

## Article

# An Integrated Methodology for Scenarios Analysis of Low Carbon Technologies Uptake towards a Circular Economy: The Case of Orkney

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**Abstract:** This study aims to create a comprehensive, holistic approach to evaluate the environmental, energy, and economic impacts of air source heat pump deployment scenarios through: (i) a life cycle assessment of air source heat pumps in Orkney houses, (ii) energy systems optimisation modelling to optimise the performance of an air source heat pump coupled with thermal energy storage tank to reduce use phase related impacts in Orkney, (iii) modelling of Orkney's domestic building stock to understand the housing condition, and (iv) economic modelling to analyse the life cycle cost of an air source heat pump and potential savings when replacing conventional heating systems. The results show that an 82% reduction in energy supply could be achieved when ambitious energy efficiency improvement measures are adopted in the circular economy scenario. The use phase related emissions could be reduced by 98% when the air source 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, total heating costs paid by consumers in Orkney could be reduced by 84% in the circular economy scenario when air source heat pump uptake is coupled with energy efficiency improvement measures, but it requires a £130 million investment to insulate the whole housing stock of Orkney. Future scenarios indicate that decision-making has significant importance on overall results. Therefore, circular economy standards for air source heat pump manufacturing and deployment are crucial to reduce the negative impacts of fuel poverty and reach the net zero target.

**Keywords:** circular economy; energy systems modelling; islands; life cycle assessment; low-carbon heating



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## 1. Introduction

The Intergovernmental Panel on Climate Change [1] declared that achieving the Paris Climate Agreement target of limiting temperature increases to 1.5 °C requires exceptional actions. 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, CE could help move from a traditional linear take, make, and waste economy to a circular model.

The UK is the first country to set legislation to achieve 'Net Zero' greenhouse gas (GHG) emissions by 2050 [2]. This requires strong commitments to avoid further delays in reducing emissions. The built environment in the UK represents 30% of the total emissions [3].

The heat pump market has been growing gradually and reached 10% of the global building heating demand in 2021 [4]. Heat pump sales in Europe reached 7 million units in 2021 led by France with 537,000 units per year [5]. In the UK, yearly heat pump uptake is lower when compared with European countries (43,000 in 2021). The UK government aims to reach 600,000 heat pump installations per year by 2028 [6]. The 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 [7]. The Scottish Government granted a slightly higher subsidy named the Home Energy Scotland (HES) loan providing a cashback of up to £7500 and an interest-free loan for the rest of the costs of up to £2500 for heat pumps [8].

The Paris Agreement declared that the reliance on fossil fuels and energy imports makes islands vulnerable to climate change. The price cap for heating homes in Shetland and Orkney islands is the highest two figures with 107% and 96% more than the average price cap in 2021 with the highest annual energy bills among UK local authorities [9]. Orkney is an archipelago in the Northern part of Scotland. Even though Orkney generates its electricity from local renewable sources, electricity prices are assumed to be 2.5 pence higher than southern Scotland values [10]. 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 [10].

Buildings are responsible for 35% of the energy use after transport (45%) in Orkney [11]. 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. The amount of electricity generated from renewables was more than the island's need in 2016 [12]. Therefore, there is a transition for electrification in heating. The number of all heat pump types deployed in 2021 was more than 1000 which accounts for 117 heat pumps per 1000 households [13]. This is the second-largest heat pump uptake among the Scottish local authorities. Therefore, 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 optimisation modelling (ESOM). 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 CE.

## 2. Literature Review

Life cycle assessment (LCA) and energy systems optimization modelling (ESOM) methodologies are widely used individually. Studies about ESOM 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 [14]. A very recent case study by Quest et al. [15] examined integrating life cycle assessment with energy system modelling. The operation of different heating and power systems is optimized with the energy model and their environmental impacts are evaluated with LCA. The optimization 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-optimized scenario and a more than 50% reduction in the CO<sub>2</sub>-optimised scenario. Ecotoxicity results 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 [16]. A multi-objective optimization 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%. The environmental impacts of electricity production technologies in Spain are investigated by Garcia-Gusano et al. [17]. 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. Pietrapertosa et al. [18] created

a framework for the integration of LCA, ExterneE (Externalities of Energy), and comprehensive analysis (a bottom-up model) to investigate energy systems. This approach has been applied to a case study in Italy where authors 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.

The circular economy (CE) definition has been widely used in the literature. Several studies have systematically reviewed the literature to identify CE features and perspectives [19–23]. Implemented studies and concepts on different levels (macro, meso and micro levels) are analyzed based on the CE framework. According to a review study conducted by Kirchherr et al. [24], the CE system aims to replace end-of-life operations with reducing, reusing, recycling, and recovering material usage in the production and consumption stages. The perception of CE also differs among people. 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. Karali and Shah [25] 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. EU’s ‘Circular Economy Action Plan’ has been utilized to create a circular ecosystem for Scotland in a previous study [26]. 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.

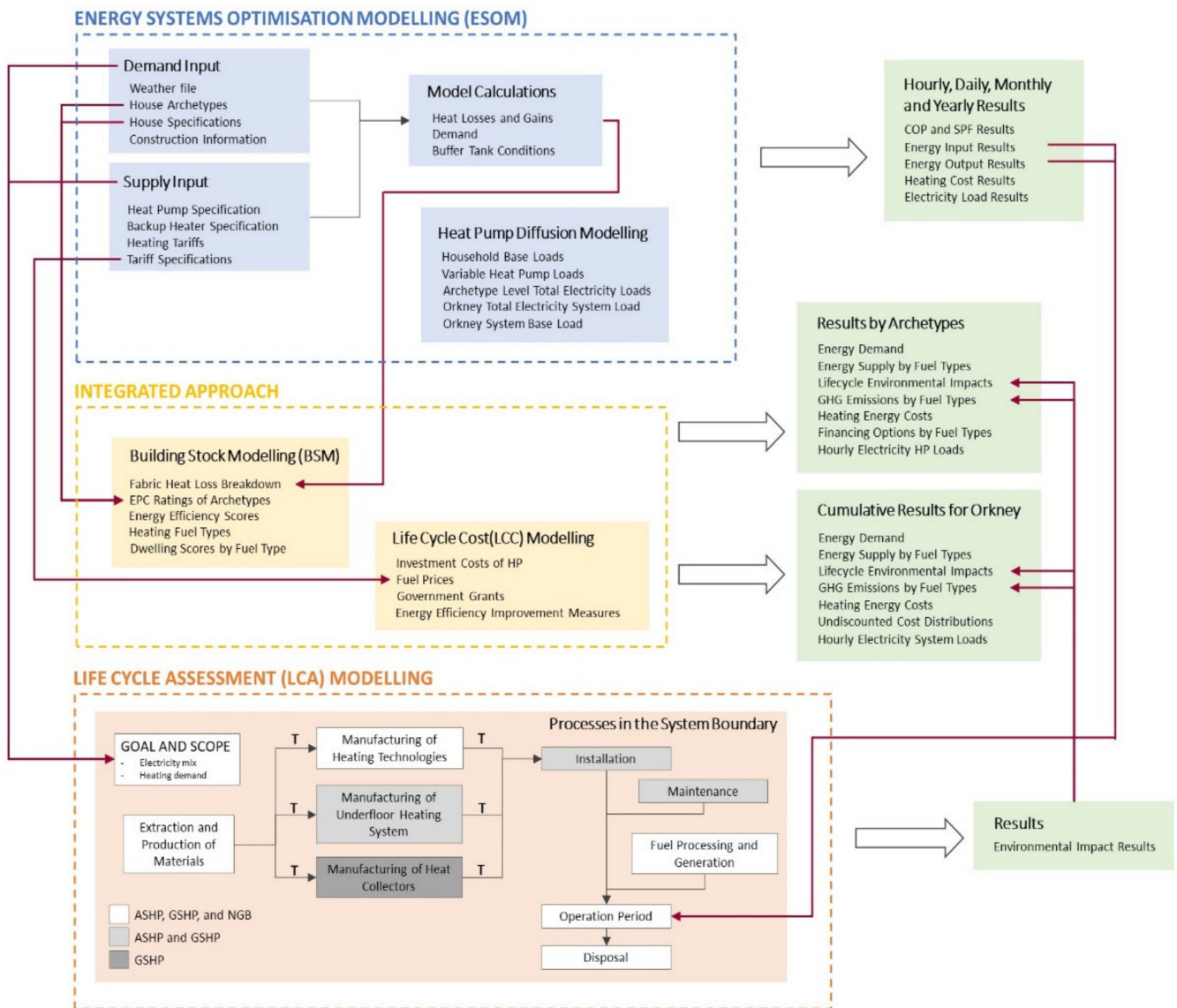
Integration of LCA and ESOM methods was investigated in the literature [14–18]. Most of the studies focused on the environmental impacts (mainly GHG emissions) of energy production technologies on a larger scale at the supply side of the system [17,18]. Some studies focus on individual low-carbon heating technologies [15,16] without assessing overall impacts. The lack of a methodological approach which does not accommodate system thinking creates difficulties between actors and the consistent development of circular practices. On the other hand, national targets on decarbonizing heating require strong commitments in terms of electrification of heating by heat pumps and energy efficiency improvements of houses. However, a holistic approach considering the end-user side by investigating archetype-level savings and system thinking with achieving macro-level targets is needed. This research advances the current literature of specialty by combining LCA with ESOM, considering a number of archetypes for the building stock and assessing the impact of ASHP at the macro level (in this case Orkney).

### 3. Methods

This study aims to create a comprehensive integrated methodological approach to support the UK’s net zero target, which sets ambitious requirements in terms of decarbonising space heating. The method consists of the integration of four different models that inform each other (Figure 1):

- (i) a building stock model (BSM) of Orkney’s domestic sector to understand the housing stock condition and evaluate the energy efficiency improvement (EEI) requirements,
- (ii) a life cycle assessment (LCA) of low-carbon heating technologies (in this case ASHP) utilised in the Orkney houses for decarbonisation,

- (iii) an energy systems optimisation modelling (ESOM) to optimise the performance of an ASHP coupled with a thermal energy storage (TES) tank for Orkney houses and
- (iv) a life cycle cost (LCC) of technologies to create a holistic approach for Orkney as described in Sections 3.1–3.4. The connections between the methods is depicted in Figure 1.



**Figure 1.** A schematic diagram of the proposed integrated approach.

First, 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 based on BSM results. Finally, a scenario analysis is conducted to compare overall results for the current situation with future scenarios to analyse energy, environmental, and financial savings. In this study, only an ASHP is considered for the analysis for simplicity. However, the study can be extended to other heat pump typologies and heating technologies. Two scenarios have been developed for the year 2050 (Section 3.5).

### 3.1. Building Stock Modelling (BSM)

Energy Performance Certificates (EPC) assess the energy efficiency of a building and include information about recommended improvements [27] showing 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 to G with a certain amount of SAP points out of 100 points as a maximum [27].

EPCs provided by Scottish Government Statistics [28] 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%. The 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 EPC dataset has been used for archetype characteristics and specifications.

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 average efficiency score of the construction element and the overall efficiency score of the housing stock.

The average efficiencies of individual construction elements (walls, roof, floor, and windows) are calculated and illustrated in 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 as in the following equation:

$$E_{overall} = (E_{wall} \times W_{wall}) + (E_{window} \times W_{window}) + (E_{roof} \times W_{roof}) + (E_{floor} \times W_{floor}) \quad (1)$$

where  $E$  refers to efficiency and  $W$  is the weight of the construction element in different house archetypes which is calculated in the energy model and illustrated in Section 4.1.

### 3.2. Energy Systems Optimisation Modelling (ESOM)

A heat pump diffusion model has been developed to explore the potential uptake of heat pumps and quantify the impact on the electrical load at the dwelling and island level for Orkney to help assess the transition from fossil fuels to electricity. The model considers 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), TES tank sizes (250 L, 500 L, 750 L, 1000 L), 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), each of them being modelled as in [29]. We assume the heat pumps have a variable operation pattern, where variable load curves are used for the analysis. The model calculates hourly heat pump electricity loads, so an electricity load profile study is conducted to investigate the Orkney grid level.

The time resolution of weather data (outside temperature and solar radiation) has been scaled to hourly for a high temporal resolution. Thermal bridging, internal gains, thermal mass, and standing loss for TES tank calculations are included in the model. 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 based on outside temperature and flow temperature.

Hourly outdoor temperature and solar irradiation data have been collected from Renewables.ninja to calculate heat gains and losses [30]. The internal thermostat set point temperature is specified as 21 °C based on recommendations from the World Health Organization [31] and Public Health England [32]. A number of archetypes have been identified to represent the housing stock (‘detached’, ‘semi-detached’, ‘end-terrace’ and

'mid-terrace') based on BSM results. These archetypes are used to analyse the variation of heating technologies' performance with different physical properties.

EPC data [28] were 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 were taken from The Building Regulations Approved Document Part L1A [33]. 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 were taken from Energy Saving Trust's report [34]. The Government's SAP for Energy Rating of Dwellings [35] was used for generic values (plan aspect ratio, floor thickness, etc.).

Electricity and gas tariff data were collected for 6 different tariffs. Standard and Economy7 tariff was gathered from ScottishPower [36] to analyse Orkney electricity prices. Moreover, tariffs which are not yet available on Orkney such as Economy12 [37], Economy20 and Comfy Heat [38] also analysed to investigate different options. The peak time prices for Economy7, Comfy Heat, Economy12, and Economy20 tariffs are identified as 20.8 p, 15.7 p, 20.7 p, and 16.3 p. Off-peak tariffs are identified as 9.0 p, 8.6 p, 8.6 p, and 11.4 p, respectively. Standing charges are also identified as 23.9 p, 20.3 p, 18.0 p, and 46.9 p, respectively. Standard electricity tariff and gas prices are identified as 16.5 p and 3.2 p for unit prices and 23.8 p and 23.3 p for standing charges (Appendix B, Table A1).

The distribution of off-peak and peak hours during the day was identified according to tariff options. Standard tariff assumes that there is no peak time pricing so standard pricing is assumed as an off-peak tariff. Economy7 tariff assumes 7 h of off-peak time during the night. The number of off-peak hours is very similar in the Comfy Heat tariff with 8 h, but they are distributed throughout the day with 4 h during the night and 4 h during the day. Economy12 and Economy20 tariffs have 12- and 20-h off-peak time with 2 h during the day and the remaining during the night (Appendix B, Table A1).

TES tanks store energy in required times and help to avoid overpricing in peak times. Therefore, four different sizes of TES tanks (250 L, 500 L, 750 L, and 1000 L) are tested in the model to explore lower peak time heating costs. Standing losses are calculated based on SAP document [35] and Hot Water Association [39] methodologies. In terms of the backup heater, both electricity and natural gas-fired heaters are tested. It has been assumed that a condensing gas boiler has a 15 kW 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.

There are various heat pump types. 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 Ozone Depletion potential) to explore various heating performances [40]. However, the PUHZ series is also investigated to test the impact of using a different refrigerant (R410) on energy performance. To select the correct size of the heat pump, three different sizes are explored, namely 8.5 kW (PUZ85), 11.2 kW (PUZ112), and 14.0 kW (PUZ140). COP and capacity data under different outdoor temperature conditions and water outlet temperatures (35 °C, 45 °C, and 55 °C) are calculated hourly in the model. 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.

A heat pump diffusion model [41] quantifying the impact of installing ASHPs on the electrical load curves at the dwelling and UK levels was integrated into this research. Data for Orkney electricity system load were taken from Scottish and Southern Electricity Networks [42]. Average household level hourly electricity load structures were taken from a study conducted by Intertek [43] for various types of household settings including with/without electricity heating. Heating-related loads were 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.

The model calculates heat gains and losses to analyze the performance of the dwelling. Fabric heat loss, ventilation heat loss, thermal bridging, solar gains, internal gains, and thermal mass properties are calculated based on SAP methodology (Appendix A—Equations (A1)–(A16)). TES tank temperature is calculated as in the following equations:

$$\sum DDHW = V_W \times 4.18 \times T \quad (2)$$

$$H_R = \sum L_{total} - \sum G_{total} + \sum DDHW \quad (3)$$

$$\begin{aligned} \text{if } T_{TS} > 5 + T_e \quad T_{TE} &= T_{TS} - \frac{\sum H_R}{V_T \times 4.18} - \frac{\sum H_P}{V_T \times 4.18} - L_S \\ \text{if } T_{TS} \leq 5 + T_e \quad T_{TS} &= T_e \end{aligned} \quad (4)$$

where  $D_{DHW}$  is DHW demand,  $V_W$  is the volume of the water (litre),  $T$  is required water outlet temperature ( $^{\circ}\text{C}$ ),  $H_R$  is required heat,  $L_{total}$  is total losses (W),  $G_{total}$  is total gains (W),  $T_{TE}$  is tank end temperature,  $T_{TS}$  is tank starting temperature,  $T_e$  is external temperature,  $H_P$  is provided heat with heat pump and backup heater,  $V_T$  is tank size (litre), and  $L_S$  is standing loss ( $^{\circ}\text{C}$ ) of the tank. Standing loss is calculated as in the following equations:

$$L_S = f_V \times f_T \times f_C \times V_C \quad (5)$$

$$f_V = (120/V_C)^{\frac{1}{3}} \quad (6)$$

$$f_C = (0.005 + 0.55/(t + 4)) \quad (7)$$

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 maximizing heat pump operation during off-peak times and avoiding gas boiler usage, and then minimizing heat pump operation during peak times and covering the remaining demand with a backup heater. The model calculated heat pump and backup heater capacities as in the following equations:

In peak times;

$$\begin{aligned} \text{if } C_{MIN} \geq H_R \quad E_P &= C_{MIN} \\ \text{if } C_{MIN} < H_R \quad E_P &= C_{MID} \end{aligned} \quad (8)$$

$$\text{if } T_E < T_L \quad \text{HP} \geq \text{ON} \quad (9)$$

In off-peak times;

$$E_P = C_{MAX} \quad (10)$$

$$\text{if } T_E > T_H \quad \text{HP} \geq \text{OFF} \quad (11)$$

At all times;

$$\text{if } T_E < T_B \quad \text{Backup} \geq \text{ON} \quad (12)$$

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, and  $T_B$  is the backup temperature.

### 3.3. Life Cycle Assessment (LCA) Modelling

A previously modelled LCA study [44] was adapted to evaluate the environmental impact associated with heat pumps in house archetypes in Orkney. The functional unit of the study is decided as generating the required thermal energy for house archetypes in Orkney during the lifetime of an ASHP which is assumed as 20 years. The amount of energy required for different house archetypes is calculated in the energy model. The LCA software SimaPro 8.0.3 [45] was used to model the products and the ReCiPe Midpoint (H) method [46] was used to calculate environmental loads. The model assumes that ASHPs are manufactured in Europe and transported to Orkney. Currently, Orkney produces a surplus of renewable electricity from wind and tidal sources, and the electricity mix in

Orkney comprises 100% renewable energy sources. Therefore, this electricity mix is used in LCA [12]. Electricity demand varies based on archetypes and their specifications. Therefore, environmental results for these individual archetypes are calculated.

#### 3.4. Life Cycle Cost (LCC) Modelling

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 LCC analysis of a heat pump is calculated based on baseline model results. Then, results for CE and resource efficiency (RE) scenarios are analysed for future results.

The cost of installing heating measures is analysed by Delta-EE [47] for different heating types including heat pumps. An existing report from the Carbon Trust [48] investigates the overview of heat pump retrofit in London through 15 case studies and CO<sub>2</sub> 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 [49–51]. In line with these studies and market research, the upfront cost of an ASHP is assumed as £9250, £10,250, and £12,000 for 8.5 kW, 11 kW, and 14 kW sizes of heat pumps (Table 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 [52] 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-year period are decided from market research and quotes from providers.

The Boiler Upgrade Scheme (BUS) replaces the Renewable Heat Incentive (RHI) and provides a grant of £5000 for the upfront cost of an ASHP [53]. Similar to this support, the Scottish Government provides a loan for EEI measures and renewable heating systems, including cashback payments [8]. 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 LCC calculations. The results are expressed in discounted costs at an annual rate of 3.5% [54].

Data for fuel prices of energy sources used in Orkney were collected from previous studies and quotes from suppliers. BEIS [55] provides historical data for fuel prices and future trends. National Infrastructure Commission [56] 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 identified [55–58]. LPG, oil, coal and wood prices are identified as 6.3 p, 5.2 p, 4.7 p, and 5.3 p, respectively. Standard electricity tariff price is identified as 16.5 p, and Comfy Heat tariff is identified as 8.6 p, 15.7 p, and 20.3 p for off-peak, peak, and standing charge prices (Appendix B, Figure A1). Fossil fuel prices are expected to increase in the future with carbon taxes, and electricity prices to decrease [57].

Specification and EEI conditions of construction elements in house archetypes are analysed in Orkney (Appendix C, Figure A2). Many 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. Moreover, 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 in refurbished detached houses is cavity insulation. Further, 54% of the total housing stock has double-glazed windows. 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.

**Table 1.** Summary of assumptions for life cycle cost analysis and future scenarios.

	Baseline	RE	CE	References
Upfront Cost (8.5 kW)	£9250	£8325	£7400	
Upfront Cost (11 kW)	£10,250	£9225	£8200	[47–49,51,52,59,60]
Upfront Cost (14 kW)	£12,000	£10,800	£9600	
Upfront Cost Change	0%	–10%	–20%	[52]
Lending Rate	3.0%	2.8%	2.5%	
Discount Rate		3.5%		[54]
Period		15 years		
BUS		£5000		[53]
HES		£7500		[8]

The cost of efficiency improvement steps for each construction element is identified by house archetypes. While deciding on the insulation type, the dominant construction element is selected. 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 also require some improvements to reach the new building category which includes secondary glazing to have higher insulation on windows, drought proofing, and further insulation on roofs and floors. The installations costs for detached, semi-detached, mid-terraced, and end-terraced houses are £9000, £7075, £6675, and £4975, respectively (Appendix C, Figure A3). The efficiency improvement costs are included in the LCC analysis for a broader perspective on the housing stock condition.

### 3.5. Proposed Scenarios

Two scenarios have been developed for the year 2050. Only the case of ASHP is considered for the analysis for simplicity. However, the study can be extended to other heat pump typologies and heating technologies.

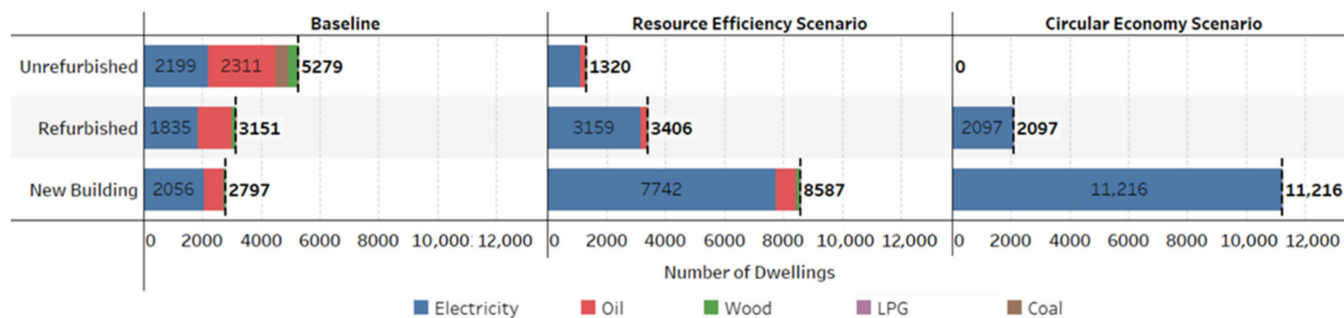
**Baseline Scenario:** It represents the current situation at Orkney. The number of heat pumps deployed on the island is around 1050 (representing one-tenth of total dwellings). The number of dwellings and fuel types of house archetypes and specifications for the scenarios are provided in Figure 2.

**Resource Efficiency (RE) Scenario:** A reduction in energy demand is expected but this decrease is lower than the CE scenario. EEI applications are limited. RE scenario assumes that 75% of fossil fuel heating technologies will be replaced with heat pumps. EEI measures are taken for 75% of unrefurbished and 25% of refurbished houses. Half of the new dwellings constructed before 2050 are assumed to be in the new building category and those remaining are in the refurbished category, all of which use heat pumps for space heating.

**Circular Economy (CE) Scenario:** High technology development and high consumer engagement are supported by policies. Therefore, more efficient houses and low-carbon technologies portend a reduction in energy demand. The uptake of heat pumps reaches 100% to achieve UK's Net Zero target. 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 before 2050 will be in the new building category and the remaining will be in the refurbished category. CE scenario assumes higher EEI measures taken with 100% heat pump uptake

Note: 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.



**Figure 2.** Number of dwellings and fuel types by house archetypes and specifications for baseline and future scenarios.

## 4. Results

### 4.1. Building Stock Modelling (BSM) Results

BSM results illustrate that most of the houses in Orkney are detached houses with a mean gross floor area of 118 m<sup>2</sup> (Appendix D—Figure A4). Only 7.4% of this archetype has an EPC rating of A or B. However, C–F bands are distributed evenly between 23–18%. Semi-detached houses have higher B–D band ratings and account for 85% of the total. The mean gross floor area is 80.5 m<sup>2</sup> for this archetype stock. Terraced houses have mainly B–D rating bands with a 73 m<sup>2</sup> 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. EPC rating 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 many of these categories comprise either new buildings built with higher energy efficiency standards or well-refurbished houses in the existing housing stock.

Heat losses occurring in the building fabric are calculated by the energy model described in Section 3.2 for different construction types (walls, windows, floor, and roof) to explore the impacts of individual construction elements on fabric heat losses (FHL). Results for four different archetypes (detached, semi-detached, end-terraced, mid-terraced) with three different specifications (unrefurbished, refurbished, new building) are investigated. The results illustrate 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 3). However, windows contribute more to 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, i.e., the impact of windows increases.

Considering these calculations, Figure 4 shows the energy efficiency categories based on their scores of individual construction components and overall results by different archetypes. 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 3.

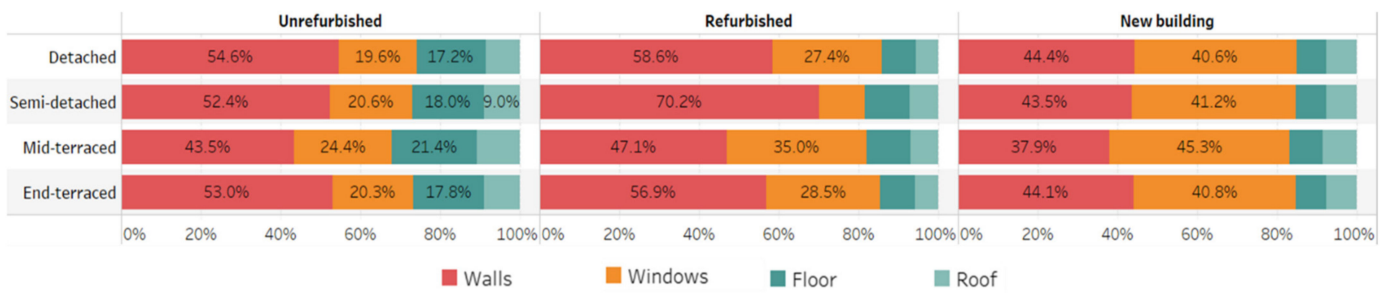


Figure 3. Contribution of construction components to fabric heat loss.

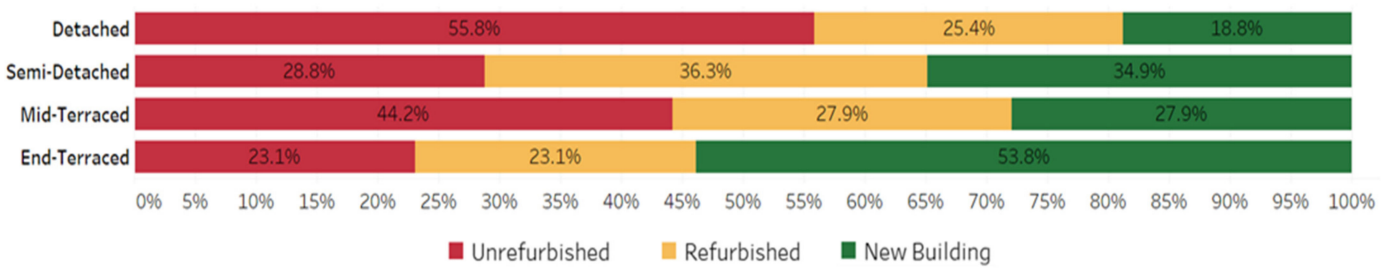


Figure 4. Energy efficiency scores for wall, roof, floor, windows and overall, by house archetypes.

The results illustrate that a majority of the houses in Orkney are categorised as refurbished with 49.7% of the total housing stock, followed by unrefurbished and new building categories with 27.6% and 22.7%, respectively. The most unrefurbished housing stock exists in detached and mid-terraced houses with 55.8% and 44.2%. The most efficient construction parts are the roof and walls with 69.1% and 60.8% 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%.

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 5). It is followed by oil boilers and heat pumps with 36.7% and 9.0%. The remainder is provided by wood, coal, and LPG boilers. The majority of heat pumps are used in the new building category with 7.7%.

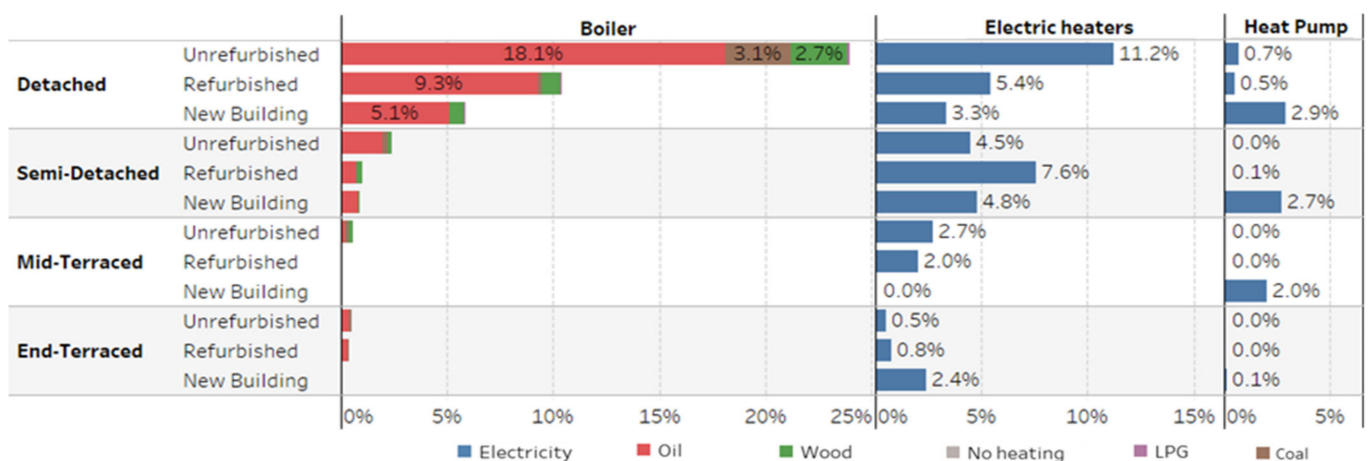


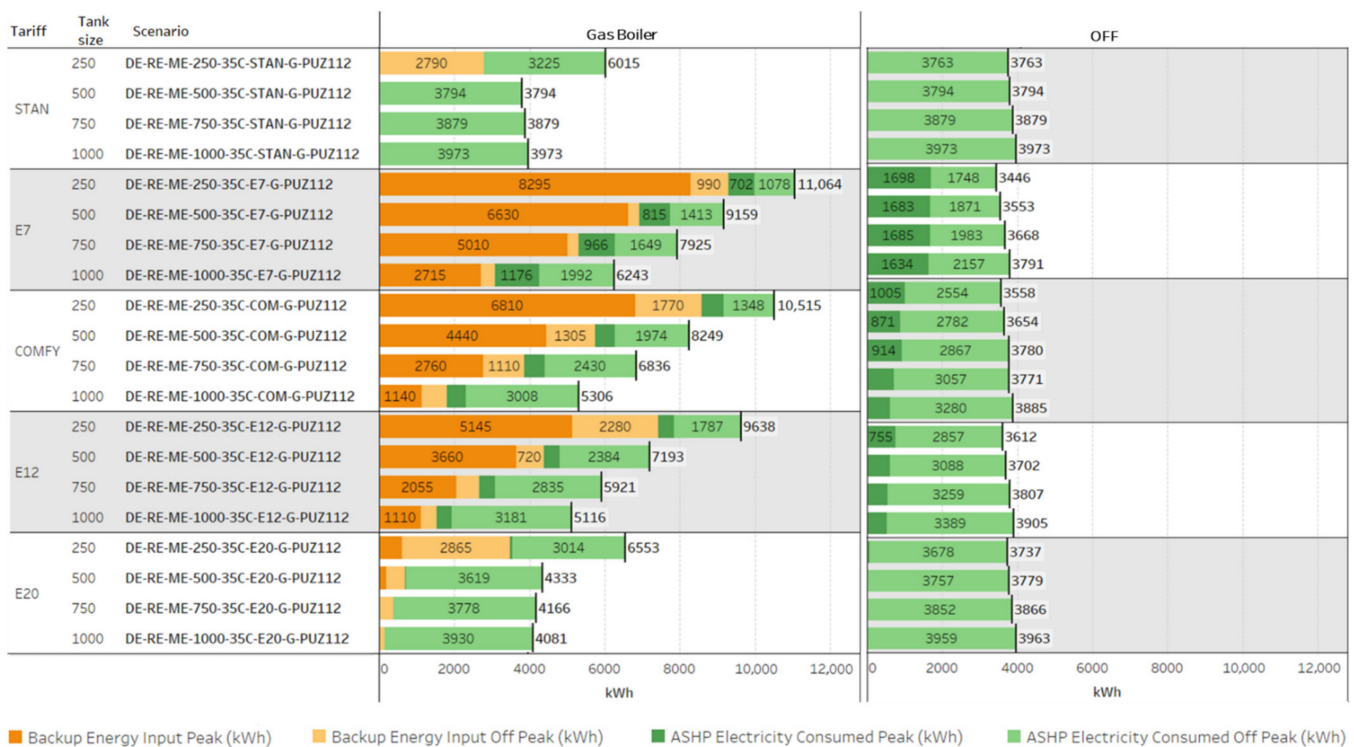
Figure 5. Proportion of main heating fuel type and the total number of heaters.

#### 4.2. Energy Systems Optimisation Modelling (ESOM) Results

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 [61]

guidance. Five types of tariffs (Standard, E7, Comfy Heat, E12, and E20) and four tank sizes (250 L, 500 L, 750 L, and 1000 L) are compared with two different settings (Gas boiler as a backup heater and no backup heater) for the optimisation.

The amount of energy produced by the heat pump and backup heater varies between 16,500 and 17,500 kWh based on TES tank sizes. Figure 6 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 250 L. Even though the consumption figure is 6015 kWh with a 250 L tank size, energy input values occur as 3794 kWh, 3879 kWh, and 3973 kWh for larger tank sizes respectively. The 250 L 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 with 250 L tank size. However, when the tank sizes increased, the consumption figures decreased in the E20 tariff. So, increasing the tank size has a positive impact on this tariff.



**Figure 6.** Energy input of backup scenario analysis for heat pump and backup heater during off-peak and peak times.

The highest consumption occurs in the E7 tariff with 250 L tank 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. Higher tank sizes help to decrease energy consumption to 9159 kWh, 7925 kWh, and 6243 kWh with 500 L, 750 L, and 1000 L 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 250 L tank size, this could be increased to 24%, 33%, and 51% with higher tank sizes, respectively.

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 1000 L 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 compared with the 9638 kWh consumption of a 250 L 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 250 L 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 205 L, 500 L, 750 L, and 1000 L 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 heating cost discussion.

Figure 7 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.

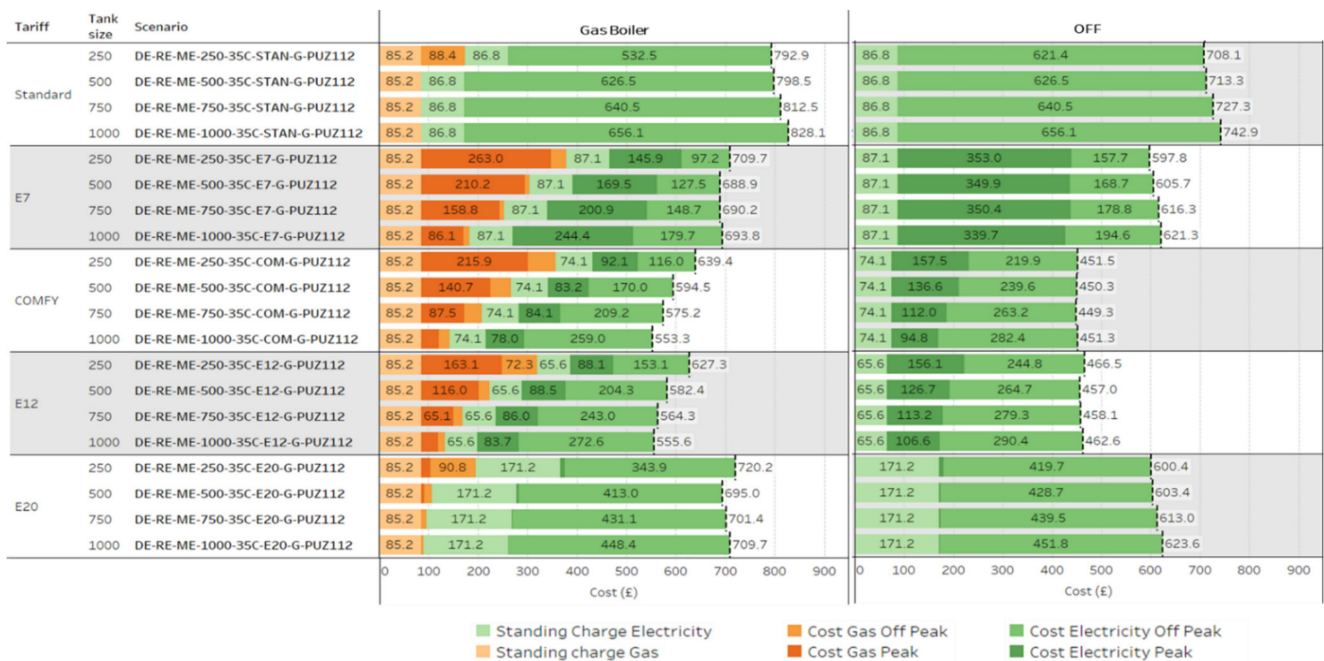


Figure 7. Heating cost of backup scenario analysis for heat pump and backup heater during off-peak and peak times.

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 250 L, 500 L, 750 L, and 1000 L tank sizes respectively. Increasing the tank size 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 h 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 250 L 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 250 L 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 sizes. Peak time electricity share in total electricity cost is 23% in both tariffs with 1000 L tank size. Although half of the cost in scenarios with 250 L tank size comes from natural gas, this contribution reduces to 25% with 1000 L 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 operations financially feasible.

### 4.3. Integrated Modelling Approach Results

#### 4.3.1. Energy Savings

Current energy results (supply and demand) and proposed scenarios are calculated at individual archetype and Orkney levels. The unrefurbished houses have the highest demand as expected, where 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 (Figure 8). 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 stricter EEI measures.

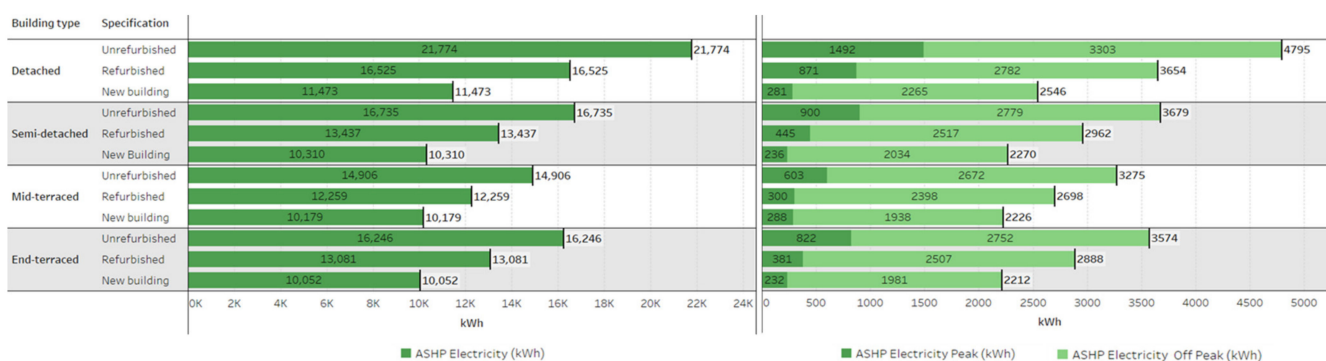
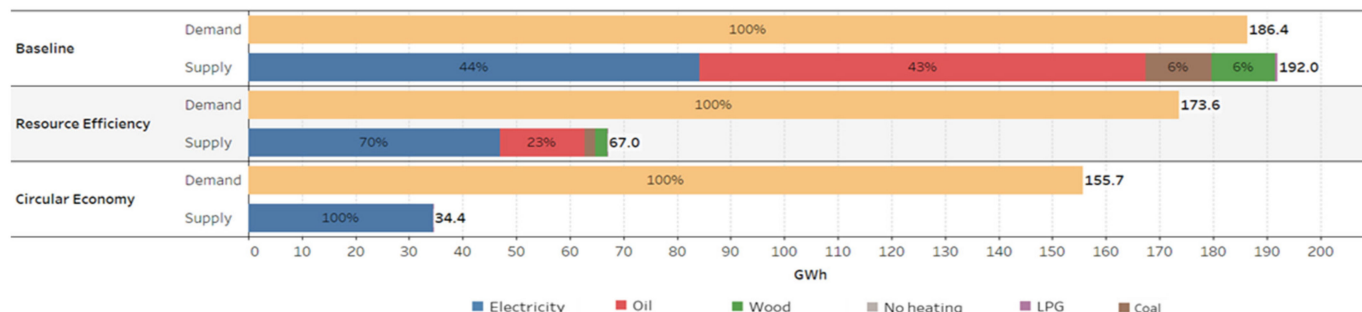


Figure 8. Energy demand results (left) and proposed energy supply (right) by house archetypes for heat pump uptake scenarios.

The demand figures and main heating fuel type results in the EPC dataset are integrated with BSM to illustrate overall results for Orkney (Figure 9). Overall domestic demand occurs at 186.4 GWh whereas supply stands at 192.0 GWh. While calculating the supply, 2.65 is used as an average seasonal performance factor (SPF) value for the current heat pumps as the field trial shows [62]. 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 75% of the electric heaters and 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 recall 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 EEI measures taken at different rates explained in the methodology section.



**Figure 9.** Comparison of energy demand and supply for house archetypes with heat pump uptake scenarios by fuel type.

RE results show that if EEI 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 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 EEI measures create less energy demand for the entire housing stock. Energy supply is expected to decrease by 82% (to 34.4 GWh) by replacing all heating technologies with ASHPs. The main reason for a higher reduction in energy supply is that heat pumps are significantly more efficient than other heating technologies. Therefore, the reduction in supply is significantly higher than demand in the CE scenario.

#### 4.3.2. Environmental Savings

Comparative LCA results of heat pumps and gas boilers are calculated for the UK in a previous study [44]. In this study, Orkney results show that there is a significant reduction in most categories when it is compared with the results for the UK (Figure 10). 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 Ionising Radiation (IR) 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 high reductions occur in agricultural land occupation (ALO), terrestrial ecotoxicity (TE) and national land transformation (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.

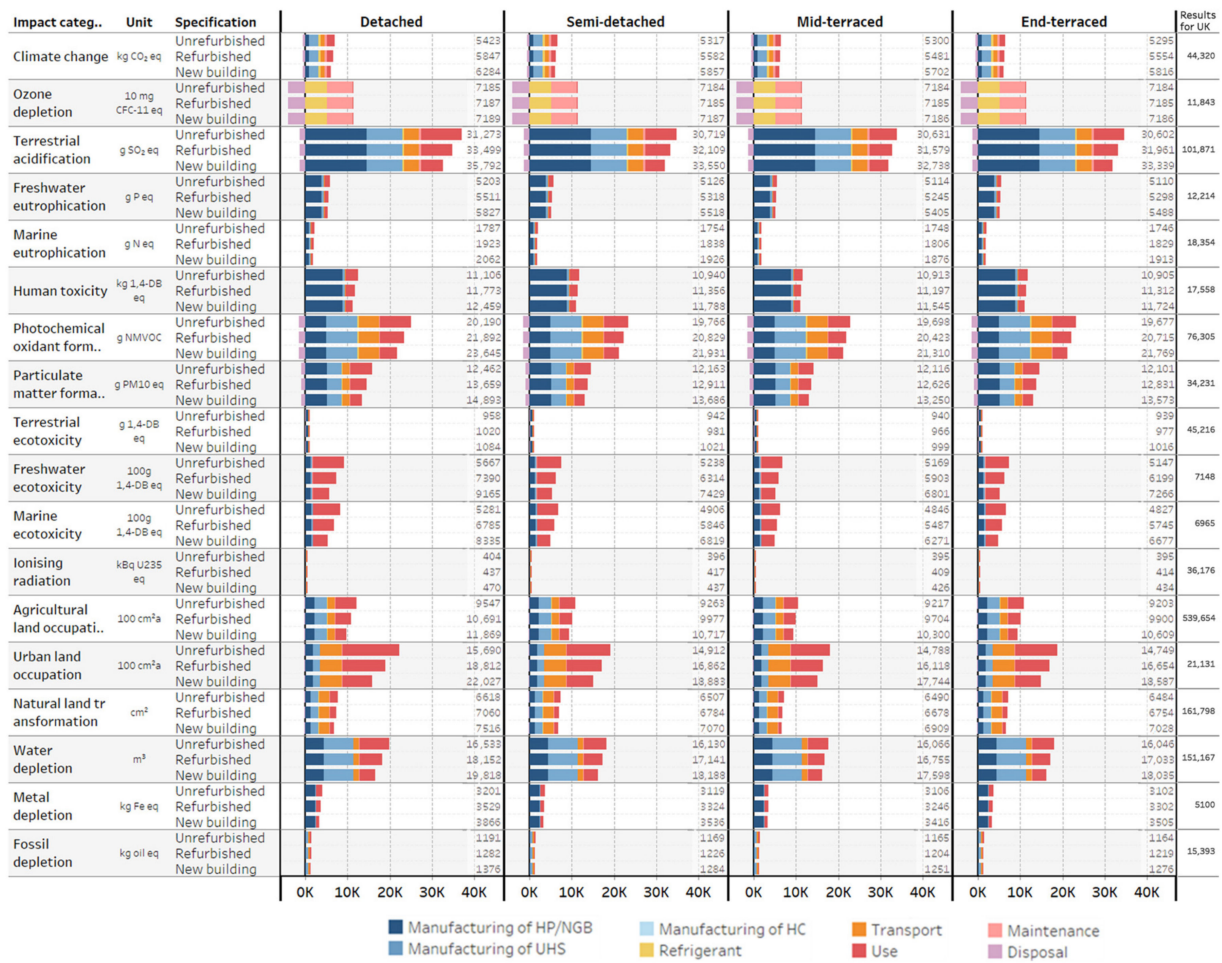


Figure 10. Lifecycle environmental impacts of heat pump uptake scenarios by house archetypes.

The lowest changes occur in freshwater ecotoxicity (FE) and marine ecotoxicity (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. urban land occupation (ULO) and metal depletion (MD) categories also have 19% and 34% lower results mainly because of the differences in the electricity mix.

The climate change (CC) category results decreased from 44,320 kgCO<sub>2</sub>e to 5621 kgCO<sub>2</sub>e 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<sub>2</sub>e if the building is an unrefurbished detached house or decrease to 5295 kgCO<sub>2</sub>e 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.

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 EEI.



Figure 11 illustrates the breakdown of GHG emissions for the baseline scenario and total emissions for future scenarios. Oil is responsible for 77% of total emissions (20,552 tCO<sub>2</sub>e), followed by coal with 16% (4248 tCO<sub>2</sub>e) and electricity with 6% (1612 tCO<sub>2</sub>e) in the baseline scenario. Wood and LPG account for only 1% (269 tCO<sub>2</sub>e) of total emissions. RE and CE scenarios reduce total emissions by 79% 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<sub>2</sub>e coming from electricity, which is very low when compared with the RE scenario. Even though the demand is higher in the future with around 2000 more new dwellings, ambitious EEI targets also help to reduce both demand and emissions. The UK’s net zero target is an ambitious target and requires ambitious steps, including not only a shift in the heating system, but also a shift in EEI.

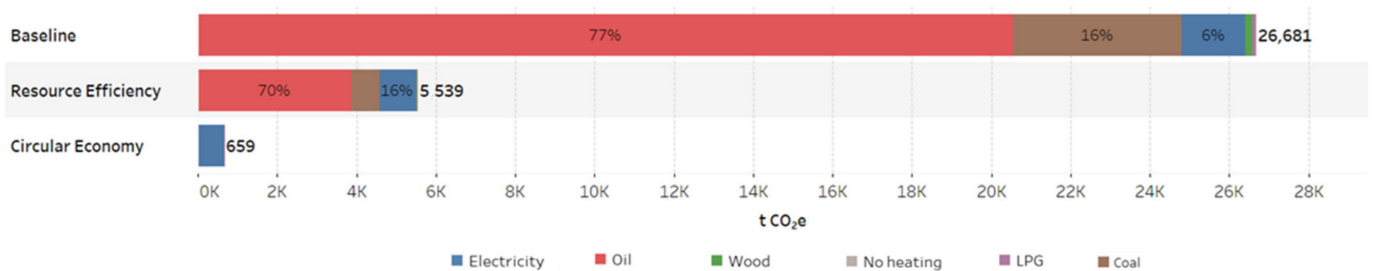


Figure 11. Comparison of current and heat pump uptake scenario GHG for house archetypes contributed by fuel type.

### 4.3.3. Heating 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 Comfy Heat tariff are presented in Figure 12. E12 results are very similar to Comfy Heat tariffs and consequently 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.

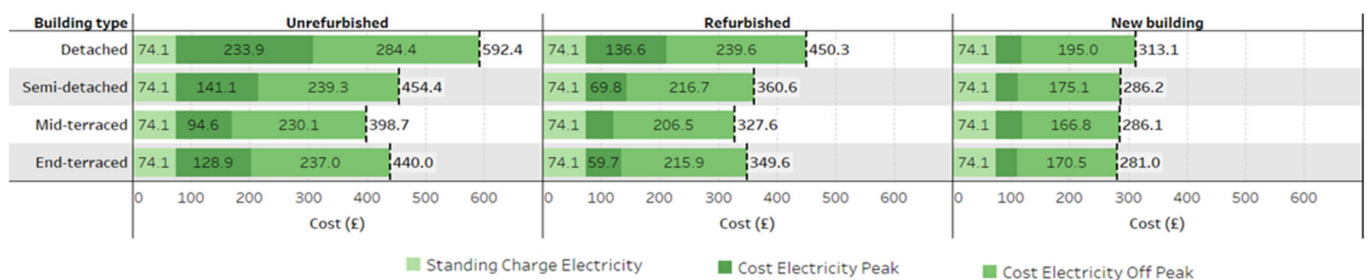
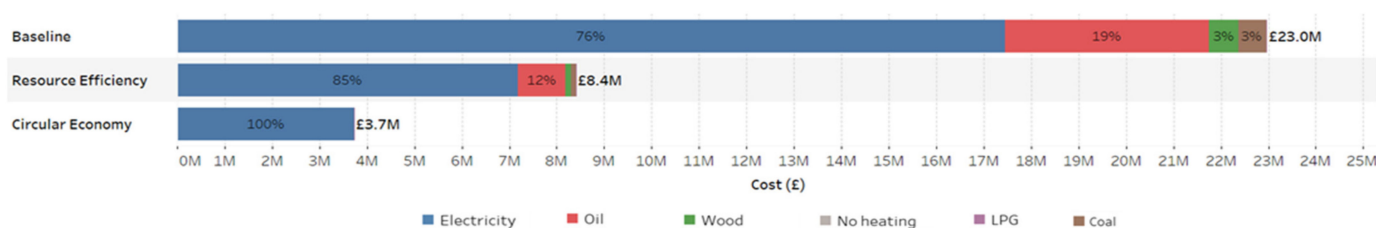


Figure 12. Heating energy cost for heat pump uptake scenarios by house archetypes from Comfy Heat tariff.

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. Moreover, 48% of this cost comes from off-peak time electricity usage and 39% comes from peak time usage. Further, 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 does the heating demand decrease with the help of EEI measures, but it also can help to shift much 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.

The total heating cost on the island is around £23.0 million and the majority of it comes from detached houses (Figure 13). Electricity is responsible for 76% of the total heating cost followed by oil, coal, and wood with 19%, 3%, and 3% respectively. RE scenario could help to reduce heating cost results to £8.4 million via replacing 75% of the heating technologies with heat pumps and EEI measures. The share of fossil fuels is reduced to 12% of the total heating cost in this scenario. CE scenario offers more reduction with more ambitious heat pump uptake and EEI 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 EEI scenario, so there will be no unrefurbished houses left and the majority of the houses are in the new building category with high-efficiency standards.



**Figure 13.** Heating energy cost of baseline model by archetypes and specifications and future scenarios.

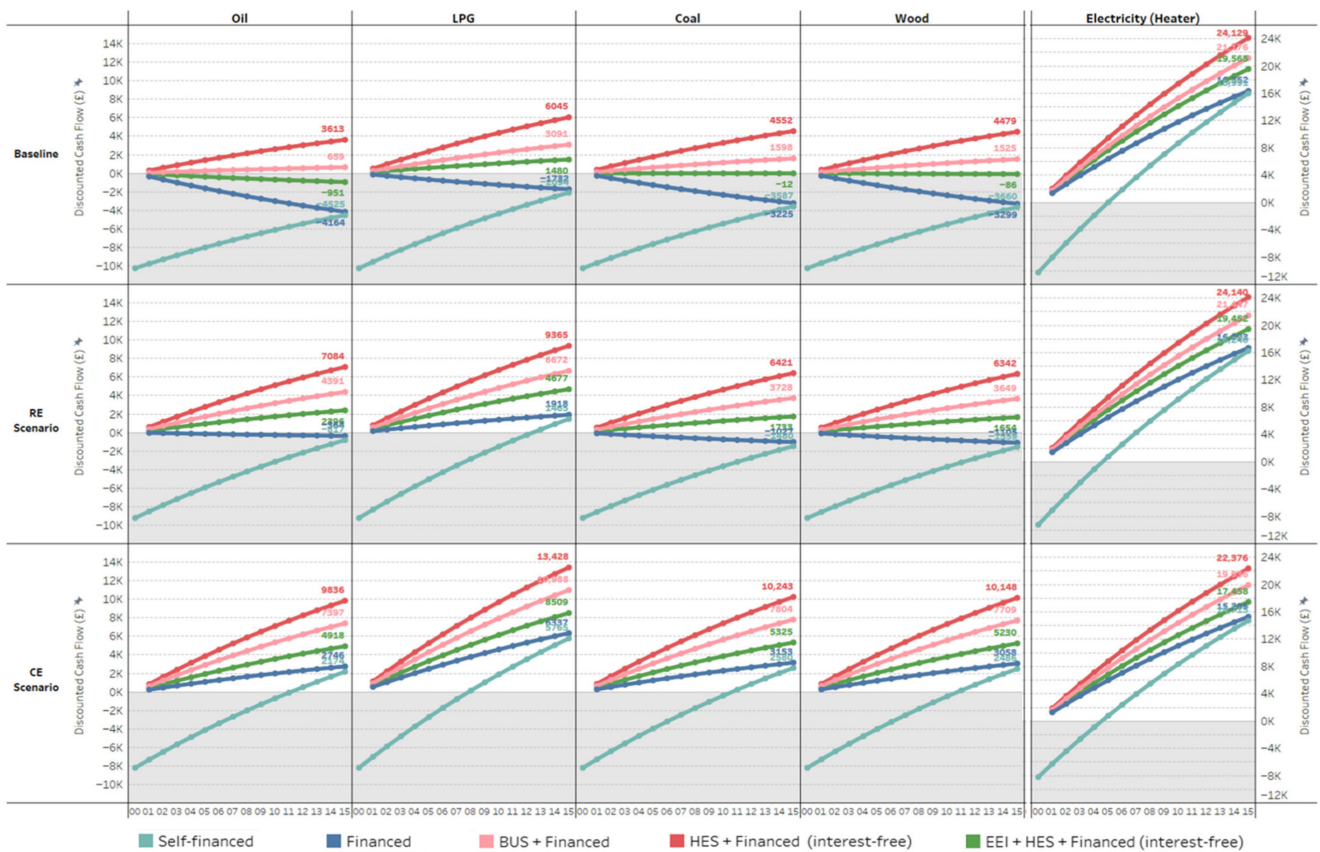
#### 4.3.4. Financial Options

The previous section shows the heating cost of heat pumps and the cost saving of replacing existing heating technologies with heat pumps. This section focuses on the LCC of heat pumps and financial alternatives. Figure 14 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 EEI costs. The results are illustrated in discounted costs of 3.5% for a 15-year period. Figure 14 only shows the results for a refurbished detached house for simplicity.

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 shows savings of £4525 and £4164 for self-financed and financed scenarios respectively. Coal and wood have similar results, while LPG still performs negatively 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 from HES and BUS grants, respectively. Coal and Wood have lower results with around £4500 for HES and £1500 for BUS grant. The oil boiler has £3613 for HES and only £659 for BUS grants.

EEI 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 Appendix C, Figure A3). A refurbished detached house requires £9000 for more ambitious EEI measures. Therefore, EEI measures become economically viable for only LPG with £1480 in LCC. The remaining fuel types, (oil, coal, and wood) show negative results with −£951, −£12, and −£86 respectively.



**Figure 14.** 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).

Replacing electric heaters with heat pumps always shows positive results for all financial options as electricity prices are higher than fossil fuels, creating 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.

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 15 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. 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. The total EEI measure cost is £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. As the energy demand is reduced, electricity cost is also reduced from £62.3 million to £49.0 million.

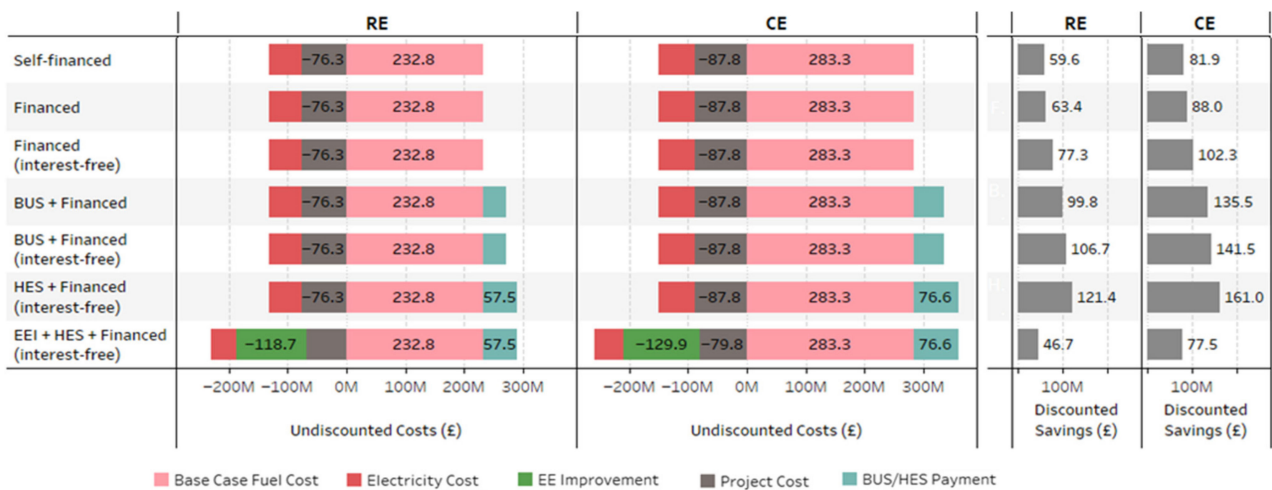


Figure 15. Cumulative undiscounted cost distribution of replacing heating technologies with heat pumps in Orkney for different financial alternatives and future scenarios by fuel types.

Even though the EEI scenario does not provide positive savings in the baseline scenario, future scenarios could help to create savings for refurbished archetypes. 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. Further, £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.

#### 4.3.5. Hourly Electricity Load Savings

Figure 16 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 Comfy Heat tariff and 3.94 kW in E12 tariff for all archetypes in the coldest winter workday. Detached houses have the highest energy demand. Therefore, the total variable load is 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, approximately 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 lower 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, respectively. The coldest winter holiday results also show similar trends but slightly lower load profile results.

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 17 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 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 total daily variable heat

pump load is 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.

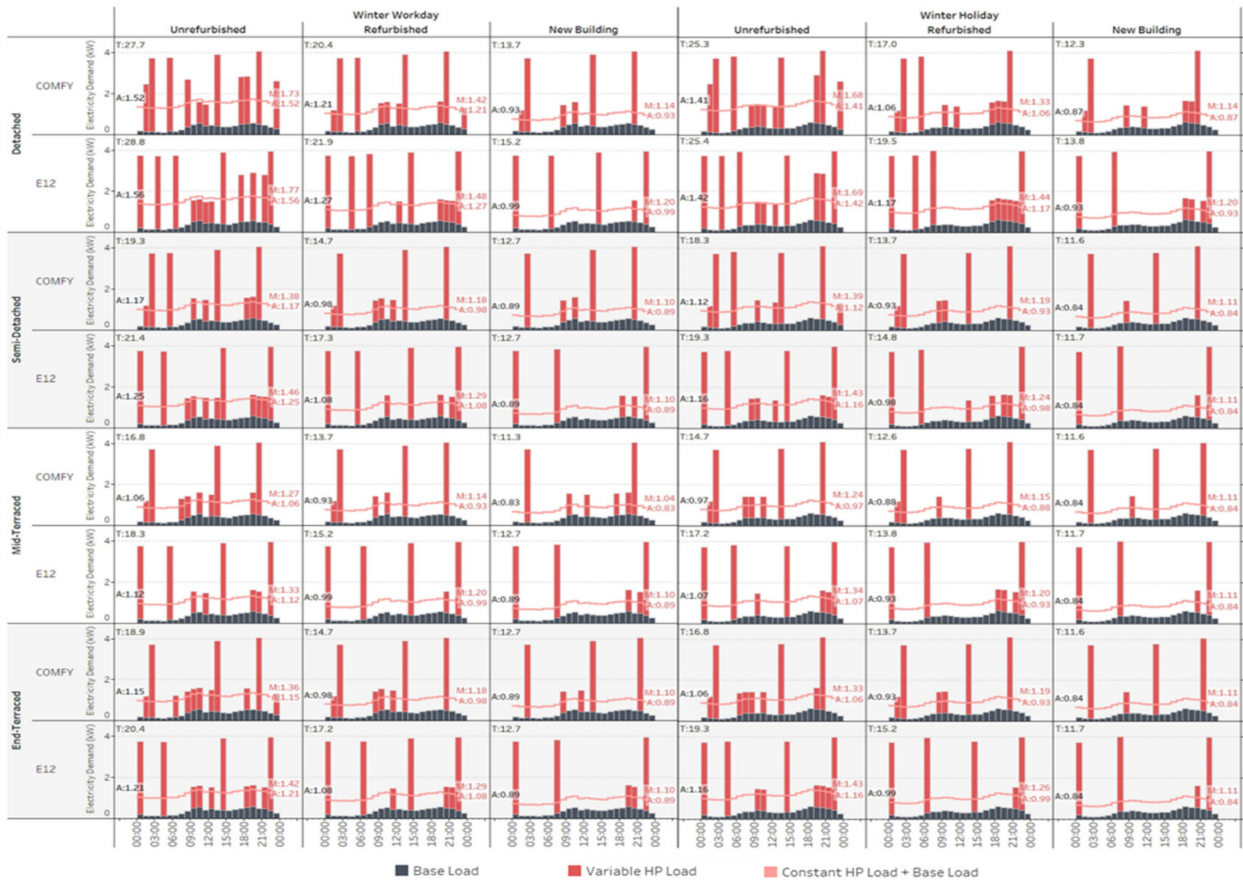


Figure 16. Average hourly electricity demand load curve of a representative heat pump profile by different archetypes and electricity tariffs for the coldest winter workday and holiday (T: Total, M: Maximum, A: Average).



Figure 17. 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).

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 CE scenario has 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), the majority of the variable loads stay below constant load, and heat pumps do not operate in the evening, which is when 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 analyzed, 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. EEI measures help to reduce the total daily variable heat pump load which is crucial 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.

## 5. Discussions

Integrating energy modelling, LCA, and financial modelling helps us to understand various aspects of heat pump uptake scenarios. Energy savings results emphasize that EEI could help to reduce energy demand by 16% in the 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 EEI in the CE scenario.

The main heating types in Orkney are electric heaters and oil boilers, so heat pump uptake could help to reduce use-phase-related GHG emissions by 98% in the CE scenario (from 26,681 tCO<sub>2</sub>e to 659 tCO<sub>2</sub>e), but this requires strong commitments in terms of EEI and heat pump deployment. Even though the electricity mix is 100% renewable, GHG 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.

ASHP perform better than other heating technologies (oil, LPG, coal and wood boilers, and electric heaters) in terms of heating costs with the optimized 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 the 100% uptake of heat pumps coupled with more efficient houses and changes in energy prices in the future. Increased levies on fossil fuels and reduced levies on electricity could make the electricity market more competitive in the future 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.

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 resulting from EEI 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 labor 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, EEI could help to reduce peak loads. At the Orkney level, a combination of Comfy Heat and E12 tariffs provides a more even 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), a 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, such as the E12 tariff, or more equally spread off-peak hours throughout the day, such as 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 EEI 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.

#### *Data Quality and Limitations*

LCA 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. Moreover, the use phase dominates most of the categories, so the importance of the manufacturing phase remains limited. Only use phase related GHG emissions are compared in the cumulative savings.

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 considered in the LCA study. This is mainly because the data are limited in terms of amount of materials used for different sizes of heat pumps.

Replacing existing heating technologies with low-temperature heat pumps requires upgrading the heat distribution system, which could mean 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 heat pumps to avoid high installation costs.

## **6. Conclusions**

This study has investigated the impacts of large-scale heat pump uptake in Orkney with circular economy (CE) principles to support the UK's 2050 net zero target. An integrated approach of different methods (LCA, ESOM, BSM) was taken. Firstly, EPC data were

used to analyze 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 (EEI) for these archetypes was decided. Existing heating technologies and fuel types were investigated to analyze the current situation in Orkney. Then, potential energy, environmental and economic savings under heat pump uptake scenarios were calculated based on the BSM and existing heating types. Financing options for heat pump uptake scenarios were also investigated for consumer engagement. 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.

By taking an integrated approach, results show that 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.

The use-phase-related GHG 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 the manufacturing of the products, energy production, and consumption.

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 could only be achieved with 100% heat pump uptake and implementation of EEI measures, which requires a £130 million investment for the entire island to insulate unrefurbished housing stock. New grants and incentives, such as vouchers similar to BUS/HES grants, interest-free loans, and reductions in VAT on equipment and labor 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.

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 represents 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 achieved through adapting CE principles could help to reduce the negative impacts on the manufacturing phase.

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 GHG emissions to reach the net zero targets while observing other negative consequences and implications, so all aspects of energy, environmental, and financial benefits can finally be achieved. Focusing on the island level, specifically in Orkney, could help to provide sustainable solutions to the economic pressure that islands are facing and to the high level of fuel poverty.

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## Abbreviations

<b>IPCC</b>	Intergovernmental Panel on Climate Change	<b>ALO</b>	Agricultural Land Occupation
<b>IR</b>	Ionising Radiation	<b>ASHP</b>	Air Source Heat Pump
<b>LCA</b>	Life Cycle Assessment	<b>BUS</b>	Boiler Upgrade Scheme
<b>LCC</b>	Life Cycle Cost	<b>BSM</b>	Building Stock Model
<b>LPG</b>	Liquid Petroleum Gas	<b>CE</b>	Circular Economy
<b>ME</b>	Marine Ecotoxicity	<b>CC</b>	Climate Change
<b>MEU</b>	Marine Eutrophication	<b>COP</b>	Coefficient of Performance
<b>MD</b>	Metal Depletion	<b>BEIS</b>	Department for Business, Energy & Industrial Strategy
<b>NIC</b>	National Infrastructure Commission	<b>DHW</b>	Domestic Hot Water
<b>NLT</b>	National Land Transformation	<b>EE</b>	Energy Efficiency Improvement
<b>OD</b>	Ozone Depletion	<b>EPC</b>	Energy Performance Certificate
<b>PMF</b>	Particulate Matter Formation	<b>ESOM</b>	Energy Systems Optimisation Modelling
<b>POF</b>	Photochemical Oxidant Formation	<b>FD</b>	Fossil Depletion
<b>RHI</b>	Renewable Heat Incentive	<b>FE</b>	Freshwater Ecotoxicity
<b>RE</b>	Resource Efficiency	<b>FEU</b>	Freshwater Eutrophication
<b>SPF</b>	Seasonal Performance Factor	<b>GHG</b>	Green House Gas
<b>SAP</b>	Standard Assessment Procedure	<b>HES</b>	Home Energy Scotland
<b>TA</b>	Terrestrial Acidification	<b>HT</b>	Human Toxicity
<b>ULO</b>	Urban Land Occupation	<b>TE</b>	Terrestrial Ecotoxicity
<b>WD</b>	Water Depletion	<b>TES</b>	Thermal Energy Storage

## Appendix A. Energy System Optimisation Model (ESOM) Calculations

Fabric heat loss is calculated as in the following equation:

$$L_F = \sum (A \times U) \quad (\text{A1})$$

where  $L_F$  is fabric heat loss (W/K),  $A$  is the area of component ( $\text{m}^2$ ) and  $U$  is the thermal transmittance of the component ( $\text{W}/\text{m}^2\text{K}$ ). Thermal bridges are calculated as in the following equation:

$$L_{TB} = \gamma \times A_{exp} \quad (\text{A2})$$

where  $L_{TB}$  is losses from thermal bridging (W/K),  $A_{exp}$  is the total area of exposed surfaces to the external environment and  $\gamma$  is the thermal bridging factor ( $\text{W}/\text{m}^2\text{K}$ ). Ventilation heat loss is calculated as in the following equation:

$$L_V = 0.33 \times n \times V \quad (\text{A3})$$

where  $L_V$  is ventilation heat loss (W/K),  $n$  is air change rate (ach) and  $V$  is the volume of heated space ( $\text{m}^3$ ). Total heat loss is calculated as in the following equation:

$$\sum L_{\text{Total}} = (L_F + L_{TB} + L_V) \times T_h - T_e \quad (\text{A4})$$

where  $L_{\text{Total}}$  is total heat loss (W),  $T_h$  is heating setpoint temperature,  $T_e$  is external temperature. Solar gains are calculated as in the following equation:

$$G_S = 0.9 \times A_w \times S \times g \times FF \times Z \quad (\text{A5})$$

where 0.9 represents typical average transmittance,  $A_w$  is the window area ( $\text{m}^2$ ),  $S$  is the solar flux ( $\text{W}/\text{m}^2$ ),  $g$  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:

$$G_I = A \times f \quad (\text{A6})$$

where  $A$  is the gross floor area ( $\text{m}^2$ ) and  $f$  is the internal gain factor ( $\text{W}/\text{m}^2$ ). Total gains are calculated as in the following equation:

$$\sum G_{Total} = G_S + G_I \quad (\text{A7})$$

The temperature reduction from setpoint temperature depends on the thermal properties of building materials used in the dwelling calculated as in the following equations:

$$HLP = \frac{\sum L_{Total}}{AGF} \quad (\text{A8})$$

$$TMP = \frac{\sum C \times A}{AGF} \quad (\text{A9})$$

$$Tau = TMP / (3.6 \times HLP) \quad (\text{A10})$$

$$a = 1 + Tau / 15 \quad (\text{A11})$$

$$T_c = 4 + 0.25 \times Tau \quad (\text{A12})$$

$$\gamma = \sum G_{Total} / (\sum L_{Total} \times (T_h - T_e)) \quad (\text{A13})$$

$$\begin{aligned} \text{if } \gamma > 0 \text{ and } \gamma \neq 1: & \quad \eta = \frac{1-\gamma^a}{1-\gamma^{a+1}} \\ \text{if } \gamma = 1: & \quad \eta = \frac{a}{a+1} \\ \text{if } \gamma \leq 0: & \quad \eta = 1 \end{aligned} \quad (\text{A14})$$

$$T_{sc} = (1 - R) \times (T_h - 2) + R \times (T_e + \eta \times G_{Total} / L_{Total}) \quad (\text{A15})$$

$$u = 0.5 \times (T_h - T_{sc}) / T_c \quad (\text{A16})$$

where  $HLP$  is the heat loss parameter ( $\text{W}/\text{m}^2\text{K}$ ),  $L_{Total}$  is total heat losses ( $\text{W}/\text{m}^2\text{K}$ ),  $AGF$  is the gross floor area of the building ( $\text{m}^2$ ),  $TMP$  is the thermal mass parameter ( $\text{kJ}/\text{m}^2\text{K}$ ),  $C$  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,  $\gamma$  is a constant,  $G_{Total}$  is total gains,  $L_{Total}$  is total losses,  $T_h$  is heating setpoint temperature,  $T_e$  is external temperature,  $\eta$  is utilisation factor,  $T_{sc}$  is internal temperature without heating,  $R$  is the responsiveness of the heating system,  $u$  is temperature reduction.

## Appendix B. Fuel Prices and Tariff Specifications

**Table A1.** Electricity and gas tariffs, and distribution of peak hours during the day [36–38].

Tariff	Peak Time Price (p)	Off-Peak Time Price (p)	Standing Charge (p)	Peak Hours
Standard		16.5	23.8	
Economy 7	20.8	9.0	23.9	00:00–07:00
Comfy Heat	15.7	8.6	20.3	02:00–06:00, 13:00–15:00, 20:00–22:00
Economy 12	20.7	8.6	18.0	00:00–08:00, 14:00–16:00, 22:00–00:00
Economy 20	16.3	11.4	46.9	00:00–13:00, 15:00–17:00, 19:00–00:00
Gas		3.2	23.0	



Figure A1. Fuel prices for baseline and future scenarios [55–58].

### Appendix C. Construction Elements of the Building Stock and Efficiency Improvement Costs by House Archetype

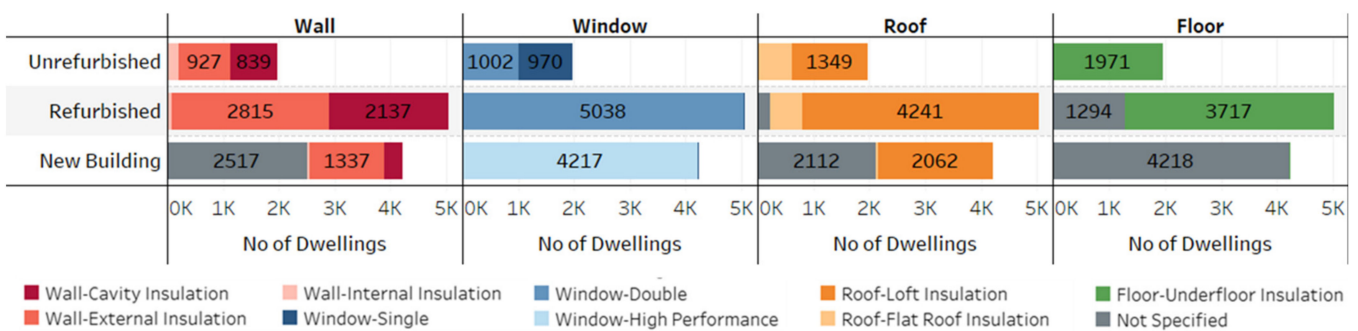


Figure A2. Types and specifications of construction elements (wall, window, roof, floor) in house archetypes and number of houses required energy efficiency requirement.

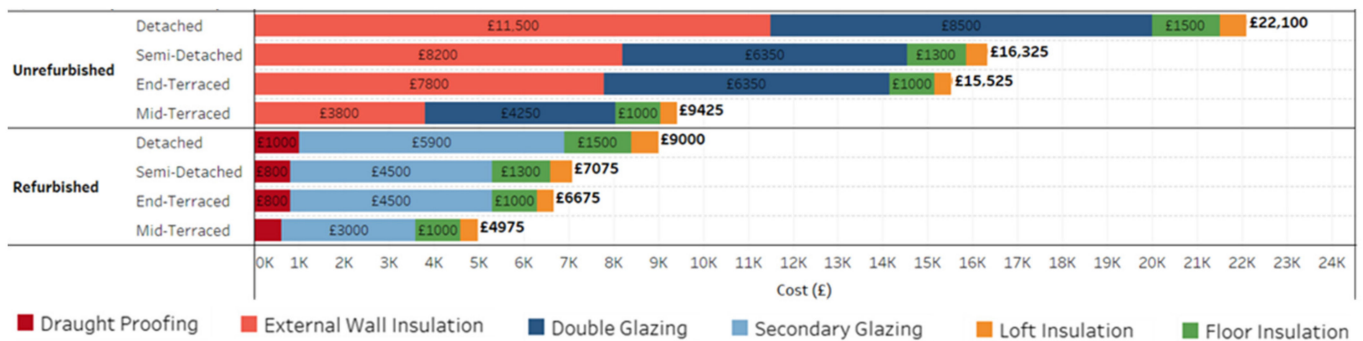


Figure A3. Breakdown of EEI costs by house archetypes and specifications.

### Appendix D. EPC Ratings and Floor Area of House Archetypes

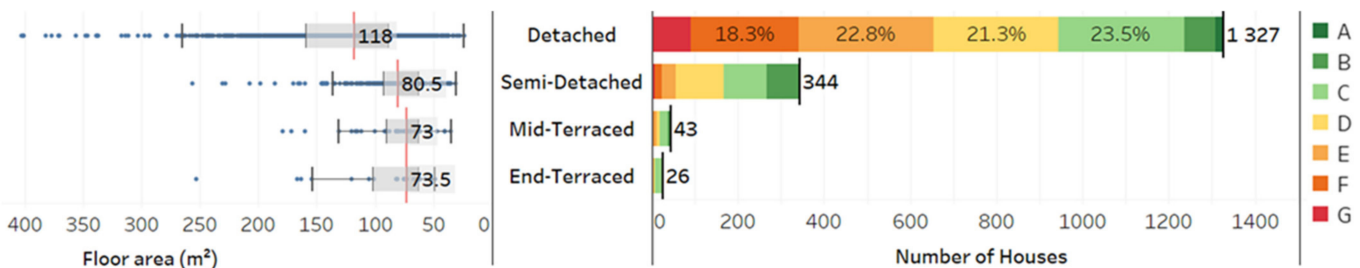


Figure A4. EPC ratings (right) and gross floor area (left) of house archetypes.

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