be doubled with the RE scenario and tripled with the CE scenario. This increase is only possible with changes in fuel prices. Electricity prices are expected to decrease in the future so potential electricity costs reduces in these scenarios. In contrast, fossil fuel prices are expected to increase so potential savings from base case fuel costs increase. Therefore, RE and CE scenarios offer higher potential benefits. However, electric heaters expect a decrease in total savings because of the increase in electricity prices so consumers using electric heaters should replace their heating type in the baseline scenario for the highest potential benefits.

Unrefurbished houses expect the highest potential savings because of their high energy demand; however, this is not the ideal option for individual houses and also for the entire island. Heat pumps perform better with low flow temperatures, and greater heat losses in unrefurbished houses have negative impacts on heat pumps' optimum operation. Previous results showed that energy efficiency improvements (EEI) could help to reduce energy demand significantly (Figure 6.12). Therefore, the impact of EEI on financial options is also investigated for house archetypes.

Figure 6.21 illustrates the breakdown of total undiscounted costs by house archetypes and different scenarios with interest-free finances coupled with HES grant and EEI costs. Unrefurbished detached houses have -£9890 cumulative savings for oil in the baseline scenario which is not a viable option financially for end users. This is mainly because of the high EEI cost which is around £22,100. Potential savings from base case fuel cost will be the same whereas electricity cost is expected to decrease with efficiency improvements. However, this reduction is not enough to cover the cost of EEI for unrefurbished houses. Refurbished houses expect less investment to increase the efficiency level of the house to the new building category. The negative discounted savings could be reduced to -£951 in refurbished houses because EEI investment is around £9000 in this category. Similar trends occur in other house archetypes and negative savings occur in nearly all of them. Only a refurbished mid-terraced house could see potential savings of £45 with coal fuel type in the baseline scenario.

Positive savings can be seen in houses using electric heaters. These savings could be as high as £19,452 in refurbished detached houses or the lowest £12,836 in unrefurbished end-terraced houses. As the electricity prices are higher than fossil fuel prices potential savings from base case fuel costs maximize in electric heaters; therefore, total discounted savings are also significantly higher than the remaining fuel types.

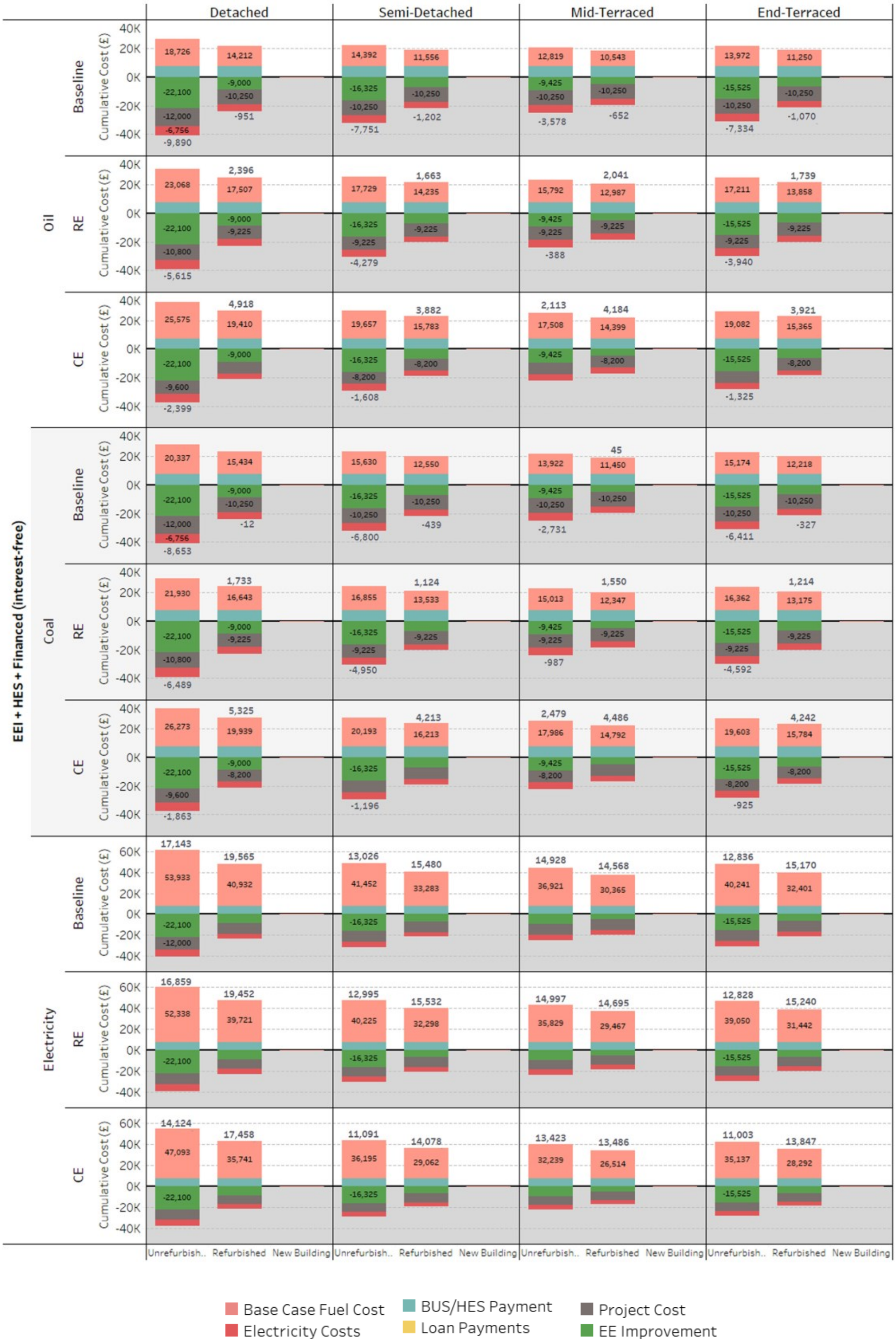

Figure 6.21 Undiscounted cost distribution of replacing heating technologies with heat pumps and future scenarios for interest-free financed coupled with HES grant and EEI costs (Labels above/below the bars show total discounted savings)

Future scenario results show that negative savings in the baseline scenario could be reduced and even become positive in some house archetypes. RE scenario could help to increase total discounted savings and make refurbished houses financially viable for consumers. The average total savings with oil in the baseline scenario is around -£970 in all houses; however, this could be increased to £1960 with the RE scenario. Similarly, negative savings in coal (average of -£183) could be increased to £1405 on average. However, these potential positive savings occur only in refurbished houses.

CE scenario offers higher potential benefits with more ambitious price changes. In this scenario, the negative savings could be reduced to -£2399, -£1608 and -£1325 in unrefurbished detached, semi-detached and end-terraced houses using oil. The savings in unrefurbished mid-terraced houses become positive in this scenario with £2113. Potential savings in coal fuel type is higher than oil; therefore, negative impacts in three unrefurbished archetypes reduce and savings in unrefurbished mid-terraced houses increases to £2479. CE scenario provides great potential benefits however, unrefurbished detached, semi-detached and end-terraced houses still perform negative savings which are not viable for consumers. More grants for high insulation costs should be introduced to make EEI measures engaging.

Electric heaters always show positive savings in all house archetypes and scenarios despite high EEI costs. These savings could be as high as £19,565 in a refurbished detached house in the baseline scenario, and the lowest savings occur in the unrefurbished end-terraced house with £12,836. However, similar to previous results, potential savings are expected to reduce in future scenarios so consumers should start the transition to heat pumps in the baseline scenario for the highest potential savings.

Total discounted cost savings and undiscounted cost distribution are calculated for individual house archetypes and specifications in previous figures. So, these results are integrated with the number of heat pump uptake in future scenarios to calculate cumulative results. Figure 6.22 shows total undiscounted savings for Orkney when heat pump uptake is followed by future scenarios and the breakdown of total undiscounted costs by fuel and payment type. Results illustrate that self-financed, financed and EEI+HES+financed scenarios result in negative savings for oil, coal and wood fuel types in the RE scenario, so these options do not offer financial benefits. However, electric heaters offer significant savings which are around £60 million on average in these options. Therefore, total savings in these categories reach £59.6 million, £63.4 million and £46.7 million respectively. The highest savings occur in HES+financed (interest-free) scenario with £24.6 million in oil, £2.7 million in coal, £2.9 million in wood and £91.1 in electric heaters. The savings in electric heaters are far more than the remaining fuel types because of high potential savings from base case fuel costs.

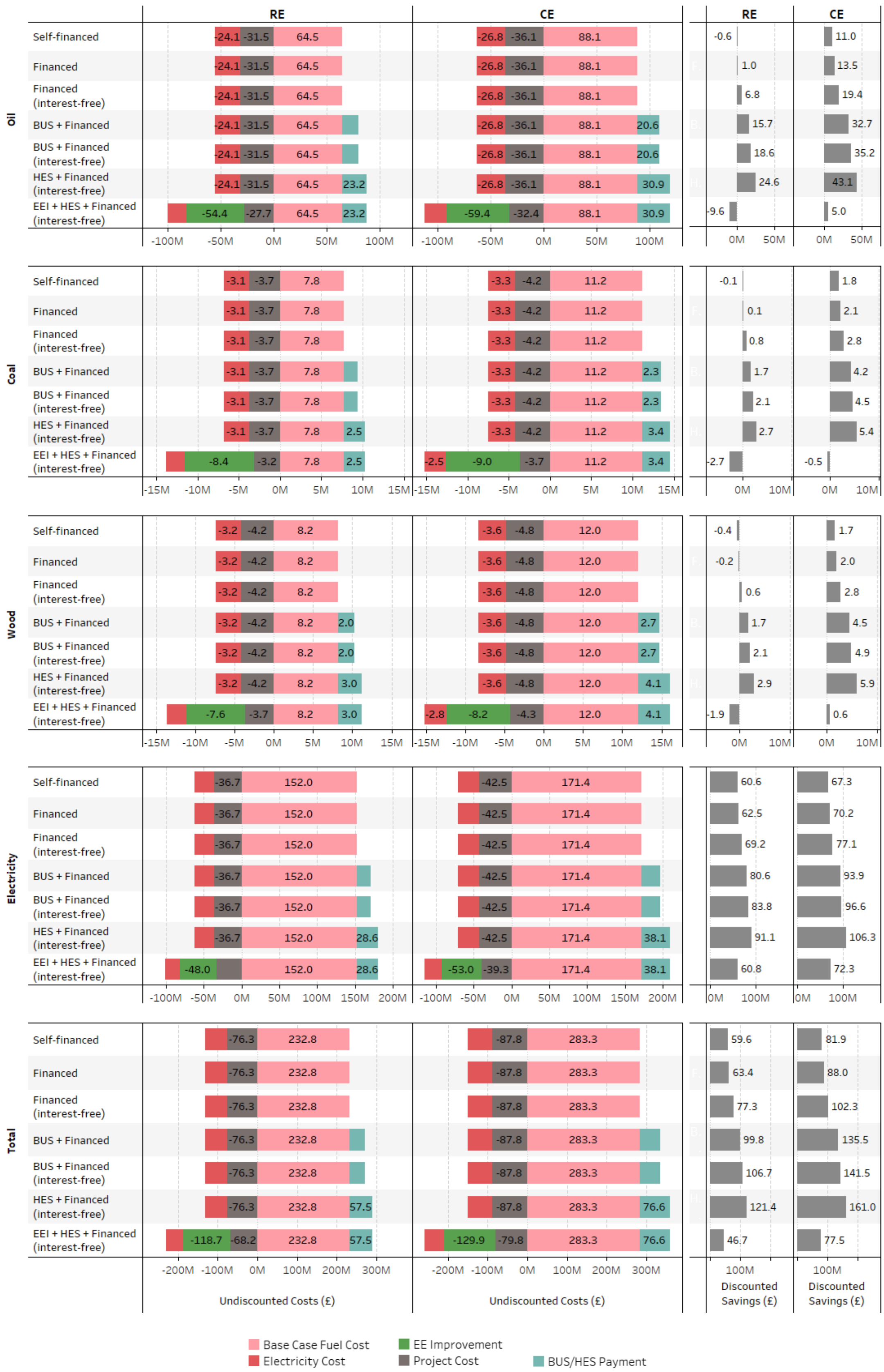

Figure 6.22 Cumulative undiscounted cost distribution of replacing heating technologies with heat pumps in Orkney for different financial alternatives and future scenarios by fuel types

CE scenario results show that all financial options offer potential positive savings. The highest savings occur in HES+Financed (interest-free) scenario with £161.0 million followed by BUS+Financed (interest-free) and BUS+Financed scenarios with £141.5 million and £135.5 million. The lowest savings occur in the self-financed with £81.9 million and EEI+HES+Financed (interest-free) scenario with £77.5 million. CE scenario helps to increase savings from EEI measures and become more viable than the self-financed scenario. Total EEI measure cost is £118.7 million in the RE scenario and £129.9 million in the CE scenario. This investment in EEI measures helps to reduce the total project cost from £87.8 million to £79.8 million with smaller size heat pumps in the CE scenario. As the energy demand is reduced, electricity cost is also reduced from £62.3 million to £49.0 million.

Even though the EEI scenario does not provide positive savings in the baseline scenario in all archetypes, future scenarios could help to create savings for refurbished archetypes as stated in the previous figure (Figure 6.21). However, unrefurbished houses require more support to make EEI measures financially viable. The total EEI measures require an investment of around £130 million in the CE scenario. £21.3 million savings could be achieved as a result of EEI (£8.0 million reduction from upfront project cost and £13.3 million reduction from electricity costs); however, £108.5 million support is still required to achieve the same total savings with HES+Financed (interest-free) scenario. Therefore, more grants are needed. The number of unrefurbished and refurbished houses eligible for EEI coupled with heat pump uptake is around 5300 and 3150 respectively. Hence, £14,000 support for unrefurbished houses and £7500 for refurbished ones could provide the required financial support to the consumers.

6.3.4. Hourly Electricity Load Results

Figure 6.23 illustrates hourly electricity loads for a refurbished detached house for the coldest winter workday and holiday by different tariffs. Base load and variable HP load show the optimized heat pump operation in the energy modelling section. The light red line shows base load and constant heat pump operation which spread the total variable heat pump load throughout the day. Constant heat pump load is presented only to give a reference, so it looks more flattened than variable load; however, variable load offers optimum performance and cost results.

The heat pump works at maximum capacity in Standard tariff as there are no peak and off-peak time periods. However, E7 and Comfy Heat tariff has 7 and 8 hours of off-peak time but with different spreads around the day. E7 tariff has maximum loads during the night to charge the buffer tank and works on minimum capacity during the day when it is needed. The maximum load is seen as 3.22 kW during the workday and 3.49 during the holiday. Comfy Heat tariff has a higher maximum load as off-peak hours are spread more evenly throughout the day. E12 and E20 tariffs have much more off-peak hours; therefore, more maximum capacity loads exist. Some of these loads occur around noon and evening when the base load is also peaking. Therefore, Comfy Heat and E7 tariffs are selected to investigate load results by house archetypes and specifications.

Figure 6.24 and Figure 6.25 shows load profiles of house archetypes and specifications for Comfy Heat and E12 tariffs for the coldest winter workday and holiday. Maximum peak loads occur as 4.05 kW in the Comfy Heat tariff, and 3.94 kW in the E12 tariff for all archetypes in the coldest winter workday (Figure 6.24). Detached houses have the highest energy demand, therefore, the total variable load occur as 27.7 kW and 28.8 kW in comfy Heat and E12 tariffs in the unrefurbished category. Semi-detached and end-terraced houses have similar total loads around 19.0 kW in Comfy Heat tariff and 21.0 kW in E12 tariffs. Mid-terraced houses have the lowest total load with 16.8 kW and 18.3 kW in Comfy Heat and E12 tariffs respectively. When houses become more energy efficient their energy demand reduces so fewer loads are seen in efficient houses. Total heat pump loads in detached houses could be reduced to 20.4 kW in a refurbished house or 13.7 kW with a Comfy Heat tariff in a new building category. Moreover, fewer peaks occur throughout the day. A similar trend occurs in other house archetypes and total heat pump loads could be reduced to 12.7 kW, 11.3 kW and 12.7 kW for semi-detached, mid-terraced and end-terraced new building categories. The coldest winter holiday results also show similar trends but slightly lower load profile results (Figure 6.25).

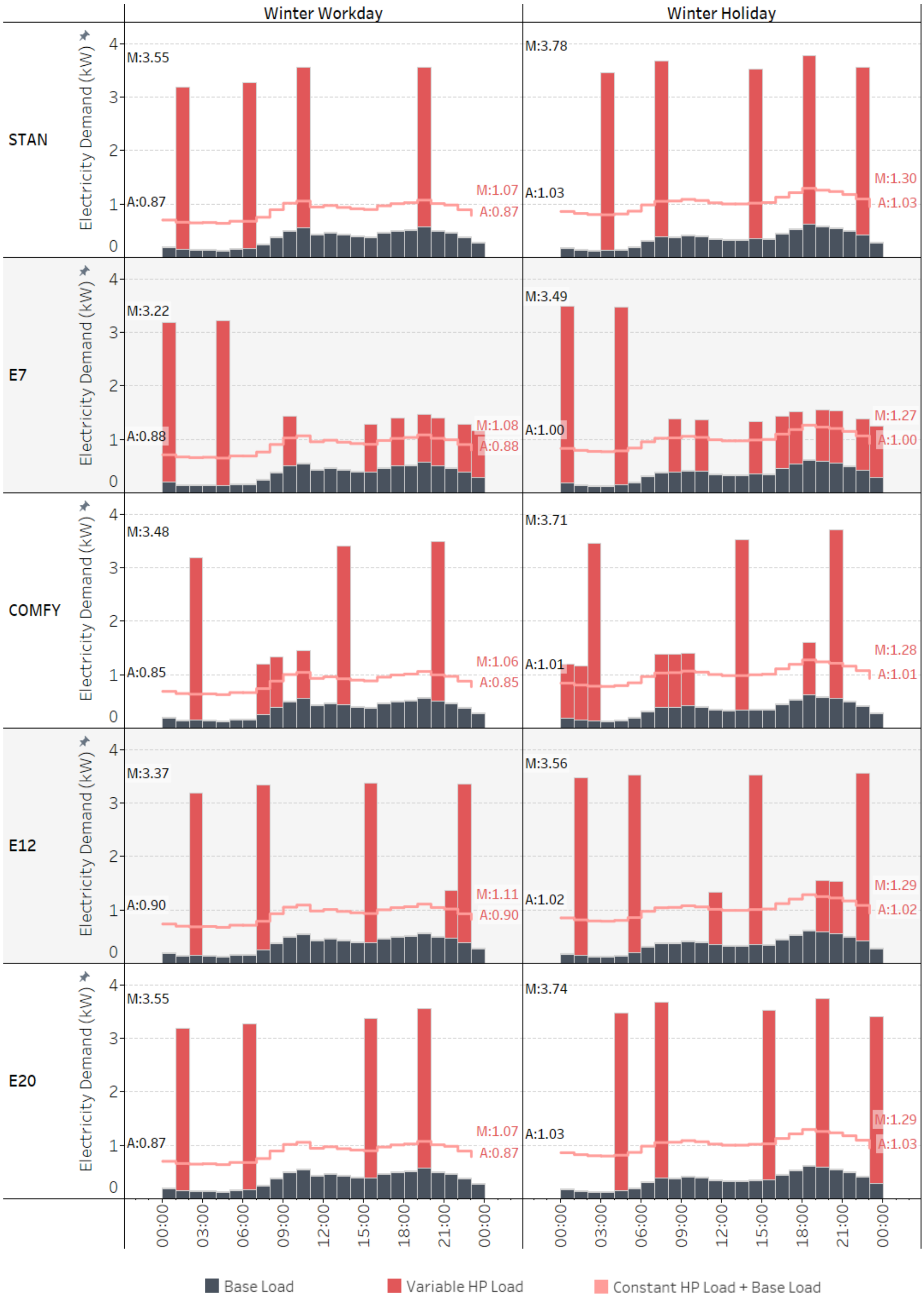

Figure 6.23 Average hourly electricity demand load curve of a representative heat pump profile for a refurbished detached house by different electricity tariffs for the coldest winter workday and holiday (M: Maximum, A: Average)

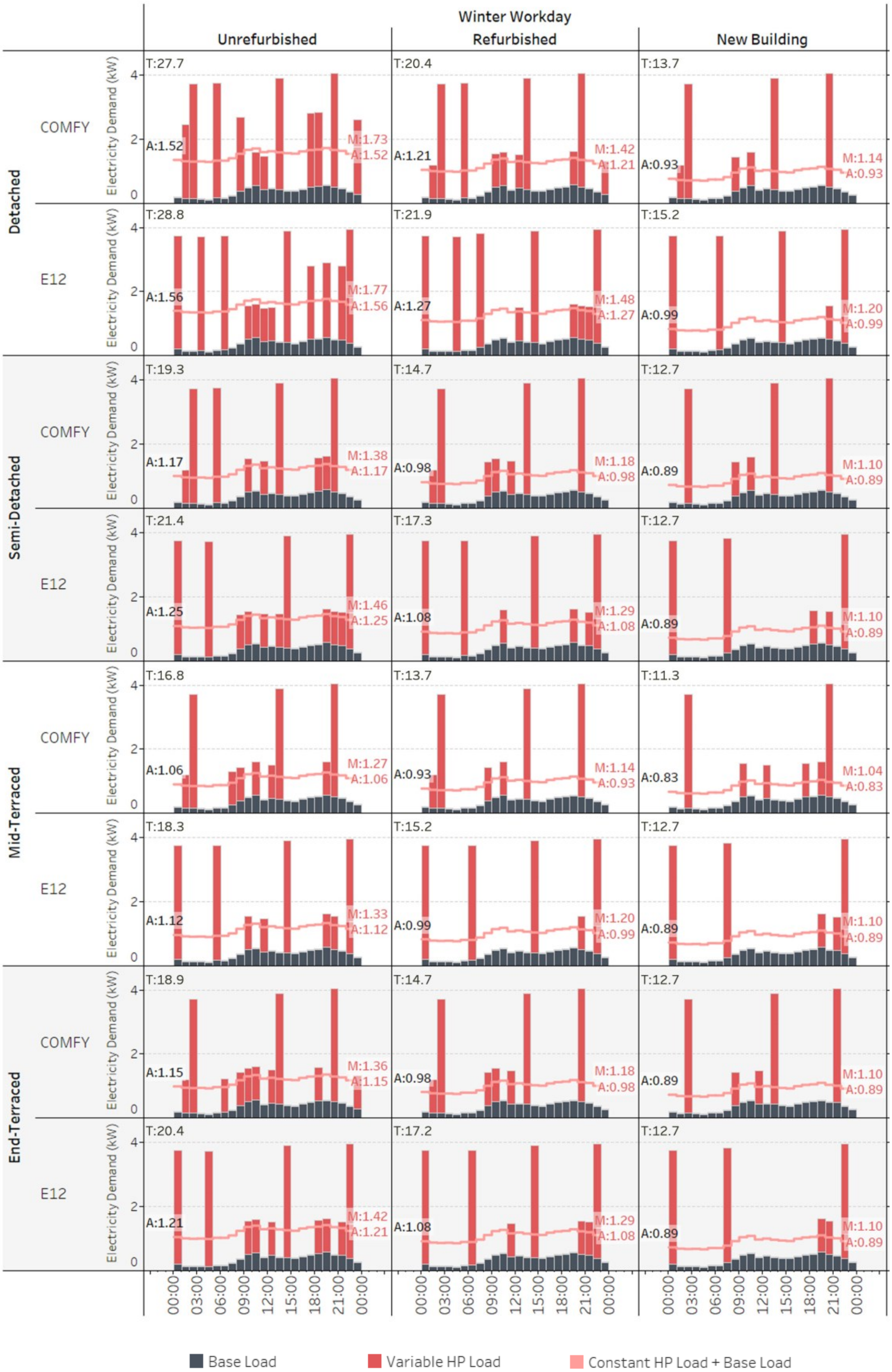

Figure 6.24 Average hourly electricity demand load curve of a representative heat pump profile by different archetypes and electricity tariffs for the coldest winter workday (T: Total, M: Maximum, A: Average)

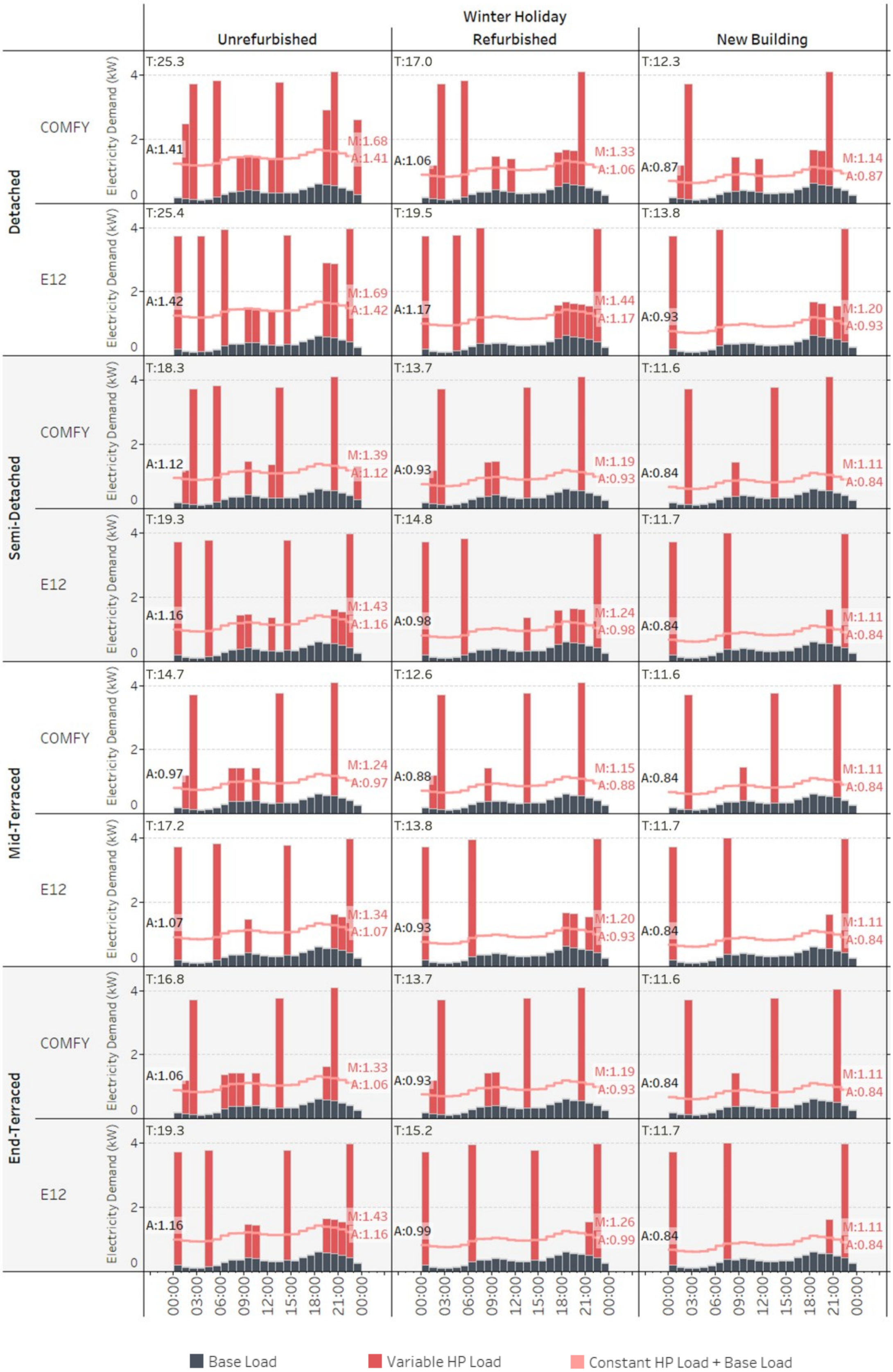

Figure 6.25 Average hourly electricity demand load curve of a representative heat pump profile by different archetypes and electricity tariffs for the coldest winter holiday (T: Total, M: Maximum, A: Average)

This study tries to break down the load results into different house archetypes and specifications so cumulative electricity system load profiles would be more accurate. Each archetype profile is multiplied by the number of houses using heat pumps for all scenarios. Figure 6.26 shows Orkney electricity system load for baseline, RE and CE scenarios for the coldest winter workday and holiday. The results are presented for Comfy Heat and E12 tariffs separately and also their equally mixed usage scenario. Existing electric loads coming from room heaters are also presented in the figures with yellow bars. The baseline scenario has a limited number of heat pumps deployed; therefore, the daily total variable heat pump load is around 14.4 MW and 15.4 MW for Comfy Heat and E12 tariffs with 27.9 MW and 26.3 MW peak loads in the coldest winter workday.

RE scenario has high deployment rates of heat pumps (around 80% of total dwellings) so daily total variable heat pump loads reach 168.1 MW and 181.9 MW in Comfy Heat and E12 tariffs with 59.9 MW and 54.7 MW peak loads respectively. Combining both tariffs reduces the peak load to 46.0 MW. When the CE scenario has, even more, total daily variable heat pump loads with 186.2 MW in Comfy Heat tariff, and 202.2 MW in E12 tariff the peak loads reach 67.7 MW and 62.9 MW in the tariffs respectively. Comfy Heat tariff has a smaller number of peaks but E12 tariffs have more spread around the day, so the mixed deployment of tariffs helps to reduce peaks to 51.2 MW. When variable heat pump load is compared with constant heat pump load (light red line) majority of the variable loads stay below constant load, and heat pumps do not operate in the evening which is the highest baseload occurs. Peaks are happening in three periods: during the night, before evening and before midnight with two peaks in each. When the coldest holiday results are analysed, these peaks are even less in the CE scenario with a mixed tariff setting. Only the peak happening before midnight needs to be handled.

Different tariffs create load peaks in different time periods which could be beneficial to combine electricity tariffs to have a more evenly electricity load spread throughout the day. Energy efficiency measures help to reduce the total daily variable heat pump load which is very important to decrease energy demand; however, peak loads remain the same. Therefore, combining more than one electricity tariff in the market could help to reduce peak loads.

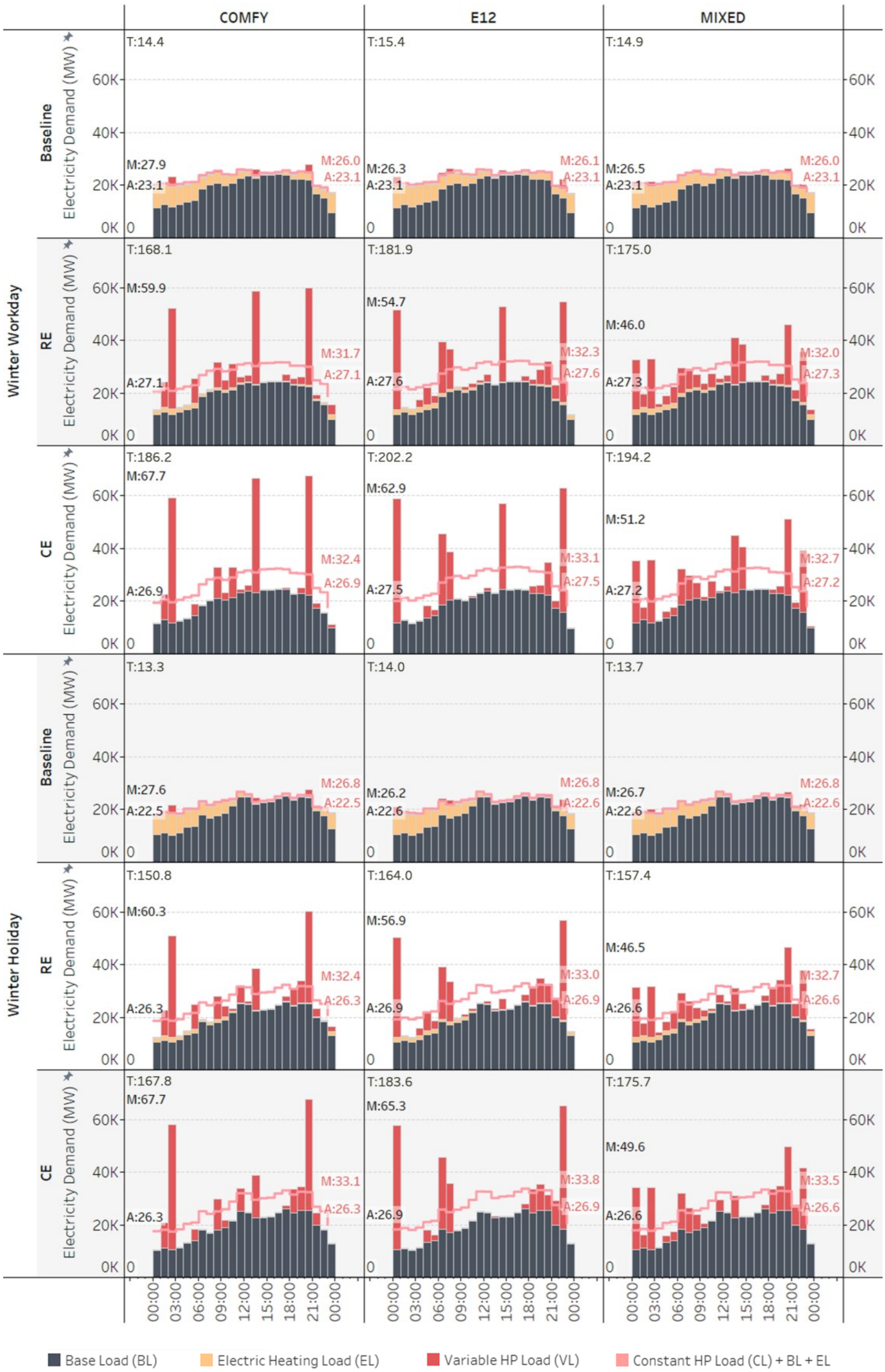

Figure 6.26 Average hourly electricity demand load curve of heat pump scenarios for Orkney for the coldest winter workday and holiday (T: Total, M: Maximum, A: Average)

6.4. Data Quality and Limitations

Integrated methodology analysed energy, environmental and financial savings for Orkney by combining life cycle assessment with energy systems modelling. Total heating related emissions are calculated as 26,681 tCO_2e which accounts for 71% of total domestic emissions (37,437 tCO_2e) calculated by National Statistics (BEIS, 2022b). According to Tyndall Carbon Budget Reports (Tyndall Manchester, 2022), an average annual mitigation rate of -12.8% is required to stay within recommended carbon budget for Orkney. The integrated approach results expect an average yearly mitigation rate of -11.25% which is very close to the Tyndall Manchester results.

The analysis has been thoroughly done but several limitations are stated as followed:

- Environmental impact results show the individual impacts of heat pumps by different archetypes and cumulative impacts for Orkney. However, in order to calculate savings for replacing the existing systems, only use-phase-related CO_2e emissions are compared. Life cycle assessment methodology requires a thorough analysis for all phases and conducting an LCA for existing heating technologies (oil, coal, wood, LPG boiler and electric heater) requires significant time and data. Therefore, this step is not taken for the simplicity of the model. Moreover, LCA results for heat pumps and gas boilers in the UK provided the required framework for the integrated approach so this step is not taken for simplicity.
- Replacing existing heating technologies with low-temperature heat pumps requires upgrading the heat distribution system which could be increasing the size of radiators or installing underfloor heating systems. Environmental impacts of underfloor heating systems are calculated in the LCA chapter to investigate the overall impact. However, financial analysis in the integrated approach only considered minor upgrades such as increasing the size of several radiators to avoid high installation costs. These costs are included in the project cost of heat pumps but underfloor heating system costs could be analysed for further studies as an alternative form of a heat distribution system.

6.5. Conclusions

This chapter focused on the integrated approach of energy system modelling and life cycle assessment supported by economic and building stock modelling to investigate potential individual savings by different households and cumulative savings for Orkney. Firstly, EPC data has been used to analyse the housing stock in terms of the conditions of construction elements (wall, window, roof, floor) by different house archetypes. The requirement of energy efficiency improvement for these archetypes has been decided. Existing heating technologies and fuel types have been investigated to analyse the current situation in Orkney. Then, potential energy, environmental and economic savings under heat pump uptake scenarios are calculated based on the building stock modelling and existing heating types. Financing options for heat pump uptake scenarios are also investigated for consumer engagement.

Integrating energy modelling, life cycle assessment and financial modelling help us to understand various aspects of heat pump uptake scenarios. Energy savings results emphasize that energy efficiency improvements could help to reduce energy demand by 16% in the Circular Economy (CE) scenario even though the housing stock is increased by 19% by 2050. The uptake of heat pumps could reduce the energy supply by 82% when coupled with ambitious energy efficiency improvements in the CE scenario.

Orkney uses electricity from 100% renewable sources; therefore, environmental results show significant reductions in most of the impact categories when compared with UK results in Chapter 4.5. The negative environmental impacts of electricity from nuclear, fossil fuels and biomass are reduced in Orkney with 100% renewable electricity.

The main heating types in Orkney are electric heaters and oil boilers, so heat pumps uptake could help to reduce use-phase-related CO_2e emissions by 98% in the CE scenario (from 26,681 tCO2e to 659 tCO2e), but this requires strong commitments in terms of energy efficiency improvements and heat pump deployment. Even though the electricity mix is 100% renewable, CO_2e emissions coming from the production of materials used for electricity supply technologies make it difficult to reach the Net Zero target. CE principles could help to reduce the impact of the manufacturing phase with greener production lines and eco-design principles.

Heat pumps perform better than other heating technologies in terms of heating costs with optimised operation. Total cumulative heating costs paid by end-users in Orkney could be reduced by 84% in the CE scenario (from £23.0 million to £3.7 million). This could be achieved by 100% uptake of heat pumps coupled with more efficient houses and changes in energy prices. Increased levies on fossil fuels and reduced levies on electricity could make the electricity market more competitive to accelerate the transition.

Financial analysis results show that self-financing or financing options without any support are not a desirable path for fossil fuel consumers in the baseline scenario. High installation costs of heat pumps still stand as a barrier. The highest benefits are achieved with Boiler Upgrade Scheme (BUS) grant and Home Energy Scotland (HES) loan and cashback scheme with £659 and £3613 for consumers using oil boilers respectively.

Total discounted savings in the baseline model could be tripled with the CE scenario with the help of reductions in electricity prices and increases in fossil prices with a carbon tax in the future. Moreover, self-financing and financing without support options also create positive savings for all fuel types in the CE scenario due to more efficient houses with lower electricity prices.

Energy efficiency improvements (EEI) maximize fuel savings whereas high upfront cost is significantly high, especially in unrefurbished houses. Energy modelling results show that the heating demand of an unrefurbished house could be reduced by 40% if the house is insulated, so the new building category is the best option for the optimum heat pump operation. The CE scenario could help to avoid negative savings occurring from energy efficiency improvement measures and creates a financially viable solution for end-users. Therefore, the CE scenario offers significant potential benefits.

EEI measures are consequential for the optimum performance of heat pumps; however, it requires a £130 million investment for the entire island. Therefore, these measures also require support to become more engaging to consumers. This support could be around up to £14,000 grant for unrefurbished houses (around 5300 houses in total) and up to £7500 grant for refurbished ones (Around 3150 houses in total). These grants could also be flexible for different archetypes based on their initial project cost, and these figures could provide around £108.5 million to support the entire island. The remaining savings (£21.3 million) could be achieved by reductions in electricity costs and project costs with the help of EEI measures. New grants and incentives could also be introduced such as vouchers similar to BUS/HES grants for some part of the total cost, interest-free loans for the remaining part of the cost and removing VAT on equipment and labour costs.

Electricity load results emphasize that detached houses have the highest peaks due to their higher energy consumption, but the new building category has the lowest load results. Therefore, energy efficiency improvements could help to reduce peak loads. At the Orkney level, a combination of Comfy Heat and E12 tariffs provide a more evenly spread of hourly load profiles. The maximum peak load is 26.5 MW in the baseline scenario whereas it reaches 51.2 MW in the CE scenario. When the increase in the heat pump capacity is considered (1203% increase in total daily system loads from 14.9 MW in the baseline to 194.2 MW in CE) 93% increase in maximum peak loads is seen. In order to achieve this, a competitive electricity market with a high number of off-peak hours like the E12 tariff or more equally spread off-peak hours throughout the day like the Comfy Heat tariff is required.

Orkney is facing a high level of fuel poverty due to lower average income and higher energy prices than the mainland. Moreover, the housing stock is older than the national average. Accelerating the heat pump uptake could help to reduce the negative impacts of volatility in oil prices and energy security problems with the help of a high level of renewable electricity generation. However, high installation costs of heat pumps and energy efficiency improvements require financial support such as grants, incentives and interest-free loans. The highest potential savings at the individual household level and island level could be achieved with these subsidies.

Chapter 6 has focused on the integration of life cycle assessment and energy systems modelling to create a comprehensive methodology to able to calculate energy, environmental and economic results of heat pump uptake scenarios. The life cycle assessment methodology has provided a comparison of the environmental impacts of an air source heat pump in Orkney. On the other hand, the energy systems modelling methodology provided a thorough analysis of the use phase of heat pumps which has the highest environmental impacts. The building stock modelling analysed the housing stock condition of Orkney for the baseline year and the year 2050. The economic model analysed the life cycle cost analysis of an air source heat pump and provided financial solutions for different house archetypes. Existing financial support options are evaluated and more solutions are offered based on successful actions from other countries. Hourly electricity load results investigated the peak loads under the baseline scenario and provided a reduction in the Orkney electricity system. The integrated approach provided flexibility to work on scenario analysis to assess both the demand and supply side of the system with life-cycle-wide thinking. This comprehensive manner is novel and fundamental to creating a holistic approach to reducing the CO_2e emissions to reach the Net Zero targets while observing other negative consequences and implications, so all aspects of energy, environmental and financial benefits could finally be achieved. Focusing on the island level, specifically in Orkney, could help to provide sustainable solutions to the economic pressure the islands are facing and to the high level of fuel poverty.

Chapter 7

Conclusions

7.1. Overview of Main Findings

This thesis has investigated the impacts of large-scale heat pump uptake with Circular Economy principles to support the UK's 2050 Net Zero target. Individual methodologies of life cycle assessment (LCA) and energy systems modelling (ESM) have been used for a proposed integrated comprehensive approach with a building stock model (BSM) to assess the suitability of heat pumps and replacing other heating technologies in terms of energy, environmental and financial benefits.

Chapter 4 evaluated the environmental impacts of heat pumps and gas boilers to decarbonise heating in the residential sector in the UK, and scenario analysis is conducted to see the impacts of the future electricity mix, energy efficiency improvements (EEI), higher recycling rates and better-performing heat pump with higher COP values in line with the government targets.

- Gas boiler performs better than heat pumps in all categories except the climate change category. Reducing CO_2e emissions in line with the Net Zero target is the priority; however, higher negative impacts in other categories are expected. A transition period which motivates hybrid applications of heat pumps and gas boilers could be suggested for smooth development.
- When environmental impacts for Orkney are compared with UK results, the findings show that increasing renewable share in the electricity mix could help to reduce negative impacts in most of the categories; however, high deployment rates of

offshore wind farms also create toxicity and metal depletion problems. These negative consequences should be considered before high wind energy uptake to be able to overcome this issue.

- Future scenarios show that decision-making has a significant impact on environmental results; therefore, developing CE standards for heat pump manufacturing (through procurement, circular material banks, use of secondary materials, eco-design etc.) is crucial to reach the Net Zero target.

Chapter 5 focused on the optimisation of heat pump operation with demand side management by aiming to reduce energy demand and heating costs in Orkney. Different electricity tariffs, buffer tank sizes, backup heater operation and heat pump sizes are investigated with scenario analysis to achieve optimum results. Orkney is selected as a case study, so specifications of house archetypes are used for this island. The optimisation is done for a refurbished detached house for simplicity, but other archetype results are analysed in the integrated chapter (Chapter 6).

- High-performing heat pumps with optimised operation do not require a gas boiler as a backup heater, and sufficiently provide the required energy demand with lower heating costs. Standing charges of gas boilers are avoided in standalone operation so consumers can use the system with the same heating cost conditions.
- Buffer tanks could help to reduce energy consumption and heating costs in hybrid applications, whereas slight decreases occur in standalone heat pumps. The optimised operation of heat pumps could compensate for high electricity prices with high COP values; therefore, standalone heat pumps outperform hybrid applications.
- Optimised heat pump operation could help to reduce energy consumption by 68% when compared with baseline heat pump operation and 81% when compared with standalone gas boiler operation. Heating cost savings could be 36% and 33% for the baseline scenario and gas boiler operation respectively.
- Comfy Heat and E12 tariffs are the optimum tariffs in terms of lower heating costs and energy consumption. Even though the E20 tariff has the highest number of off-peak hours high electricity prices make this tariff more costly.

Chapter 6 proposed an integrated approach of LCA and ESM to be able to calculate the impacts and savings of heat pump uptake scenarios in Orkney as a case study. Building stock modelling (BSM) of Orkney has been modelled to calculate cumulative savings at the island level. LCA results provided the environmental impacts of a heat pump and gas boiler, and the phases responsible for these impacts. Scenario analysis helped to monitor these impact categories under projected government targets. As the use phase is the dominant part of the life cycle of a heat pump energy system modelling results tried to reduce energy demand and heating cost by optimising heat pump operation. The life cycle cost analysis of an air source heat pump aims to introduce the financial aspects of these heating technologies and energy efficiency improvement (EEI) measures. Moreover, hourly electricity load calculations aim to identify and reduce maximum peak loads in the baseline model and future scenarios by the heat pump diffusion (HPD) model. The results are illustrated at both the house archetype level for end-users to provide individual savings and the island level to emphasize cumulative savings.

- Integrated approach results emphasize that heat pumps could provide significant benefits in terms of energy reductions with higher efficiencies. The heat pump uptake scenarios could help to reduce energy supply by 82% with ambitious energy efficiency improvements in the CE scenario despite a 19% increase in the number of houses by 2050.
- It is possible to reduce the Climate Change impact category associated with fossil fuels with heat pump deployment scenarios; however, they do not provide sustainable solutions for other impact categories. Hybrid operation of the heat pump with a gas boiler could reduce the negative impacts whereas this creates a significant barrier to UK's Net Zero targets. Moreover, standalone heat pumps perform better than hybrid ones with optimised operation in terms of both energy and heating costs. The upfront cost will also be higher in hybrid applications.
- The use-phase-related CO_2e emissions could be reduced by 98% in the CE scenario with EEI measures taken and 100% heat pump uptake. The life cycle-wide approach includes the emissions coming from the production of energy supply technologies (manufacturing wind turbines, etc.) so reaching the Net Zero target requires strong commitments in all industries covering manufacturing of the products, energy production and consumption.
- The differences between LCA results in the UK and Orkney show that a more renewable electricity mix reduces the negative impacts in the use phase whereas increases the importance of the manufacturing phase. It is not possible to reach the Net Zero target by decarbonising only electricity.
- Environmental impact results show the harmful effects on the environment; however, it is also important to keep in mind that some of these impacts occur in other countries. The current territorial emission methodology does not count emissions that occurred in other countries because of different manufacturing locations. This methodology has created a shift of production lines from developed countries to developing ones. Therefore, the life cycle-wide approach to the system is crucial and consumption-based emissions should be used while calculating CO_2e emissions of countries to achieve more accurate results and targets.
- Total heating costs paid by consumers in Orkney could be reduced by 84% from £23.0 million to £3.7 million in the CE scenario. However, it requires 100% heat pump uptake and implementation of EEI measures. Energy modelling results emphasize that the heating demand of an insulated house could be 40% lower than an uninsulated one

so improving energy efficiency is crucial to reducing energy intensity. However, it requires a £130 million investment for the entire island to insulate unrefurbished housing stock. 15% of the housing stock in 2050 will be built after the baseline scenario, so energy efficiency improvements in existing dwellings are crucial to reach desired energy demand reductions.

- Self-financing and financing without any support options do not create any benefit for end-users in the baseline scenario. The highest benefit can be seen with Boiler Upgrade Scheme (BUS) and Home Energy Scotland (HES) loan and cashback. If energy efficiency improvement measures are taken these grants also cannot sufficiently support consumers. New grants and incentives such as vouchers similar to BUS/HES grants, interest-free loans, and reductions in VAT on equipment and labour costs should be introduced to cover the cost of energy efficiency improvement measures.
- Increased levies on fossil fuels and reduced levies on electricity could make the electricity market more competitive against fossil fuels. All financing options including self-financing and financing without support could create positive discounted savings in the CE scenario with the help of changes in energy prices.
- Orkney is facing economic pressure similar to small islands all around the world due to high imports of oil used for heat; however, renewable energy potential and increasing deployment numbers of heat pumps create an opportunity to decarbonise heating in Orkney. Moreover, the high level of fuel poverty numbers indicates that actions need to be taken in the domestic sector. A competitive electricity market with government support to install heat pumps and energy efficiency improvement measures could provide the required acceleration to both decarbonise the heating system and overcome fuel poverty.
- Comfy Heat and Economy 12 tariffs have the maximum benefit in terms of energy reduction, heating costs and hourly electricity load results. A competitive electricity market with a high number of off-peak hours similar to the Economy 12 tariff and a more equally spread of these off-peak hours throughout the day similar to the Comfy Heat tariff is required. This could reduce the maximum electricity peak loads during the day with cheaper electricity prices.
- CE scenario results show benefits in all energy, environmental and financial results; therefore, developing CE standards for the production of heat pumps including the use of secondary materials, circular material banks, eco-design and re-usability of all components is crucial. Developing a stock and flows for materials could help to improve material efficiencies and reliance on raw materials.
- Different heating technologies require similar material demands and waste streams despite technological differences. The boiler industry holds the second largest UK heat pump market after air conditioning manufacturers, so reshaping these production lines could benefit the market knowledge used by the companies. Moreover, a market

introduction program should be provided before shifting from one technology to another so greener production lines through adapting CE principles could help to reduce the negative impacts on the manufacturing phase.

Consumer engagement is an important step for the uptake of heat pumps. Current heat pump deployment figures are very low when compared with 2030 targets. The majority of the consumers find installation and running costs of heat pumps high. Therefore, strong policies for high technology development and heat pump uptake should be supported with high consumer engagement to accelerate the deployment. A holistic approach through a circular framework for decision-making tools by not only focusing on recycling and repurposing concepts but also closing the loop approach could be created for sustainable practice.

Heat pumps are promising technologies offering a reduction in demand through high energy efficiencies and creating a less energy-intensive built environment. Moreover, carbon reductions through renewable electricity mix help to achieve environmental targets. This study illustrates energy reduction results through heat pump uptake and efficient houses and provides financial saving options for different fuel types. Environmental impacts of heat pump uptake scenarios are also investigated. This system-thinking approach can influence the national housing policy by emphasizing the importance of energy efficiency improvements and potential savings achieved by less electricity consumption and installation costs. Government grants are crucial to achieving these targets, and one-third of these investments could be saved directly with more efficient housing stock. However, more grants and incentives are necessary to accelerate the transition and include renovation costs. The government's carbon reduction target, achieving net zero emissions, is quite ambitious; therefore, the only way to achieve this target requires bold actions.

7.2. Contribution to Knowledge

This research aims to undertake a novel contribution to system thinking, by combining energy systems modelling, life cycle assessment and building stock modelling to take a holistic understanding of heat pump uptake in the domestic sector. Scenario analysis aims to create pathways with circular economy (CE) strategies in line with government targets for 2050. Such practices could help to achieve the UK's Net Zero target and a considerable number of Sustainable Development Goals (SDGs) targets because of their similar contexts. Thus, the connection between environmental studies, energy modelling and financial perspective could provide a comprehensive approach by combining technological advances and a better design approach to assess environmental impacts. Sustainable design and CE approach in construction chain and energy technologies adapted to the built environment could be a driver for the UK.

This research contributes to the understanding of the transition to the high penetration of low carbon technologies (in this case heat pumps) in the built environment, by analysing the environmental impacts of technologies' material extraction, manufacturing and disposal phases together with energy demand in buildings. It takes a combined approach of life cycle assessment (LCA) of selected low carbon technologies, energy system modelling (ESM) of heat pump operation by house archetypes in the domestic sector, building stock modelling (BSM) to calculate cumulative savings, life cycle cost (LCC) analysis to assess investment costs and financial options, and heat pump diffusion (HPD) model to quantify electric loads of heat pump uptake scenario. The novelty of this study consists of two aspects, firstly the integrated modelling approach (LCA+ESM+BSM+LCC+HPD) with Circular Economy (CE) principles (through reuse and recycle options assessed for 2050 with scenario analysis) and secondly temporal assessment.

Life cycle assessment methodology evaluates the environmental impacts of heat pumps compared with gas boilers. Previous studies investigated this comparison in different locations including the UK; however, each study is unique due to the different goal and scope of the study, functional unit and system boundary. Moreover, the major contributor stage to the impact categories is the use phase in the previous studies, and the impact of high renewable penetration in the UK electricity mix has not been investigated during the last decade. Therefore, investigating the impacts of individual heating technologies (air source heat pump, ground source heat pump and gas boiler) on the current electricity mix is novel. The results are illustrated for the baseline model and scenario analysis is conducted to assess the possible hybrid applications of heat pumps and gas boiler with an alternative manufacturing location scenario. On the other hand, the impacts of these technologies are investigated for the year 2050 in line with the government targets.

Energy system modelling provides insight into the major contributor stage (use phase) of the life cycle assessment model to reduce energy consumption by optimising heat pump operation. A previously developed energy model has been developed further with higher temporal resolution and more details are included in terms of house archetypes (detached, semi-detached, mid-terraced, end-terraced), building specifications (unrefurbished, refurbished, new building), thermal energy storage tank sizes (250L, 500L, 750L, 1000L), flow temperatures (35 °C, 45 °C, 55 °C) and electricity tariffs (Standard, E7, Comfy, E12, E20). Hourly heat pump capacity and COP curves are calculated by the model based on outside temperature and flow temperature. The aim of the model is to reduce energy consumption and heating cost by regulating off-peak and peak time usage depending on electricity prices and with the help of thermal energy storage. The novel element of this model is to be able to investigate variable heat pump operation and thermal energy storage tanks for different house archetypes and climatic conditions in Orkney.

The economic model analyses the life cycle cost analysis of an air source heat pump and discounted savings when existing conventional heating systems are replaced with heat pumps. Savings for individual house archetypes and cumulative results for Orkney provides alternatives to the end-users under different financing options and outlook to the policymakers during the transition period. The novel element of this part is assessing the economic viability of grants and vouchers and providing the amount of required support at the island level.

Hourly electricity load results provide the maximum peak loads under different electricity tariffs for house archetypes in Orkney. The assessment of optimised variable heat pump operation and reduction in peak loads are provided at the archetype and island levels.

The model has been applied to Orkney as a case study, which was chosen because of the vulnerability to high energy prices, reliability on imports, poor energy efficiency measures in domestic buildings, and higher fuel poverty figures than the mainland. On the other hand, Orkney has a high potential for renewables, specifically wind, by providing electricity more than its needs. Therefore, focusing on an island, specifically Orkney, creates a testing ground to analyse the integrated approach.

Integrating these models creates a more holistic and life cycle-wide approach to both demand, supply and end-user side of the system. This comprehensive manner is fundamental to creating a holistic approach to reducing the CO_2e emissions to reach the Net Zero targets while observing other negative consequences and implications, so all aspects of energy, environmental and financial benefits could finally be achieved. Moreover, this research can be extended to other heat pump typologies and heating technologies. As an application, the model can be adjusted to other locations based on different house archetypes and climatic conditions; therefore, cumulative results for the UK could be achieved. The importance of renovating existing housing stock or highly insulated new houses should be assessed prior to the integrated approach so the uptake level of EEI measures could be decided. Orkney has an older housing stock than the national average so renovating existing housing stock is crucial whereas this situation could be different for other areas.

7.3. Limitations of the Study and Recommendations

This thesis has investigated the potential savings of large-scale heat pump uptake in Orkney with Circular Economy principles to support the UK’s 2050 Net Zero target. A comprehensive integrated approach is proposed by integrating life cycle assessment with energy systems modelling. This methodology has thoroughly analysed energy, environmental and financial results for Orkney; however, several limitations that need to be addressed in the future to improve the results are discussed below.

- The life cycle assessment study analysed the impacts of all phases; however, scenario analysis has mainly focused on the end-user side of the system by investigating the use-phase impacts and the disposal. The impacts of Circular Economy principles through reduce, reuse and recycle options in the disposal phase are investigated in Chapter 4. However, modelling more efficient/greener production lines, the reuse of secondary materials in the manufacturing phase and closing the loop approach is fairly complex. An engagement between the manufacturing industry and researchers is required to overcome this problem. This issue stands as the main limitation of the study.

- The alternative manufacturing location scenario in the LCA analysis assumed that the heat pump is manufactured in South Korea, so transport values are revised accordingly. However, as manufacturing data, generic RoW (Rest of the World) data is used because of the lack of data. As the use phase is the dominant stage, the impact of the manufacturing phase won't be significant. Therefore, these values are used for simplicity. These values represent average world data so to generate more accurate results manufacturing data from South Korea should be required.
- Thermal mass calculations in building physics models require dynamic modelling which accounts for time-shifting capabilities. However, energy system modelling done in this study only considers the capacity of thermal mass in the houses. High thermal mass materials could have a positive impact on heat pump operation by energy storage during off-peak times and using this energy in peak times. However, these impacts are not covered because of a limitation of the study.
- Field trials of heat pumps show a discrepancy between projected and real performance. This could be mainly because of poor installation of heat pumps, inaccurate design and sizing or human behaviour. 58% of consumers find heat pumps as complex technologies so a performance discrepancy in the optimum operation of heat pumps could be seen. In order to avoid this problem, an introduction support program should be provided to the heat pump installers to increase the quality of installations. Moreover, another introduction program for consumers should also be provided to raise awareness about the operation of heat pumps. These measures could help to reduce the discrepancy between estimated and real performance. Optimisation behaviour for occupancies could be further investigated in future studies.
- Environmental impacts of heat pumps are assessed individually and cumulatively but while comparing with other heating technologies only use phase-related CO_2e emissions are compared because LCA analysis is not conducted for other individual heating technologies. In order to conduct an LCA analysis for oil, coal, wood and LPG boilers, and electric heaters, a complex data collection and modelling process is required. However, this step is not taken for simplicity because focusing on the integrated approach framework was much more significant. Moreover, comparing the life cycle assessment results of heat pumps and gas boilers provided the essential framework for the integrated approach. For further studies, LCA analysis of these heating technologies could help to compare the remaining environmental impacts.

- Replacing existing heating technologies with low-temperature heat pumps requires an upgrade in heat distribution systems. Increasing the size of the radiators is the cheapest alternative whereas underfloor heating is the best option. The life cycle assessment study assessed the environmental impacts of underfloor heating technologies; however, life cycle heating costs analysis in the integrated approach only considered the cost of minor upgrades such as increasing the size of radiators. Moreover, underfloor heating requires high installation costs; therefore, high upgrades to the heat distribution system are not considered.

Chapter 8

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