Techno-Economic Optimisation of Low-Carbon Domestic Energy Technologies and Systems

by

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering

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Michael Ryland, June 2023

Declaration

This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree.

Published Work Arising from Thesis

Work presented in this thesis is based on the previously presented peer reviewed publications:

M. Ryland and W. He, "Heating economics evaluated against emissions: an analysis of low-carbon heating systems with spatiotemporal and dwelling variations" in *Energy and Buildings*, vol. 277, 2022.

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Where chapters contain previously submitted work it is highlighted at the start of the relevant chapter.

Abstract

With increasing global temperatures and to achieve net zero targets', consumers will have to decarbonise their energy demands. A third of emissions come from these consumer heating, transportation, household, and cooking demands. It is critical to understand the interactions between demands, technologies, and tariffs from the consumer's perspective to identify their optimum solution and what technologies to purchase. However, current research focuses only on specific demands, technologies, and tariffs. The work presented in this thesis analyses the costs and emissions of these interactions. A novel holistic framework is created which mathematically simulates all consumer demands.

An initial investigation looks at how the spatiotemporal and UK dwelling variations alter the position of heating systems. For average demand dwellings across the technology's lifetime, air source heat pumps are the most viable technology, however in lower demand dwellings or when considering shorter payback periods direct electrical heating is preferred. This potential high preference from consumers for direct electrical heating is not realised in current research and would have a significant impact on national electricity demands.

In addition, when considering holistically all consumer demands, the sensitivity of technology economic viability is shown from different tariff rates pre and post energy crisis and using different tariff structures, finding a minimum required difference between peak and off-peak rates for energy storage to payback of 6, 10, and 24p/kWh from thermal energy storage, vehicle to home, and battery energy storage respectively. Thermal storage parameters were then analysed to find that sensible heat storage couples best with direct electrical heating with high energy storage potential whereas heat pumps integrate well with latent heat storage if the capital cost can remain low.

These new insights are critical to the field, to ensure incentives and tariff structures are tailored in the right way to promote the uptake of low-carbon technologies.

Abbreviations

ASHP	Air Source Heat Pump
BES	Battery Energy Storage
CapEx	Capital Expenditure
COP	Coefficient of Performance
DEH	Direct Electrical Heating
EV	Electric Vehicle
FC	Fuel Cell
GSHP	Ground Source Heat Pump
H_2	Hydrogen
LHS	Latent Heat Storage
NPC	Net Present Cost
OpEx	Operating Expenditure
PV	Photovoltaic
PVT	Photovoltaic/Thermal
SHS	Sensible Heat Storage
TCS	Thermo-Chemical Storage
TES	Thermal Energy Storage
V2H	Vehicle to Home
VToU	Variable Time of Use

Symbols

A_d	Dwelling total floor area (m^2)
A_n	North facing window constant
A_{pv}	PV or PVT area (m^2)
A_s	South facing window constant
A_{st}	Solar thermal collector area (m^2)
B_n	North facing window constant
B_s	South facing window constant
δ_m	Monthly solar declination (°)
C_d	Dwelling heat capacity (kWh/K)
C_n	North facing window constant
C_s	South facing window constant
E_{pv}^i	PV or PVT electrical energy generation (kW)
$f_{\varphi\delta}^i$	Solar height factor
f_{pitch}	Window pitch factor
G_m	Metabolic gains (kW)
$G_{s,n}^i$	Gains from north facing windows (kW)
$G_{s,s}^i$	Gains from south facing windows (kW)
h_{tes}	TES cylinder height (m)
$h_{t,c}^i$	Height ratio of thermocline
$I_{i,n}^i$	Incident solar irradiance for north facing windows (W/m^2)
$I_{i,roof}^i$	Incident solar irradiance on the dwelling roof (W/m^2)
$I_{i,s}^i$	Incident solar irradiance for south facing windows (W/m^2)
$I_{h,n}^i$	Horizontal solar irradiance for north facing windows (W/m^2)

$I_{h,s}^{i}$	Horizontal solar irradiance for south facing windows (W/m^2)
φ	Dwelling latitude (°)
η_{pv}^{i}	PV or PVT electrical efficiency
N	Number of occupants
$P_{hp,el}$	Heat pump electrical power (kW)
$P_{hp,th}$	Heat pump thermal power (kW)
Q_{dhw}^{i}	Domestic hot water demand (kWh)
Q_{hl}^{i}	Dwelling heat loss (kWh)
Q_{sh}^{i}	Space heating demand (kWh)
Q_{sh}	Yearly space heating demand (kWh)
Q_{st}^{i}	Solar thermal collector energy generation (kWh)
Q_{tes}^{i}	TES thermal energy capacity (kWh)
$Q_{tes,low}^{i}$	Heat loss from lower part of TES (kWh)
$Q_{tes,up}^{i}$	Heat loss from upper part of TES (kWh)
r	TES cylinder radius (m)
r_d	Discount rate
$R_{dhw,h}^{i}$	Domestic hot water hourly ratio
$R_{dhw,m}$	Domestic hot water monthly factor
$R_{h-p,n}^{i}$	Horizontal to pitched ratio for north facing windows
$R_{h-p,s}^{i}$	Horizontal to pitched ratio for south facing windows
t	Time interval for NPC calculations
$T_{cw,m}$	Monthly cold-water temperature (°C)
T_g	Ground temperature at 100m depth (°C)
T_{hw}	Hot water temperature (°C)

T_d	Desired indoor temperature (°C)
T_{in}^i	Inside temperature (°C)
T_{out}^i	Outside temperature (°C)
T_{st}^i	Solar thermal collector temperature (°C)
$T_{tes,low}^i$	Temperature of lower part of TES (°C)
$T_{tes,up}^i$	Temperature of upper part of TES (°C)
U_d	Dwelling U value, thermal transmittance (W/m^{2}K)
U_{tes}	TES U value (W/m^{2}K)
V_b	Daily volume of domestic hot water for baths (L)
V_o	Daily other volume of domestic hot water (L)
V_s	Daily volume of domestic hot water for showers (L)
V_t	Daily total domestic hot water volume (L)
V_{tes}	Volume of TES being simulated (m^3)

Chapter 1 Introduction

1.1 Background

Global temperatures have increased to over 1.1°C above the average from pre-industrial period, which leads to climate change, this warming is due to human activity mainly from burning of fossil fuels releasing greenhouse gases into the atmosphere [1]. Climate change and air pollution, which is also from the combustion of fossil fuels, together are estimated to kill 7 million people each year globally, which is a tenth of all deaths [2]. Many countries are committing to net zero emissions to help tackle climate change, despite global emissions still increasing, the majority targeting net zero by 2050, with immediate action needed to be taken now [3].

The majority of the carbon reduction will come from decarbonising nearly all energy sectors, as there is a limited amount that emissions that can be extracted from the atmosphere naturally and by engineered methods [4]. Historically the building sector and the transport sector have been some of the highest emitting sectors, where emissions are mainly from the burning of fossil fuels to meet the energy demands. With the power sector making strong improvements in decarbonisation, primarily with the deployment of variable renewable energy, the building and transport sector are set to being key areas that need development. When including direct and indirect emissions from heating, electricity, and cooking the building sector accounts for 28% of global emissions, followed closely by the transport sector with 27% [5]. Approximately 60% of emissions from both sectors are from consumer energy demands, making consumer energy use from residential buildings and cars around 33% of global emissions.

From an energy perspective the scale of decarbonising heating and transportation in Great Britain can be seen from the data Figure 1-1. The amount of energy required for transportation is typically double the electrical energy demand. Due to 85% of UK homes relying on gas boilers, the national gas demand is closely linked to domestic heating demand, minus the gas used by gas power stations which fluctuates around 500GWh/day [6], [7]. The remaining gas demand for heating varies significantly across the years proportional to ambient temperature, with daily heating demands in Winter three times that of electrical demands. Emphasising that to decarbonise the heating and transport sectors requires significantly large quantities of new low-carbon energy in the UK.

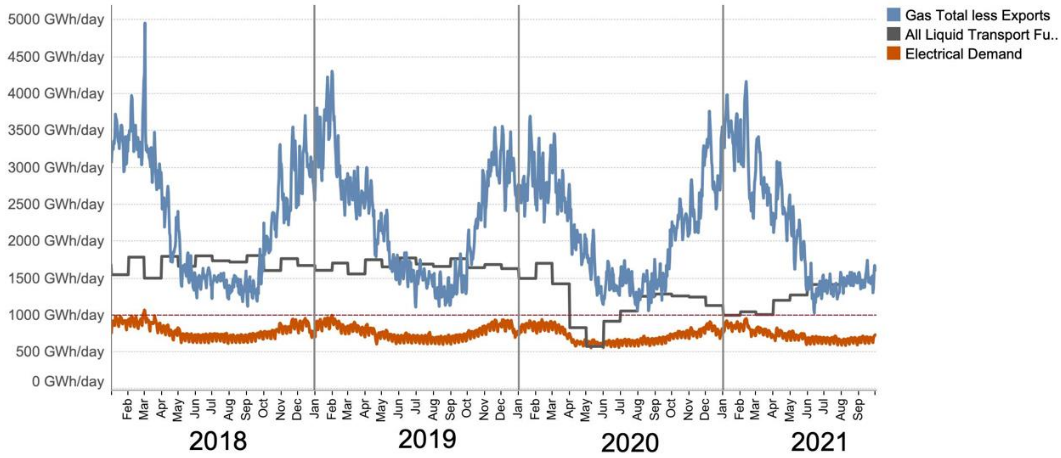

Figure 1-1 Multi-vector energy diagram for Great Britain [7].

The challenge of decarbonising heating and transport is felt globally, although for heating more so in colder climates where per capita heating demands increase. Such countries use various ratios of different heating technologies, from Norway with over 60% electrified, to Canada and Sweden with 50% district heating, which either use low-caron heating or can switched across the low-carbon heating sources away from fossil fuels at relative ease compared to on an individual household basis. However, most countries globally are still heavily reliant on fossil fuels for heating, where the UK has little district heating infrastructure [8]. The path to decarbonise UK heating is less clear than for other energy sectors. Although the UK Government is aiming for 600,000 Air Source Heat Pump (ASHP) installations a year by 2028, this rate will take many decades to decarbonise the 25 million dwellings, it is also keeping its options open by trialling hydrogen for heating which would be even later to come to the market on mass [9]. Whereas in consumer transport the adoption of Electric Vehicles (EV) is becoming more of an accepted route for passenger vehicles although there is some limited competition from hydrogen (H_2) cars, any combination of EV or H_2 vehicles could be used to meet the UK Governments technology agnostic strategy to ban to any new cars with any tailpipe emissions from 2035 [10]. Although it is likely that EV will be dominant there may still be the option of hydrogen cars so is included in this technology comparison study.

Decarbonising heat faces challenges at multiple levels, from higher regional levels to the consumer level. Regionally there is no clear pathway to decarbonise heat demand that is currently reliant on fossil fuels either by using electrification or low-carbon gas. Both of these face great challenges due to requirements of a significant upgrade or rebuilding infrastructure, and more importantly the uncertain financial return of the required billions of pounds of investments, which all must be implemented alongside the decarbonisation of the transportation and the adoption of higher amounts of variable renewable energy [11]–[13]. Similarly, from the end users' perspective, which this study is focused on, consumers face challenges from the lack of knowledge and experience of low-carbon heating technologies and the immaturity of the low-carbon heating market in many countries. In order to convince consumers to switch over from fossil fuels, low-carbon heating and transport technologies needs to be economically competitive with incumbent fossil fuel burning boilers (e.g. gas) and cars [14]. Achieving this cost constraint will particularly influence low-income households, where fuel poverty was already of concern for between 50-125 million people across Europe before the energy crisis and there is limited capital available to purchase the high cost heat pumps and EV [15].

The consumer's perspective is often overlooked in academic research with more focus being put onto the overall regional system analysis. Yet the consumer's perspective is critical in decarbonisation of heat, as consumers will be the ones that are selecting and purchasing the products. Even if at a national and network level one low-carbon heating technology may be preferential, if it is not the most cost-effective solution for the consumer this will not be implemented by the majority, in addition to consideration of if the technology is an option for the consumer such as access to connecting to district heating network or space for a heat pump. Low-carbon solutions generally have higher capital expenditure (CapEx) than fossil fuel boilers, alongside higher fuel costs than fossil fuels. In the US, electricity is in the region of five times more expensive than natural gas [16], [17]; and low-carbon gas like H_2 produced in steam reforming or electrolysis is also more expensive than gas, before taking into account any additional infrastructure construction cost [11]. Thus, simply replacing fossil fuel boilers with alternative low-carbon heating solutions could lead to significant Operational Expenditure (OpEx) increases and poses a huge challenge for consumer decarbonisation [18].

Combining this uncertainty for consumers to decarbonise their energy demands alongside the potential cost increases from low-carbon technologies creates the motivation for this research. Which is to identify the potential technology combinations and tariffs available to consumers and to techno-economically analyses the systems holistically to find the lowest lifetime cost optimum combination for consumers depending on their specific variables of the application.

1.2 Contribution and Objectives

Decarbonising consumer energy faces many challenges and for any technology to be taken up at scale it needs to be acceptable in all aspects, not least economically for consumers. The research problem is formulated by bridging the following areas identified in the literature review with potential for further development and understanding. The literature on low-carbon heating does not compare the full spectrum of technologies and tariff options and has little consideration for how the position of technologies differ with spatiotemporal and dwelling variations. The studies which include all consumer demands focus on operational optimisation of a pre-defined set of technologies and a single tariff, neglecting if these technologies and this tariff structure is the right one and if the technologies are economically and environmentally viable. The significant increase in energy costs from the energy crisis are also yet to be analysed in detail to demonstrate how this alters low-carbon technologies with the modern array of tariffs. Development is underway on many technologies, in particular for Thermal Energy Storage (TES) materials, but it is unclear what parameters are actually viable to TES system economic viability and how this differs depending on the heater it is coupled with and the cost of energy.

This study collates these gaps in the literature to raise the following research questions:

1. How does the economically optimum heating system alter with changes in dwelling demands and spatiotemporal variations?
2. Determine tariff structure changes required to incentives the use of energy storage for consumers?
3. Which TES parameters are most valuable to be developed to improve their viability?

In order to answer the research questions, the following objectives are set for the study:

1. Build a novel comprehensive mathematical framework to simulate consumer demands across the range of low-carbon technologies with versatility to adjust dwelling and spatiotemporal parameters. That optimises results by holistically simulating all combinations of variables to record the lowest lifetime cost solution.
2. Simulate the economic viability of the range of technologies from different types of tariff structures from pre and post energy crisis.

3. Analyse the range of low-carbon systems and their parameters environmental and economic performance to identify what technologies are most attractive, and what changes in technology parameters can improve their viability.

The insights and choices identified in this study likely will be of interest to homeowners, manufacturers of heating systems, network operators, and policymakers in energy sectors.

1.3 Thesis Outline

The thesis is structured as follows:

Chapter 2 completes a comprehensive literature review of the consumer demands of space heating, domestic hot water, domestic baseload, cooking, and transportation. It goes on to examine each of the technologies and methods which can be used to meet these demands, as well as thoroughly reviewing current studies analysing low-carbon consumer technologies.

Chapter 3 develops the Methodology for a novel framework which will be used throughout the thesis. Explaining in detail how the heating demands are simulated for any dwelling and how all the demands are brought together to create a holistic mathematical model. An explanation is given into what parameters are required for the model and what the key outputs are. The case study inputs that are used in the study are explained and used as verification of the model.

Chapter 4 analyses simulation results of the range of heating technologies and their economic and environmental performance. With focus on analysing how the changes to the dwelling and spatiotemporal parameters alters the position of different technologies to answer the first research question.

Chapter 5 brings together all consumer demands combining heating, baseload, cooking, and transport demands and technologies to complete the holistic model. It analyses combined systems, with additional ancillary generation and storage technologies of Battery Energy Storage (BES) and Vehicle to Home (V2H) functionality. Evaluation is complete on how the position of energy storage technologies changes with increased energy costs and what tariff structures and parameters are beneficial for the promotion of low-carbon technologies to address the second research question.

Chapter 6 answers the third research question by thoroughly reviewing TES parameters. Initially by analysing how TES material and system level performance changes when coupled with different low-carbon heating technologies of either Direct Electrical Heating (DEH) and ASHP. It then goes on to complete simulations using the framework to allow analysis of which TES parameters, identifying the most valuable to improve the lifetime cost for consumers and therefore improve their uptake.

Finally, Chapter 7 brings all the work together to conclude the key points that have been learnt from the study and discusses potential future work to further develop this study.

Chapter 2 Overview of Consumer Demands and Technology

As introduced demands from consumers need to be decarbonised, which is currently mainly down to the responsibility of individual consumers with no incentive to do so other than to reduce their own emissions. Demands that will be analysed in this study include heating, domestic baseload, cooking, and personal transportation demands. Although restrictions will come into force to prevent new high emitting technologies (boilers, petrol, and diesel cars) there is no single technology to replace current ones for each demand. This is especially the case for heating demands which face a large range of technology options, where different dwelling spatiotemporal characteristics may lend themselves well to different technologies.

Alongside the need to decarbonise these demands, the reduction in demand from efficiency increases is partially offset by the demands increasing from a combination of increasing populations and increasing energy demand per capita by pursuing, an increased quality of life from larger homes, higher thermostat set points, and more travelling [19], [20]. All of these factors increase the challenge of decarbonisation, therefore the combination of these factors presents significant extra pressure on decarbonisation.

2.1 Heating

The range of heating technologies are introduced in this section, which need to be able to satisfy the heating demands of dwellings. The key demands for domestic heating come from space heating and domestic hot water demands. Average UK domestic hot water annual demand is 1950kWh, where the demands stay fairly constant over the year and are related to the quantity of people in the dwelling, with slight variations down to changing cold water inlet temperature and changes in heating technologies efficiencies with changing temperatures [14]. However, space heating demands vary significantly across the year as shown by Figure 2-1 and averages 11050kWh per year for UK homes [14]. With variations occurring from changing ambient temperatures, leading to increased heating demands with colder ambient temperatures at cooler locations and times. Additionally dwelling size and thermal efficiency have a large effect on the heating demand. Combining the parameters can lead to a wide variation in space heating demands for different dwellings, locations, and times.

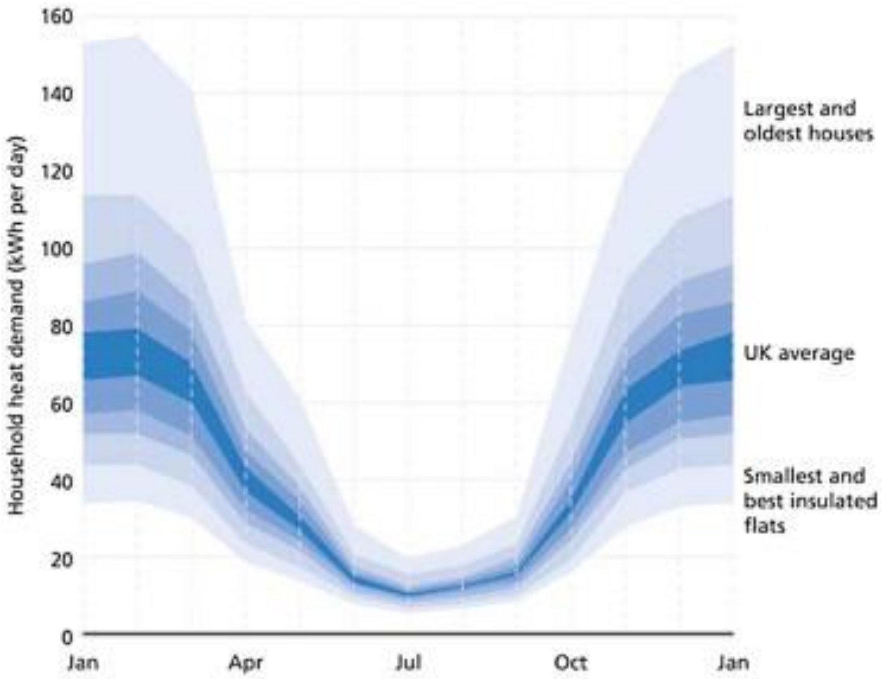

Figure 2-1 Annual heat demands across the UK for different households [21]

The gas boiler is used as the baseline in this study as it is used by 85% of UK dwellings, due to the lower cost of gas to electricity and reasonable installation costs of boilers [6]. A key competing technology to the gas boiler, is the electrification of heating, which can reduce emissions relative to natural gas depending on the emissions of the electricity production and the efficiency of the heating technology. DEH is the simplest form, which uses resistance heating and is commonly already used in smaller dwellings in the Europe [22]. DEH can offer comparable emissions to gas with current from many countries electrical grids but will reduce as grid emissions come down. The main challenge for DEH is the higher OpEx due to only being marginally more efficient than boilers but with much higher fuel prices [23].

More sophisticated, and investment heavy, electrified heating options are heat pumps, common options being ASHP and potentially Ground Source Heat Pumps (GSHP) where more external space is available. Both convert low grade heat from an ambient source and upgrade it to useful temperature using electricity. Heat pumps operate at higher efficiencies than DEH, with the efficiencies measured by the Coefficient of Performance (COP). COP is improved as the temperature difference between the heat source and heat sink is reduced, meaning that ASHP suffer from lowest COP at times when heating demand is highest, at cold ambient conditions. GSHP on the other hand is less susceptible to this as the ground temperature can remain more consistent across the year, especially with the use of deeper vertical heat exchangers [24].

In combination with the prime heaters of DEH or heat pumps, solar technologies can be used to help reduce costs and emissions. Investing in solar photovoltaic (PV) panels can create a source of low-carbon electricity with no running cost that can be used by electrified heating, heat pumps or DEH, to reduce costs and emissions. Solar thermal collectors on the other hand directly generate thermal energy, but in heating seasons will commonly still need to be coupled with other forms of heating due to their inability to provide sufficient heating all year around for the majority of dwellings [25]. Photovoltaic/thermal (PVT) collectors take these principles a step further and offer the ability to combine PV panels with solar collectors to maximise efficiencies, although at a further increased cost [26].

H_2 for heating has recently been considered more seriously as a competitor to heat pumps for low-carbon heating [9], [27], [28]. H_2 could be used in boilers, in a similar method to natural gas boilers, or with Fuel Cells (FC) generating thermal and electrical energy simultaneously. Although the current main method of manufacturing H_2 is Grey H_2, which converts hydrocarbon fuels into H_2 with the by-product of CO_2, lower emissions methods would be required to ensure H_2 for heating reduces emissions over gas boilers [29]. Blue H_2 can go one step further and uses carbon capture and storage to reduce emissions from H_2 production, crucially though, this is currently not commercially available and thought to have an upper carbon capture efficiency of 90% therefore Blue H_2 is mainly seen as an intermediate step for H_2 while use of H_2 is increased [30]. The end goal for H_2 production is H_2 Electrolysis from water and electricity, which can become low-carbon when using a high percentage of renewable electricity [11].

To allow any technology which does not have sufficient heating power and flexibility to meet instantaneous heating demands, in particular domestic hot water demands which can have higher power demands, a level of energy storage is required. TES is therefore commonly used alongside DEH or heat pumps, as they have lower thermal power than combination gas boilers. Alongside meeting the power restrictions of some heaters, TES aids in meeting a misalignment between times of low-cost electricity rates, which is typically in the night, and times of heating demands. The mismatch of supply and demand is further exacerbated with variable renewable energy, or with local solar thermal generation where TES is required [31].

In many estimated future national and international scenarios for decarbonising heating a mixture of technologies are expected to be deployed depending on the dwelling's suitability for different heating technologies [27], [28], [32]. When considering low-carbon heating technologies they offer little benefits over gas boilers other than emission reduction potential, but each have their own advantages and disadvantages against each other, resulting in no clear next best option after natural gas. Consumer surveys highlight the aspects of low-carbon heating that are preventing adoption of these technologies. Although there are many consumer concerns from the questionnaires such as space, noise, aesthetics, and confidence in the heaters to keep the dwelling warm, the high CapEx and OpEx are consistently the largest reason for not adopting low-carbon heating [33], [34]. However, consumers are very much aware of their lack of knowledge around low-carbon heating systems [35]. From the literature reviewed, there are many comparisons for low-carbon heating technologies for domestic applications, many of which compare at a high level and do not give a comparison for the consumer on overall costs for different technologies and so do not indicate which technologies will actually likely be taken up [11]–[13], [36]–[39]. Table 2-1 shows the studies that have been reviewed which analyse low-carbon heating technologies at the consumer level for low temperature heating, most of which are for domestic dwellings other than Wang et al. that use the case study of a sports centre and Jenkins et al. that analyse an office [26], [40]. Current studies fall short on being able to offer an economic and environmental analysis for the full range of low-carbon heating technology combinations and lack the ability to show how this is affected by dwelling and spatiotemporal factors. There is no current combined optimisation of the different combinations of prime heaters, ancillary solar technologies, TES sizes and tariffs together, without this full consideration of all parameters the true preferential low-carbon heating systems is not known.

Of all the studies reviewed, the only one which offers a framework that is aimed to be easily tailored to different dwelling and occupant requirements is by Renaldi et al., using occupancy profile and current annual heat demand as key personalised inputs, although it only compares ASHP to gas boilers, with a limited range of TES sizes and only with traditional tariffs [41]. Other studies do consider a range of dwelling efficiency case studies, the broadest being from Vatougiou et al. who consider seven different dwelling efficiencies across two types of owners but only for ASHP against oil boilers and for a single location [42]. This is not easily adopted to other dwellings due to the complexity of data required which is likely beyond what most residents can quickly obtain.

			Modelling		Economics and Environment				Technologies										
									Electrified heating				H_2 heating		Solar resource				
Study Reference	Tailorable / Cases	Num of Locations	Simulation resolution	Analysis duration	Emissions	OpEx	CapEx	Fossil fuel baseline	DEH	ASHP	GSHP	Multiple tariffs	H_2 boiler	FC / CHP	PVT	ST	PV	Biomass	TES options
[25]	3	8	1 hour	Avg day/month												✓			✓
[43]	3	3	1 hour	1year	✓	✓	✓	✓		✓		✓					✓		
[44]	3	1	15 min	1year		✓	✓			✓		✓					✓		✓
[45]	1	8	1 hour	1year	✓	✓	✓	✓	✓	✓		✓				✓			
[42]	14	1	10 min	Season		✓		✓		✓		✓							✓
[46]	1	1	1 hour	Season		✓		✓		✓		✓							
[47]	4	1	1 hour	Avg day/month	✓	✓	✓	✓	✓	✓				✓			✓		✓
[41]	Yes	1	1 hour	1year	✓	✓	✓	✓		✓		✓							✓
[14]	1	1	1 year	1year	✓	✓	✓	✓	✓	✓	✓								
[48]	1	1	1 hour	1year		✓	✓									✓			✓
[26]	1	1	1 hour	1year	✓	✓	✓	✓						✓	✓	✓	✓		✓
[49]	1	1	30 min	Avg day/month	✓	✓	✓	✓							✓		✓		
[50]	1	1	1 year	1year	✓	✓	✓	✓		✓			✓	✓					
[51]	3	1	1 hour	1year	✓			✓	✓					✓					
[40]	2	1	1 hour	1year	✓	✓		✓		✓									
[52]	1	1	1 hour	1year	✓	✓		✓			✓								
[53]	1	1	1 min	1year	✓	✓		✓	✓	✓									
[54]	5	3	1 hour	1year	✓	✓		✓		✓									✓
[55]	3	1	5 min	Avg day/season	✓	✓	✓	✓	✓	✓				✓					

Table 2-1 Heating analysis studies for consumers reviewed in the literature.

Many studies are seen to focus on ASHP and neglect GSHP, even though this is found to be one of the lowest OpEx heating technologies, from the high level analysis by Barnes and Bhagavathy [14] and from the detail analysis focused on GSHP by Jenkins et al. [52]. There are many studies which consider a single solar technology working alongside ASHP and demonstrate their potential as combined systems, such as by Pena-Belo et al who couple PV with ASHP [44]. Yet there are no studies found that combine either GSHP with solar technologies or show the trade-offs of different solar technologies when integrated with heat pumps, despite Wang et al. demonstrating different solar technologies have distinct economic and environmental strengths depending on the demands of the application [26].

With many studies considering case studies at a single location, a key aspect these do not take into consideration is the effect of geographical climatic variations on the demand profile and feasibility of each technology. Ma et al. consider this when analysing solar thermal feasibility across the UK, as do Treichel and Cruickshank when they compare ASHP with solar thermal across North America, both finding variation in effectiveness of technologies across regions, justifying the importance of spatiotemporal considerations [25], [45].

Reviewing the 15 studies in Table 2-1 that considered electrification of heating, only six identified the use of electricity tariffs other than the flat rate tariff and most of these include only traditional economy 7 or 10 tariffs. Yet when multiple tariffs are considered the flat tariff is normally one of the most expensive, as found by Eguiarte et al. in their analysis aimed at ASHP cost optimisation with different tariffs [46]. In addition to the use of multiple electricity tariffs the use of TES is critical to maximise off-peak electricity for the consumer. Although studies find that larger capacity TES reduces OpEx, Harb et al. find that the largest size TES may not be the optimum solution for the consumer when including TES CapEx [47].

With the range of potential heating and thermal storage technology options and sizes that can be integrated together alongside different tariff structures, the full insight of low-carbon heating systems is yet to be realised in the literature. This prevents consumers, policy makers, and network managers from understanding which technologies are most cost effective and therefore most likely to be taken up, and how they could compare against incumbent gas boilers. There is crucially a lack of studies demonstrating how spatiotemporal and dwelling changes together alter the position of the optimum heating systems.

This study's first objective focuses on addressing the challenges of clarifying the performance of low carbon heating technologies for a dwelling depending on its specific heating demands, characteristics, and spatiotemporal conditions from the consumers' perspective. A new framework created allows any user, with a small amount of input data, to see the economic and environmental costs of the range of heating systems for a dwelling. This involves complex interactions between the range of heating technologies considered in the framework, along with the sources of their fuel and the use of TES, to meet the specific dwelling's space and domestic hot water heating demands. The combination of different fuel sources is used for electrified heating options to determine if the optimum lifetime solution is when coupled with PV, solar thermal collectors, or PVT or to rely solely on electricity from the grid. H_2 heating technologies also consider use with the range of production methods as this alters the economic and environmental case for the H_2 boilers and FC. Collated together with a range of electricity tariffs, TES sizes and solar technology sizes the framework results in hundreds of combinations for heating systems, which are optimised to determine the lowest lifetime cost solution. The effect of a dwelling and spatiotemporal variations on technologies' economic and environmental performance is reviewed in case studies across the UK for average, high and low demand dwellings. The versatile framework created is applicable to other regions internationally.

2.2 Domestic Baseload

The terminology domestic electrical baseload demands, hereafter known as baseload, will be defined in this study as the electrical demands used by dwellings when excluding any electrified heating or EV charging loads. This domestic baseload demand has been gradually reducing with improvements in appliance efficiency and for an average UK home is now 3,500 kWh/year, unlike many of the other demands [56]. For cooler climates this demand is significantly smaller than heating demands discussed which totalled 13,000kWh/year in the UK, but remains significant enough that it should not be neglected [14]. This baseload demand is from electricity use by lighting, kettles, white goods such as fridge, freezers, washing machines, and dishwashers and other domestic products such as audio-visual devices most prominently televisions [57]. Domestic baseload often includes any electrical devices which are used for cooking, such as ovens, hobs (stoves), microwaves, and toasters, however in this study the cooking devices which can potentially use a combustion fuel (i.e., gas or H_2) will be separated out to be considered independently. Leaving microwaves, toasters, and kettles in the domestic baseload category as they tend to be powered by electricity.

Although the dominant source of energy for the domestic baseload is electricity via the national grid network, which will reduce in emissions alongside decarbonising the electrical network, which consumers have little control over, the addition of other technologies and the time of use of demands does affect the consumer. With the potential inclusion of home generated electricity using PV or PVT this can reduce consumer emissions and OpEx from their baseload demands. Additionally in analysing PV with electrified heating systems it is important to also consider the baseload as this will have additional electrical demands and alters the consumption and availability of any surplus self-generated electricity and therefore viability of such technologies. Not only does the time of baseload demands alter the effectiveness of the integration with PV, but it can also change the cost to the consumer as tariffs are available which have different rates at different times of the day, meaning if baseload demands can occur at times of off-peak, low cost, electricity this can reduce OpEx for consumers.

2.3 Cooking

As discussed in section 2.2, cooking demands are often captured within the domestic baseload, but for this study the cooking appliances which could use a range of energy sources are considered separately. The appliances considered separately are ovens and hobs (stoves), which currently use either natural gas or electricity, which can be compared in their emissions and OpEx. Looking forward there is also possibility of using H_2 to fuel these cooking demands which alters the economic and environmental position of the demand especially depending the potential source of the H_2 [58].

Although these cooking demands typically only have an annual demand of 500kWh, it can remain important factor due to the potential different energy sources and its time of use [57], [59]. For gas and H_2 the hourly time of use of the demand does not alter the cost or emissions for a consumer, however it can for electrical demands. Cooking demands tend to happen at peak electricity times, partly because they are the reason for the typical daily peak demand in the early evening, and are not easy to shift, therefore they will occur at the highest tariff cost time of day and often the highest electrical emissions time of day [57], [59]–[61]. No studies have been found that compare this range of cooking fuels of electrification, gas, and H_2 using different sources in environmental aspects and economical aspects with different electricity tariffs.

2.4 Transport

Consumer transportation using cars is an energy sector which has historically not been closely linked with buildings, domestic baseload demands, and heating, as the prime sources of energy has come from petrol and diesel which are not typically used in modern buildings. With the decarbonisation of the transport sector this will require a shift away from combustion of fossil fuels and towards electrification or potentially greater use of H_2, sharing energy vectors with the building sector.

The shared use of the same energy vector between consumer transportation and buildings creates more interactions between these sectors. If they both use the same energy sources, then the shared use of the same infrastructure comes with advantages and disadvantages. On the one hand this puts increased reliance on the potential future electrical or H_2 networks which means they must cope with large total demands, but with this comes more utilisation of the infrastructure which can lead to reduced overheads per unit of energy used, benefiting both sectors. Equally this same increased utilisation effect also can occur with any domestic PV which EV owners may consider installing, reducing the payback of any PV system. In the case of electrified transportation alongside electrified heating not only is the time of demand important for locally generated energy, but also for selecting the preferred tariff. As tariffs are emerging to target EV owners with short very low cost off-peak periods this may not be the ideal tariff for other electrified demands [62]. In addition to EV being a competition for electricity use, they also have the potential to be used as a battery storage which will be discussed in section 2.5.

Consideration of different energy sources for transportation and comparison to other demands OpEx and emissions is also important for consumers to priorities where they may want to focus their investment. By including both transportation and the variety of domestic demands consumers can see the associated emissions and potential emissions reduction for each of their demands, helping to priorities where is the most cost-effective technologies and which are likely to have the biggest impact on their carbon footprint. Although studies have compared EV vs H_2 technologies, there is little on the consideration of the different types of H_2 fuels and how these may perform compared to the baseline petrol car or EV coupled with domestic PV [11], [63].

2.5 Energy Storage

As introduced, there is often a mismatch between supply of variable renewable energy and demand from any electrified technologies, to help mitigate this challenge energy storage can be used to charge up during times of off-peak, low emissions electricity, then discharge when there is any electrified demand.

Utilisation of TES needs to be considered alongside many low-carbon heating technologies to resolve the gap in energy supply and demand. TES can therefore reduce the curtailment of either local or grid scale variable renewable energy by storing thermal energy until it is required by the dwelling, with electrified heating or using solar thermal collectors directly to provide thermal energy [31]. This method can also help reduce the OpEx for electrified heating as electricity costs can vary across the day, allowing heating systems with TES to use more lower cost off-peak electricity rates. However, the transition to low-carbon heating technologies and TES has been slow in many regions due to various technical and economic challenges [14]. Both TES and low-carbon heaters face challenges of high investment cost and space constraint challenges in retrofitting [14].

A range of TES technologies exist which can be broken down into three key categories, Sensible Heat Storage (SHS), Latent Heat Storage (LHS) and Thermo-Chemical Storage (TCS). SHS stores energy by raising the temperature of the storage material, this simple mechanism allows for low-cost solutions but comes with lower storage efficiencies as thermal energy is lost to the surroundings during storage. LHS allows increased storage densities over SHS by changing the state of the storage material during charging, commonly by melting a solid, then during discharging removes thermal energy to restore the storage material back to its lower phase. TCS is typically the highest energy densities TES, it relies on a reversible thermo-chemical reaction which can take many forms. Charging separates the reactants, which are then held in different containers and brought back together to react when there is a thermal demand.

Currently, water tanks are the most used domestic TES technology, but water storage suffers from low energy density, so the storage usually only provides domestic hot water that is about 15% of domestic heating demand [14]. The only other TES that has seen reasonable uptake is in lower demand dwellings that have historically been a popular choice for electrical storage heaters which use ceramic materials and so can reach elevated temperatures, although this technology differs to other TES as it is also acts as the radiator [22]. Although cost is not the sole influence on consumer purchasing decisions, low-carbon heating and TES will only achieve a dominant market share if they are affordable to most of the population.

Previous studies of TES technologies typically focus on the material level analysis of the storage materials [64]–[67], which may not create feasible solutions to scale up to commercialisation and does not include economic parameters of investment and operational costs, and associated emissions, for consumers using these TES concepts. Analysis studies of TES alongside low-carbon heating technologies that have been completed typically focuses only on water tanks as TES storage material and give little comparison of TES technologies and parameters other than variation in sizes [25], [41]. Yet new TES designs are emerging and entering the marketplace, alongside the development of new ideas which are at the prototype stage. Emerging TES technologies include the use of higher temperature SHS which are smartly charged at off-peak times using modern tariffs and, have significantly higher storage capacities than the traditional electrical storage heaters [68], [69]. In addition to SHS, LHS technologies have begun commercialisation by storing thermal energy from the phase change of salt hydrates without the need for higher temperatures [70].

More sophisticated forms of energy storage for consumers are also emerging in the form of electrical batteries. Although these are typically higher absolute cost and higher cost per stored unit of energy than TES, they offer other advantages [71]. BES has greater flexibility in meeting other demands than TES, as TES is limited to meeting heating demands only, BES can assist in meeting any electrified demand. BES also offers greater energy density and storage efficiency than most TES [72]. In dwellings with limited space the higher volumetric density of BES becomes more advantageous. BES for domestic applications is considered using dedicated batteries which mount to an internal wall of a dwelling and permanently form part of the dwellings electrical circuit. If the dwelling also has access to an EV, with a two-way charging unit and EV software and hardware, the EV can be used as a BES when it is at the dwelling and plugged in. The EV can use this V2H functionality, allowing it to charge at off-peak times and discharge back to the home to power other electrified devices and reduce import costs and associated emissions at that time.

2.6 Tariffs

Tariff terms used throughout the study are average day rate, which is the average tariff cost across the 24 hours of the day, peak which is a time when the tariff rate is higher than the average day rate, and off-peak which is when the tariff rate is lower than the average day rate. Two traditional tariffs are used, the flat rate tariff where electricity costs the same at all times of the day and an economy 7 tariff, where there are seven off-peak hours in the night. Additionally, two emerging tariffs are considered, a tariff designed for EV charging, with four very low off-peak hours at night, Variable Time of Use (VToU) tariff, which has different prices for each half hour of the day and is released the day ahead, which typically has the lowest average day rate across the 24 hours of the day but very high peak electricity costs in the early evening. Except for the flat tariff, the other tariffs are designed to encourage users to shift their demands away from the typical peak demand times of the day, which fall in the mornings when people wake up and, in the evening, when they get home and start cooking. However, with cooking and often heating, without energy storage this is not easy for consumer to shift their demands to the lower cost times of the day.

Tariffs costs used in this study represent real data from 2020 and 2022 to the consumer from an energy supplier. These costs include energy generation costs and profits, national and local transmission costs, supplier costs and all other costs which make up the end total cost to consumers. The flat rate tariff and the night off-peak tariff are more traditional tariffs, with the flat tariff being the basic rate across the day irrelevant of time of use, and night off-peak tariff which was created to help encourage use of electricity during low demand times from electrical storage heaters [22]. EV tariff uses similar principles but for shorter periods of time targeted to help reduce costs for EV owners while making the most of the typical lowest four hours of demand across the day [73]. The VToU tariff has different costs for each half hour of the day, which is released the day before, the cost variations across the day reflect the difference in market price across the day when estimating the future supply and demands of energy, this tariff can benefit consumers who can be flexible with their energy demands [60].

In the future with potentially more demands directly electrified, this increased electrical demand puts extra strain on the networks which likely would require reinforcement upgrades and pass on the associated extra costs to the consumers. On the other hand, the increased penetration of low-cost renewable energy may bring down the cost of electricity. As there are many unknowns about future electricity costs, as demonstrated by the volatile global energy crisis, this study does not attempt to predict future prices, instead it uses a snapshot of two real world prices which demonstrate large differences in cost of electricity and how that alters the position of technologies. Four different tariff structures are considered in the analysis as quantified in the Chapter 3.

2.7 Summary

A through literature review has been conducted in this Chapter on consumer energy demands and technologies to decarbonise these demands. Ultimately the choice to decarbonise these demands comes down to the consumer and is paid for by them, but there are many options the consumer needs to consider and there is no one solution to fit all scenarios. The review has highlighted gaps in the research that leave consumers with a lack of clarity about the most effective way to decarbonise their demands when considering variations in spatiotemporal and dwelling demands away from average dwelling demands and the effect of tariff structures on low-carbon technologies.

A wide array of technologies currently exists to help reduce consumer emissions and there is further development in potential future technologies. Different avenues are being investigated for heating, cooking, and transport, primarily consisting of either electrification or H_2, and within those categories there are further options and ancillary generation and storage technologies which can be considered. Heating technology comparison has been covered in many valuable studies, often comparing only a few technologies at a time, in heat pumps and DEH to current fossil fuel technologies [41], [53], [74]–[76], H_2 technologies to electrified heating [11], [13], [21], [77], or solar technologies in competition or alongside other technologies [25], [26], [78], [79], although there is little work including different low-carbon cooking fuels and baseload demands in the analysis. The use of batteries for decarbonising energy consumption in EV against H_2 FC cars and stationary BES economic and environmental viability has also received significant attention [63], [80]–[85].

Some previous studies focus on the interaction between these demands, with work completed primarily at national level [37], [86]–[88]. However, investment for consumer energy decarbonisation is usually paid by the customers. Making it critical to understand if low-carbon technologies will be viable for consumers, and therefore if they will be taken up at mass, which may lead to different results to that which is optimum by regional level long term analysis. Studies on home energy management systems combine demands and optimise the hourly/sub-hourly electrified demands, storage and supply with VToU tariffs, but typically targeting reduced OpEx, self-consumption of PV, or peak shaving but with little consideration of investment and lifetime costs [89]–[95]. These studies often focus on electrification approaches alone, and give little comparison of different technology systems, technology sizing and the range of tariffs and if the technologies are even viable financially or environmentally. By including all demands, instead of just focusing on one, it allows a more realistic reflection of the distribution of electricity standing charges, more utilisation of PV, and can see if there are any trade-offs in preferred tariffs from different demands. Consideration of all consumer energy demand vectors simultaneously creating a multi-vector approach allows the possibility, and broader functionality, of V2H technologies, which uses stored energy in the EV battery and reverses the charging direction to discharge the battery and power the home demands from the EV. This multi-vector approach also allows a comparison for the consumer to how much they can reduce emissions from each demand, and which demands, and technologies are the most cost-effective way to reduce their emissions.

Many factors will influence consumers choices on adoption of low-carbon technologies, from range anxiety and charging infrastructure concerns for EV, to noise and space requirements for heat pumps and energy storage, but one of the most important factors is the financial cost for reducing their emissions, which is where this study is targeted. Studies of techno-economic analysis are often focused on what technology improvements are required in the future to make them techno-economically viable, commonly for batteries [83], [85] however changes to tariffs can also have a large effect on technology uptake and tariff changes have much less technical barriers to implement and novel tariff structures have been emerging in the market [60]. Yet tariff structure effect on technologies has received limited attention, mainly focused on aggregated and smart meter data analysis [96], [97], as opposed to from an optimisation and comparison perspective for a consumer.

This study takes a step back to holistically consider all consumer demands and technology pathways simultaneously, to give a consumers' perspective of what technologies may be adopted, and how changes to tariff structures alter the position of energy storage technologies, which to the best of the authors' knowledge has not been done before. A novel framework has been created to take a holistic approach at comparing the OpEx, CapEx, 20-year Net Present Cost (NPC), and emissions of combinations of technologies, sizes, and tariffs.

Chapter 3 Methodology

Having identified various gaps in the current research in Chapter 2, a new versatile framework is required which can be used to simulate and analyse a range of variables for decarbonisation of consumer demands. To answer the research questions posed the consumer centric mathematical model has been created, this Chapter explains the methodology used in the novel holistic framework. The methodology for the hourly simulation across the year for each demand of heating, household baseload, cooking, and personal transportation is explained. Where the heating demand is tailored to suit any dwelling characteristics and UK location. When local generation technologies are considered, such as PV, the generation is also simulated for each hour. The energy supply and demands are combined at each hour. The framework iteratively considers every combination of technology, sizing, and tariff for the demands and evaluates and compares the economic and environmental outputs. Allowing a thorough understanding of the interactions between all the variables and identification of the overall optimum lowest cost solution.

3.1 Overview, Demand Integration, and Optimisation

The model simulates domestic energy and transport demands across the year at an hourly resolution holistically for each combination of technologies, solar technology sizes, TES sizes, and tariffs. This versatile framework fills the gaps in: heating studies by exploring more parameters simultaneously to create the full landscape of heating technologies; holistic demand studies by thoroughly looking at the tariff structures available and including non-electrified technologies as well as considering CapEx and lifetime costs; and finally by investigating TES parameters alongside different electrified technologies. Analysis is completed from the end-users' perspective so does not consider infrastructure upgrade costs of electrical or gas networks, and assumes electricity (excluding PV and PVT), gas, and hydrogen can be provided by national and district networks to the dwelling. The study is completed without financial incentives to give a comparison of the technologies and allow quantification of incentives that would be required to make them competitive.

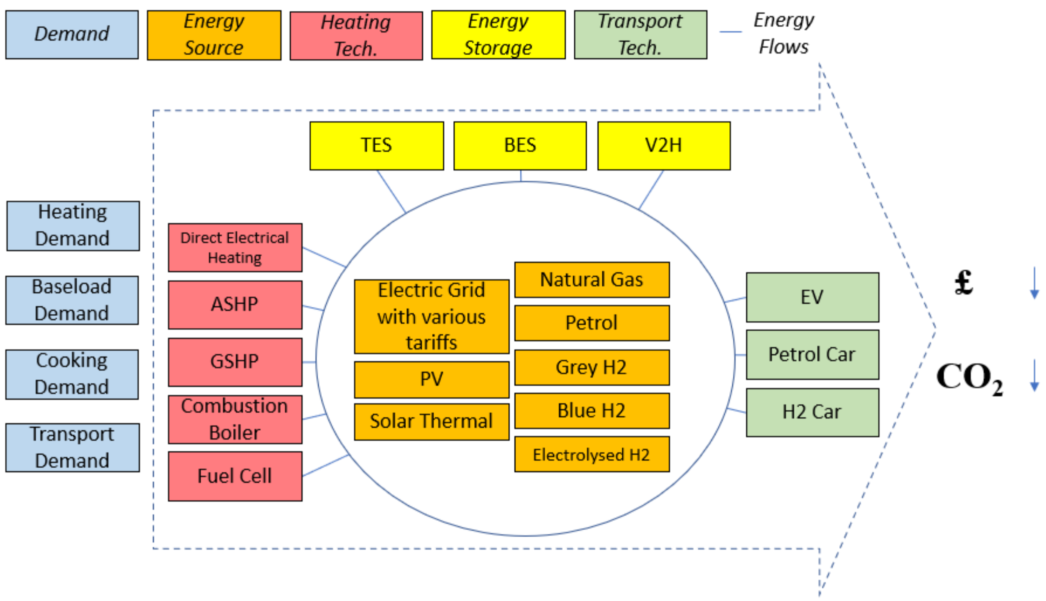

Figure 3-1 Demands, energy sources, and technologies considered in the framework. Air Source Heat Pump (ASHP), Battery Energy Storage (BES), Electric Vehicle (EV), Ground Source Heat Pump (GSHP), Hydrogen (H_2), Photovoltaic (PV), Thermal Energy Storage (TES), Vehicle to Home (V2H).

Figure 3-1 shows the: demands; fuel sources; prime technologies; ancillary solar technologies, and storage technologies considered in the new holistic framework. The study's focus is on regions where heating demand dominates over cooling demands, although the framework could incorporate cooling demand. Within this study the framework will be used to assess the full range of all consumer energy demands and technologies' costs and emissions in integrated systems when analysed holistically.

Inputs to the model are: dwelling location; number of occupants; desired thermostat temperature; dwelling floor area, and annual space heating demand (or thermal efficiency), the latter two can be found on the dwelling's energy performance certificate in many countries. For each combination of technologies, sizes and tariffs, the heating, baseload, cooking, and transport demands are collated at each hour. A rule-based approach is used for each hour to meet energy demands. In peak tariff hours, demands are met firstly by any local generation at that time, then by discharging any relevant energy storage, and finally by importing energy as required. For off-peak tariff hours, and at times of insufficient surplus solar PV energy, demands are met by importing energy, then charging of energy storage devices occurs where possible. The CapEx and the single years OpEx are then used to calculate the 20-year NPC. The OpEx, CapEx, NPC, and emissions values are used for technology comparisons. Emissions include operational emissions and embodied emissions, to give an equivalent annual emission.

The lifetime cost of the heating system is used as the comparison metric, to allow the consideration of the contribution of CapEx and OpEx of technologies. NPC methodology is calculated as shown in equation (1) over 20 years, which is considered as the lifetime of all technologies, other than FC which have a life of 10 years, requiring twice the CapEx frequency compared to other technologies [21]. A time period, t, of a year and a discount rate, r_d, of 0.035 are used for the calculation. Every combination of technologies, sizes, and tariffs is iterated through in the simulations, where the minimum NPC for each prime heater and transport options are recorded and if any new system combination with ancillaries, sizes, and tariffs results in a lower NPC for those prime heater and transport technologies it replaces the current minimum. By systematically going through every combination this optimises for the lowest possible NPC option is captured and gains greater understanding for the sensitivity of the different variables.

$$NPC = \sum_{t=0}^{n} \frac{OpEx}{(1+r_d)^t} + CapEx \quad (1)$$

3.2 Heating Methodology

The simulation model was created to compare the range of heating technologies for a dwelling taking into consideration spatiotemporal variations, with hourly simulations completed for each time interval over a year. The heating framework is based on the logic flow diagram as shown in Figure 3-2.

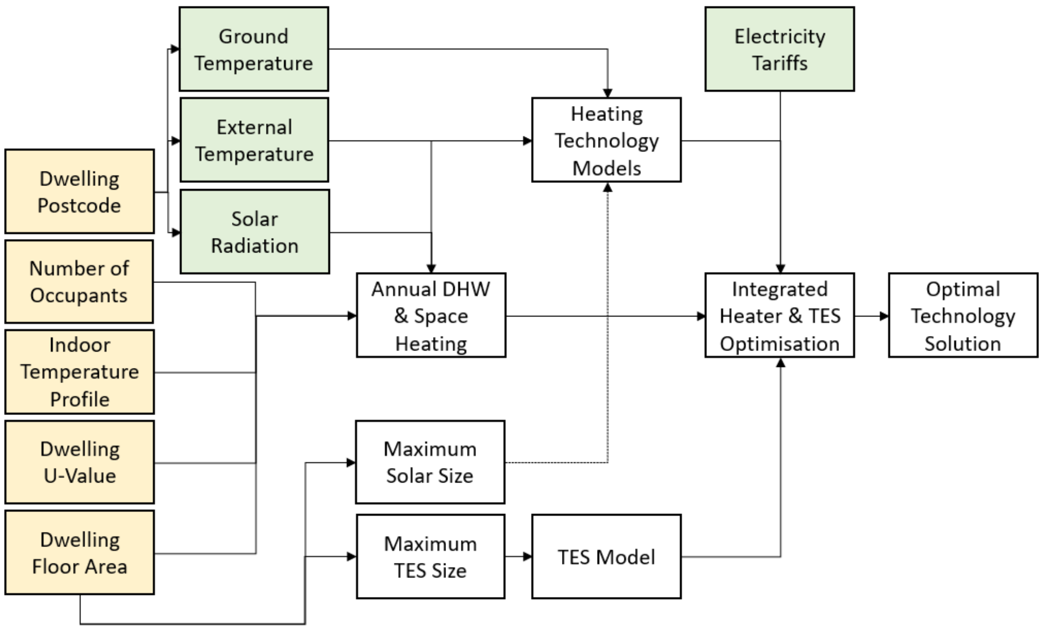

Figure 3-2 Logic flow diagram for the heating model. Yellow boxes are inputs, green are datasets and white are model calculations with references to equations used shown in brackets. Domestic Hot Water (DHW), Thermal Energy Storage (TES).

The user inputs are: number of occupants in the dwelling N; dwelling's location (e.g., postcode); dwelling U-value U_d; dwelling floor area A_d; desired thermostat set point T_d. In the case where dwelling U value is not known, this can be calculated in the framework from current heating demands, or from energy performance certificates which are common place for dwellings in many countries [15], [98].

Source	Formula	Equation Number
[99]	$f_{\varphi\delta}^{i} = cos(\pi/180 \times (\varphi - \delta_m))$	(2)
	$f_{pitch} = sin(\pi/180 \times 90/2)$	(3)
	$A_n = 26.3 \times {f_{pitch}}^3 - 38.5 \times {f_{pitch}}^2 + 14.8 \times f_{pitch}$	(4)
	$B_n = -16.5 \times {f_{pitch}}^3 + 27.3 \times {f_{pitch}}^2 - 11.9 \times f_{pitch}$	(5)
	$C_n = -1.06 \times {f_{pitch}}^3 - 0.0872 \times {f_{pitch}}^2 - 0.191 \times f_{pitch} + 1$	(6)
	$A_s = -0.66 \times {f_{pitch}}^3 - 0.106 \times {f_{pitch}}^2 + 2.93 \times f_{pitch}$	(7)
	$B_s = 3.63 \times {f_{pitch}}^3 - 0.374 \times {f_{pitch}}^2 - 7.4 \times f_{pitch}$	(8)
	$C_s = -2.71 \times {f_{pitch}}^3 - 0.991 \times {f_{pitch}}^2 + 4.59 \times f_{pitch} + 1$	(9)
	$R_{h-p,n}^{i} = A_n \times f_{\varphi\delta}^{i} + B_n \times f_{\varphi\delta}^{i} + C_n$	(10)
	$R_{h-p,s}^{i} = A_s \times f_{\varphi\delta}^{i} + B_s \times f_{\varphi\delta}^{i} + C_s$	(11)
	$I_{i,n}^{i} = I_{h,n}^{i} \times R_{h-p,n}^{i}$	(12)
	$I_{i,s}^{i} = I_{h,s}^{i} \times R_{h-p,s}^{i}$	(13)
	$G_{s,n}^{i} = (I_{i,n} \times (A_d \times 0.15)/2 \times 0.77 \times 0.7 \times 0.76 \times 0.9)/1000$	(14)
	$G_{s,s}^{i} = (I_{i,s} \times (A_d \times 0.15)/2 \times 0.77 \times 0.7 \times 0.76 \times 0.9)/1000$	(15)
[100]	$[100]G_m = (N \times 60)/1000$	(16)
[101]	$Q_{hl}^{i} = A_d \times U_d \times (T_{in}^{i} - T_{out}^{i})/1000$	(17)
[100]	$C_d = (250 \times A_d)/3600$	(18)
	$T_{in}^{i} = T_{in}^{i-1} + (Q_{hl}^{i} + G_{s,n}^{i} + G_{s,s}^{i} + G_m)/C_d$	(19)
	$Q_{sh}^{i} = \begin{cases} (T_d^i - T_{in}^i) \times C_d; If\ T_d^i > T_{in}^i \\ 0; If\ T_d^i \leq T_{in}^i \end{cases}$	(20)

Table 3-1 Space heating demand model formulas.

Space heating demand is calculated for each hour of the year using formula, data and assumptions in the Standard Assessment Procedure and Building Research Establishment Domestic Energy Model and equations are shown in Table 3-1 [99], [100]. It is assumed that half of the windows point due north and half due south, and all windows are vertical.

The total window area is taken as 15% of the dwelling floor area [102], and an average Standard Assessment Procedure overshading of 0.77, a frame factor of 0.7 and a transmission factor of 0.76 are used [99]. The dwelling heat capacity C_d, is based on using a typical dwelling specific heat capacity of 250 kJ/m^{2}K [100].

The ambient and solar irradiance data uses the closest 0.5° longitude and latitude reanalysis weather dataset from renewable ninja from the year 2019 [103]. For ASHP and GSHP the dwelling is kept at the desired indoor temperature all of the time, as per heat pump manufacturer's and installer's recommendations to allow maximum heat pump efficiency, reduce the risk of having insufficient heater power and radiator sizing, and for heat pump longevity [37]; for all other heating technologies the thermostat is kept at the desired temperature from 07:00-22:00 and is lowered by 2°C outside of those times.

Domestic hot water demand is based on Building Research Establishment Domestic Energy Model calculations with the assumptions that, there is both a bath and a shower in the dwelling and that the shower uses a mixer tap [99]. An hourly run off profile across the day, from Energy Saving Trust [104], is used to create an hourly hot water ratio of the daily hot water volume. A monthly domestic hot water factor is also applied from Building Research Establishment Domestic Energy Model [99]. Monthly values are used for the temperature of the cold-water entering the hot water system depending on the regional location of the dwelling [104]. A temperature of 51°C is used for the hot water temperature, to remain above the temperature of legionnaire growth but remain low to aid higher efficiency of heating technologies, the same temperature is used for space heating to allow use of conventional radiators, preventing further CapEx requirements in larger radiators or underfloor heating [105]. Using this combination of information and the equations in Table 3-2, the hot water demand is calculated based on the specific heat formula.

Source	Formula	Equation Number
[99]	$V_s = (0.45 \times N + 0.65) \times 28.8$	(21)
	$V_b = (0.13 \times N + 0.19) \times 50.8$	(22)
	$V_o = 9.8 \times N + 14$	(23)
	$V_t = V_s + V_b + V_o$	(24)
[106]	$Q_{dhw}^{i} = \left(V_t \times 4.18 \times \left(T_{hw} - T_{cw,m}\right)/3600\right) \times R_{dhw,m} \times R_{dhw,h}^{i}$	(25)

Table 3-2 Domestic hot water demand model formulas.

The annual tailored heating demand is calculated separately for both the continuous heat pump temperature profile and the on/off profile for other technologies. Heat pumps are sized based on the heating demands simulated. COP is determined for ASHP dependent on the outside temperature and for a vertical GSHP using the ground temperature at 100m depth which remains approximately constant over the year, using the formula in Table 3-3. A worst-case COP is calculated based on the coldest ambient temperature in the weather dataset for the location to size ASHP. The highest hour heating demand, with the constant desired temperature, is divided by the worst-case COP to determine the heat pump electrical power. A reference COP is calculated using ambient conditions of 7°C and a flow temperature of 35°C to determine the reference condition thermal power of the heat pump. The reference condition thermal power is limited to a minimum value of 4kWth as this is a common minimum power for domestic heat pumps, and electrical power is limited to a maximum of 7kWe to suit a typical maximum electrical power for a household [107], [108]. The upper limit is found to be sufficient for most homes when operating at continuous temperature profile, if larger heaters are required a more industrial scale heat pump may have to be considered. Sizing in this method means the backup electrical heaters which were often used in older heat pumps do not need to be used (with this weather dataset) and therefore reduces OpEx. It also allows smaller heat pumps to be sized compared to the mean 10.0kWth ASHP and 13.7kWth for GSHP installed in the UK, by using the constant temperature profiles, reducing CapEx and space heating higher flow requirements which would otherwise be required to elevate the dwelling temperature instead of simply maintaining it [24], [109]. DEH is sized in the same manner with the same constraints but using an efficiency of 100% and the on/off thermostat demands. DEH is taken as an immersion heater for providing space heating and domestic hot water demands.

Source	Formula	Equation Number
[24]	$COP_{ASHP} = 6.81 - 0.121 \times (T_{hw} - T_{out}^{i}) + 0.00063 \times (T_{hw} - T_{out}^{i})^2$	(26)
	$COP_{GSHP} = 8.77 - 0.150 \times (T_{hw} - T_g) + 0.000734 \times (T_{hw} - T_g)^2$	(27)
[110]	$T_g = 15 - (\varphi - 50) \times (4/9)$	(28)

Table 3-3 Heat pump model formulas.

Alongside heat pumps or DEH there is the option to have solar technologies. These solar technologies are also optimised in their size for each combination of technologies, by simulating each combination of possible sizes. Their maximum possible size is a quarter of the dwelling floor area, which would be able to fit on half the roof of a two-story dwelling using the typical 35° roof pitch, which is assumed to be a south facing pitch. A minimum size of $2m^2$ is used, and optimisation is in $2m^2$ increments [100]. Multiple configurations of solar technologies are considered alongside the electrified heating options, where multiple solar technologies are considered at the same time the total size equals the maximum available size and each technology is limited to a minimum of $2m^2$.

The solar technology configurations considered are:

- No solar technologies.
- PV panels alone.
- Flat plate solar thermal collectors alone.
- Evacuated tube solar thermal collectors alone.
- Flat plate solar thermal collectors alongside PV panels.
- Evacuated tube solar thermal collectors alongside PV panels.
- PVT collectors alone.

TES sizes are simulated from a minimum size of $0.1m^3$, up to the user set maximum size, in increments of $0.1m^3$, for each of the combinations of electrified and solar heating technologies. Simulations are completed for each combination of heating technologies, solar system sizes, TES sizes, and multiple electricity tariffs, with the tailored heating demand. Electrical demands are determined and minimised along with their associated costs using; TES to shift demand to off-peak times, maximising the use of solar generated energy and using typical higher ambient temperature times of the day for ASHP to charge the TES (where applicable with the tariff).

The supply, demand, and losses of TES are calculated for each hour of the simulation and updates the quantity of stored energy in the TES using formulas in Table 3-4. The TES volumes are taken as being hot water cylinders with a height equal to double the radius and use a TES U value of 1.3 W/m^2K which is a calculated as a typical value from hot water tank data [41], [111]. TES capacity is calculated based on a minimum useful temperature of 40°C. Initially simulations start with charge of the TES at nominal full capacity using 51°C, although it is allowed to be raised above 51°C to a maximum temperature of 95°C for solar thermal collectors before they waste excess thermal energy generated. An ideal stratified model is used for the TES. The temperatures above and below the thermocline are fixed values of the current cold-water temperature, 51°C, or 95°C depending on the energy stored in the TES. All the heat lost out of the TES enters the building increasing the average dwelling temperature.

Source	Formula	Equation Number
[106]	$Q^{i}_{tes} = V_{tes} \times 1000 \times 4.18 \times (T_{hw} - 40)/3600$	(29)
[112]	$Q^{i}_{tes,up} = \left(T^{i}_{tes,up} - T^{i}_{in}\right) \times U_{tes} \times \left(\pi \times 2r \times \left(h^{i}_{t,c} \times h_{tes}\right) + \pi \times r^{2}_{tes}\right)/1000$	(30)
[112]	$Q^{i}_{tes,lower} = \left(T^{i}_{tes,low} - T^{i}_{in}\right) \times U_{tes} \times \left(\pi \times 2r \times \left(\left(1 - h^{i}_{t,c}\right) \times h_{tes}\right) + \pi \times r^{2}_{tes}\right)/1000$	(31)
[100]	$T^{i}_{in} = T^{i-1}_{in} + \left(Q^{i}_{tes,up} + Q^{i}_{tes,lower}\right)/C_{d}$	(32)

Table 3-4 Thermal Energy Storage model formulas.

Energy generated from solar technologies is calculated at every time step using equations shown in Table 3-5. For PV a fixed electrical efficiency of 19.28% is used, as efficiency changes are relatively small for cooler climates, which mainly require heating demands (not cooling demands) [111]. Solar incident irradiance for the solar technologies on the roof is calculated with the same formula as south facing windows, except using a 35° roof pitch instead of 90° for the vertical windows.

Without solar radiation or in cold ambient conditions low solar energy input can lead to the solar collectors losing thermal energy, the energy is therefore limited to a minimum value of zero as the collector pump should be turned off in this scenario. The energy generated from the collectors is added into the TES up to the maximum TES maximum capacity at 95°C, with any overflow energy above that level being lost.

Source	Formula	Equation Number
[31]	$T_{st}^{i} = \left(T_{tes,up}^{i} + T_{tes,low}^{i}\right)/2$	(33)
[26]	$\eta_{pv}^{i} = 14.7 \times \left(1 - 0.0045 \times \left(T_{st}^{i} - 25\right)\right)$	(34)
[100]	$E_{pv}^{i} = A_{pv} \times \eta_{pv}^{i} \times I_{i,roof}^{i} \times 0.8$	(35)
[31], [100]	$Q_{st,fp}^{i} = A_{st} \times \left(0.78 \times I_{i,roof}^{i} - 0.0035\left(T_{st}^{i} - T_{a}^{i}\right) - 0.000038\left(T_{st}^{i} - T_{a}^{i}\right)^{2}\right) \times 0.8$	(36)
[31], [100]	$Q_{st,et}^{i} = A_{st} \times \left(0.625 \times I_{i,roof}^{i} - 0.0009\left(T_{st}^{i} - T_{a}^{i}\right) - 0.00002\left(T_{st}^{i} - T_{a}^{i}\right)^{2}\right) \times 0.8$	(37)
[26], [100]	$Q_{st,pvt}^{i} = A_{st} \times \left(0.726 \times I_{i,roof}^{i} - 0.003325\left(T_{st}^{i} - T_{a}^{i}\right) - 0.0000176\left(T_{st}^{i} - T_{a}^{i}\right)^{2}\right) \times 0.8$	(38)

Table 3-5 Solar technology model formulas.

For each time interval there are multiple different scenarios that could occur. Heating demand first comes from TES as much as possible, if it has insufficient energy it is assisted by the DEH or heat pump. Heating is prioritised towards domestic hot water, so if there is insufficient heating capacity the space heating is reduced, and the desired indoor temperature is not met.

After meeting the heating demands, if there is spare heating capacity from the DEH or heat pump and it is at a time of off-peak electricity, or there is surplus PV generated electricity, the TES will be charged up as close to full capacity as possible. However, even if it is not at an off-peak time or if there no surplus PV energy, TES capacity is kept above 10L of hot water at 51°C as much as possible with the heating capacity of the DEH or heat pump.

With any PV generated electricity that is remaining after heating demands, TES charging has been completed, and any other electrical demands are met is exported. The surplus is taken as sold to the grid at the feed in tariff rate. This reduction to the OpEx, allows very low to potentially negative heating OpEx from simulations with large PV or PVT.

For the other heating technologies, as their fuel costs are not dependant on the time of use (i.e., electrified technologies), and efficiency differences with changing ambient conditions are negligible in comparison to heat pumps and solar thermal technologies, the analysis is therefore simplified by not requiring TES. Any heating demands are met instantaneously by the heaters using the temperature profile which reduces 2°C at night, then demand is then multiplied by the technology efficiency and fuel costs. Natural gas, H_2 and biomass boilers all use an efficiency of 90%.

H_2 FC efficiency is based on a proton exchange membrane FC which is typically used in domestic applications, with a thermal efficiency at 39% and an electrical efficiency at 55% [21]. As with surplus PV generation, any surplus FC generated electricity that is not required by electrical demands at that time is exported at the feed in tariff rate under consideration during that simulation. Due to lower power output, FC operation is continuous, as per heat pumps, and therefore uses the demand from the continuous temperature profile.

3.3 Baseload and Cooking Methodology

In addition to the heating demands, this study also considers the baseload electricity demands and cooking demands. Where cooking demands are defined here only as the oven and hob (stove) cooking appliances, which are simulated from the options of using gas, electricity, or H_2. All other cooking equipment such as toasters, kettles, and microwaves are included in the baseload as they predominantly powered by electricity. Although baseload demands are met by electricity, which will mainly be sourced from the electricity grid, with the inclusion of solar PV and BES alongside multiple electricity tariffs in the framework, the utilisation and therefore viability of these technologies is critically affected by the timing and quantity of the baseload demands.

The synthetic baseload and cooking demands are created using appliance demands and typical usage times from the Household Electricity Survey [59] and Centre for Renewable Energy Systems Technology Demand Model [57]. Using this data typical weekday and weekend hourly profiles are created as shown in Figure 3-3, dishwasher loads occur at a time which is lowest cost in all the tariffs used, as this is deemed easily shiftable [89]. Summing these profiles across the year results in 3,006 kWh from the baseload and 3,553 kWh from baseload and cooking combined. This aligns with the average annual demands of 3,116 kWh from the Household Survey and 3,500 kWh from the UK Department for Business, Energy and Industry [56].

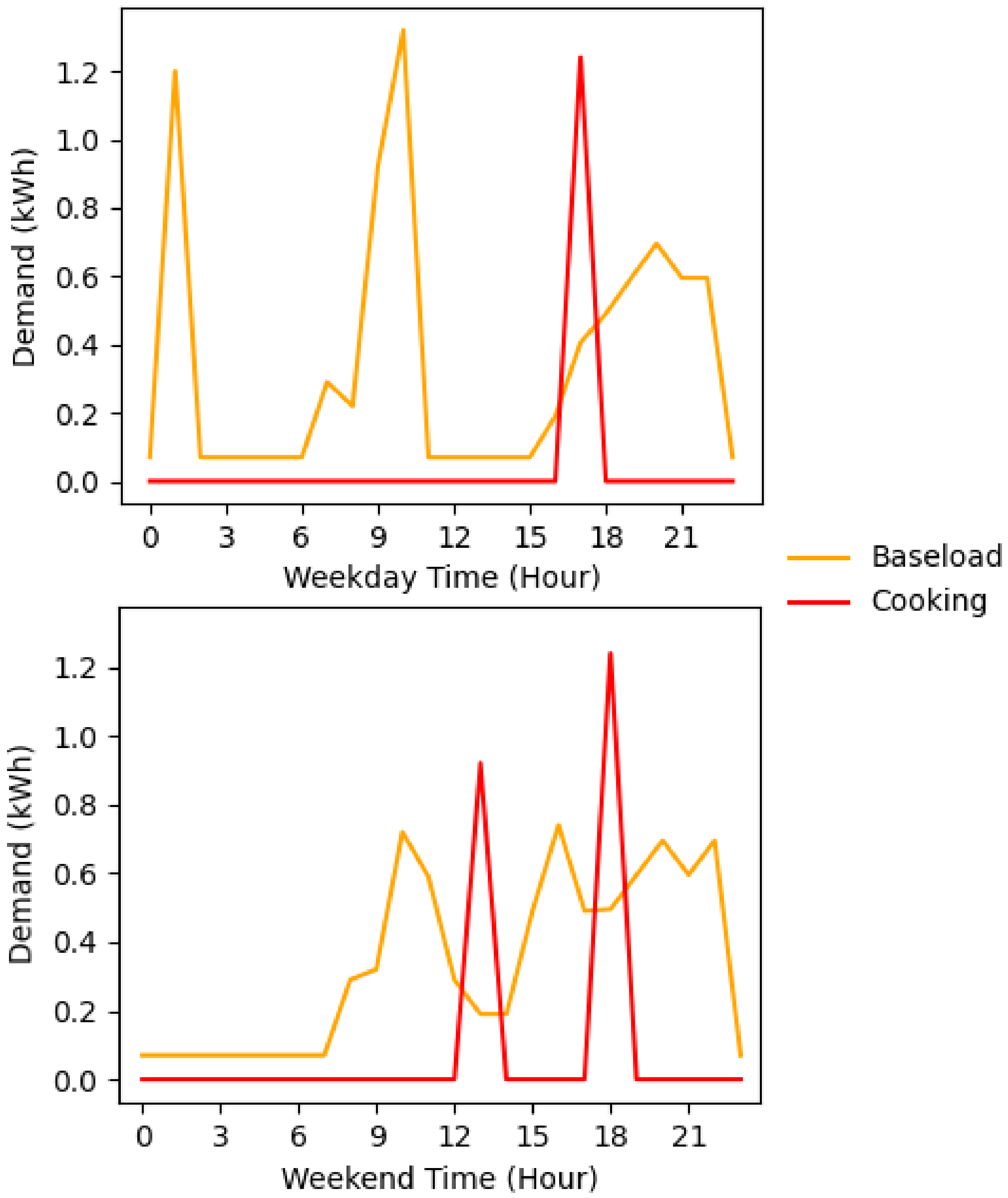

Figure 3-3 Synthetic weekday and weekend baseload and cooking demands used in the model.

3.4 Transport Methodology

The inclusion of the car transportation demands completes the typical consumer energy demands. A typical weekly drive cycle is created from the average annual mileage of 7400 miles and a weekly commute of 22 miles, with the remaining 32 miles a week used as a single weekend trip [113], [114]. As petrol and H_2 cars are not affected by hourly variations in fuel costs and domestic energy generation, like EV, making their models are considerably simpler. Petrol cars use the fuel costs of £1.24/litre [115], a vehicle efficiency of 36 mpg (UK gallons) [116], operational emissions of 0.28053 kgCO2e/mile [23], and embodied emissions totalling 6289 kgCO2e [117]. The Vauxhall Corsa is used for investment costs, as it is the most popular UK car and has an EV derivative, a CapEx value of £17015 is used [118], [119]. Due to the limited commercially available H_2 cars, the Toyota Mirai data is used which has an efficiency of 69.4 miles/kg H_2 [120], where H_2 has an energy density of 33.3 kWh/kg [121], the CapEx is £50,000 [122], and the embodied emissions total 9815 kgCO2e [117]. Although there is currently a limited option of H_2 cars, Japan and the EU in particular are pushing significant development in a H_2 economy, which could bring further development H_2 networks and transport due to their strong position in the global automotive industry [123], [124].

As mentioned, the heavy integration of EV with other electrified demands, generations, the EV location, and varying tariffs requires a more detailed approach. To allow the assumption that all charging is completed at home, it is required to know when the EV is at home. For the workday the EV is taken as away from the home from 09:00 to 18:00, the single larger weekend trip has the EV away from the home from 12:00 Saturday to 12:00 Sunday using this timing prevents the night-time typical lowest cost tariff time to be used at least one night a week and gives the potential for more EV charging from PV in Saturday morning and Sunday afternoon. The battery capacity is taken as 61.2kWh and an average annual driving efficiency of 3.25 miles/kWh is used, which are the averages for new EV, the efficiency is also adjusted by a monthly variation of up to 0.5m/kWh from the average to correspond to lower efficiencies in colder months and higher efficiencies in the warmer months [125], [126]. A maximum charge rate of 7.0kW is used as per single phase domestic chargers, a minimum rate of 1.4kW in line with legislations is considered and a charging and discharging efficiency is taken as 96.8% [127]. Maximum charging is completed every time the EV is home during tariff off-peak times, or when there is any surplus PV energy above the minimum charging rate, if at any time when the EV is at home its state of charge drops below 25% it will be increased back to this level even if it requires peak electricity use, as this allows for the longest journey with the worst-case winter efficiency. The EV is then discharged during the journeys. The CapEx from the Vauxhall Corsa-e is £26640 and the EV embodied emissions for an average EV of 6900 kgCO_2e are used [117], [128].

3.5 Battery Storage Methodology

A potential key ancillary technology in decarbonising consumer energy is the use of electrical storage, which can either be by dedicate stationary BES wall battery or by using the EV for V2H functionality. The models for both technologies work in a similar way, charging at off-peak times or when there is surplus PV energy targeting charging to full capacity. The batteries will then discharge at any time which is during peak tariff hours and there is a net household demand, for the BES this can completely discharge its usable capacity, for EV the discharging is limited to a minimum state of charge of 25% and when the vehicle is at home.

The BES input data is based on a middle range stationary wall battery which has the capacity of 8.2kWh, a 10 year life and a max charge and discharge rate of 3.0 kW [129]. The charging and discharging efficiencies for stationary batteries are found to be very similar as for EV and so also uses 96.8% and the BES embodied emissions is 115 kgCO_2e/kWh (kWh BES capacity) [127], [130]. As the BES life already accommodates for its use of the BES in this way, no additional degradation modelling is required for it, however for the EV, the use of V2H is an additional function and so the additional degradation of V2H above its normal expected degradation is modelled. As simulations, and degradation calculations, are only complete for the first year and then it multiplied to get degradation across the 20-years, a linear degradation methodology is chosen as proposed by Bai et al [81].

3.6 Economic and Environmental Parameters

Technology systems are compared with multiple parameters: OpEx; CapEx; equivalent annual emissions in gCO_2e/kWh, and lifetime costs. CapEx costs of heating technologies and TES is dependent on the sizing, be it power capacity or geometric sizing, Table 3-6 shows the values or formula used in the framework.

Tariffs are key factors which alter the position of electrified technologies compared to the baseline fossil fuel technologies, of gas boilers and petrol cars, and also the relative performance of the new electrified technologies and ancillary technologies against each other. In this study four different electricity tariffs are compared for the heat pumps and DEH, each with different times of peak and off-peak cost and times as shown in Table 3-7. Tariff terms used throughout the study are average day rate, which is the average tariff cost across the 24 hours of the day, peak which is a time when the tariff rate is higher than the average day rate, and off-peak which is when the tariff rate is lower than the average day rate.

Source	Formula	Equation Number
[131]	$TES\ Capex = 2068.3 \times {V_{tes}}^{0.553}$	(39)
[111]	$DEH\ Capex = 100 + 1000\ (installation)$	(40)
[24]	$ASHP\ Capex = \left(200 + 4750/{P_{hp,th}}^{1.25}\right) \times P_{hp,th} + 1500$	(41)
[24]	$GSHP\ Capex = \left(200 + 4750/{P_{hp,th}}^{1.25}\right) \times P_{hp,th} + 800 \times P_{hp,th}$	(42)
[49], [111]	$Solar\ PV\ Capex = A_{pv} \times 50 + 3400$	(43)
[49], [111]	$Flat\ Plate\ Capex = A_{st} \times 244 + 2090$	(44)
[49], [111]	$Evacuated\ Tube\ Capex = A_{st} \times 299 + 2090$	(45)
[49]	$PVT\ Capex = A_{st} \times 319 + 3370$	(46)
[30], [111]	$Gas\ Boiler\ Capex = \begin{cases} 15000 + Q_{sh,epc}/25\ ; If\ Q_{sh,epc} \leq 25000 \\ 2500; If\ Q_{sh,epc}\ > 25000 \end{cases}$	(47)
[30]	$H2\ Boiler\ Capex = \begin{cases} 2000 + Q_{sh,epc}/25\ ; If\ Q_{sh,epc} \leq 25000 \\ 3000; If\ Q_{sh,epc}\ > 25000 \end{cases}$	(48)
[111], [132]	$Biomass\ Boiler\ Capex = \begin{cases} 9000 + Q_{sh,epc}/4\ ; If\ Q_{sh,epc} \leq 40000 \\ 19000; If\ Q_{sh,epc}\ > 40000 \end{cases}$	(49)
[21]	$Hydrogen\ Fuel\ Cell\ Capex = 12000$	(50)

Table 3-6 Technologies CapEx formulas.

Two traditional tariffs are used, the basic flat rate tariff where electricity costs the same at all times of the day irrelevant of time of use and a night off-peak tariff, where there are seven off-peak hours in the night which was created to help encourage use of electricity during low demand times from electrical storage heaters [22]. Additionally, two emerging tariffs are considered, an EV tariff designed for EV charging, with four very low off-peak hours at night designed to help reduce costs for EV owners, while making the most of the typical lowest four hours of demand across the day [73]. The other emerging tariff is a VToU tariff, where the rate for each half hour is released the day ahead, the cost variations across the day reflect the difference in market price across the day when estimating the future energy supply and demands. Figure 3-4 shows a profile for the low cost and high cost VToU tariffs used in the simulations, although the values change every day, this figure uses the average cost for each hour of the day to illustrate a typical daily profile and costs. This VToU tariff can benefit consumers who can be flexible with their energy demands as it typically has the lowest average day rate across the 24 hours of the day but very high peak electricity costs in the early evening [60]. Except for the flat tariff, the other tariffs are designed to encourage users to shift their demands away from the typical peak demand times of the day, which fall in the mornings when people wake up and, in the evening, when they get home and start cooking. However, with cooking and often heating, without energy storage this is not easy for consumer to shift their demands to the lower cost times of the day. Our analysis aims to find the most cost-effective technologies to reduce consumer emissions, what tariff changes are required to incentivise energy storage, and assess these technologies' ability to achieve future emissions targets.

Tariffs costs used in this study represent real data from 2020 and 2022 to the consumer from an energy supplier for a central England location of the West Midlands. Most analysis is complete using the more stable pre-energy crisis energy costs from 2020. Some further analysis is also complete using the higher rates found during the energy crisis in 2022 to find the effect of different energy costs on the technologies. Tariffs used are the lowest tariffs available in the respective years for each of the tariff structure types, except for the VToU tariff which uses data from across the whole year of either 2020 or 2022. These costs include energy generation costs and profits, national and local transmission costs, supplier costs and all other costs which make up the end total cost to consumers. In the future with potentially more demands directly electrified, this increased electrical demand puts extra strain on the networks which likely would require reinforcement upgrades and pass on the associated extra costs to the consumers. On the other hand, the increased penetration of low-cost renewable energy may bring down the cost of electricity. As there are many unknowns about future electricity costs, as demonstrated by the volatile global energy crisis, this study does not attempt to predict future prices, instead it uses a snapshot of two real world prices which demonstrate large differences in cost of electricity and how that alters the position of technologies.

Tariff [60], [73]	Peak Cost	Off-Peak Cost p/kWh	Off-Peak Times Hour	Export Tariff p/kWh	Standing Charge p/day
Flat rate (low tariff)	13.35	N/A	N/A	5.5	20.06
Night off-peak, Eco7 (low tariff)	15.33	8.91	23-06	5.5	20.06
EV off-peak (low tariff)	13.45	5.0	0-4	3.0	25.0
VToU (low tariff)	Variable day ahead tariff. Average cost 9.3p/kWh, min -10.4p/kWh, max capped at 35p/kWh. Off-peak considered as anything less than 9.0p/kWh.			5.5	21.0
Flat rate (high tariff)	32.42	N/A	N/A	7.5	23.76
Night off-peak, Eco7 (high tariff)	35.93	21.63	23-06	7.5	23.85
EV off-peak (high tariff)	34.43	7.5	0-4	4.1	44.48
VToU (high tariff)	Variable day ahead tariff. Average cost 31.3p/kWh, min -8.6p/kWh, max capped at 35p/kWh. Off-peak considered as anything less than 31p/kWh.			7.5	21.0

Table 3-7 Electricity tariffs simulated.

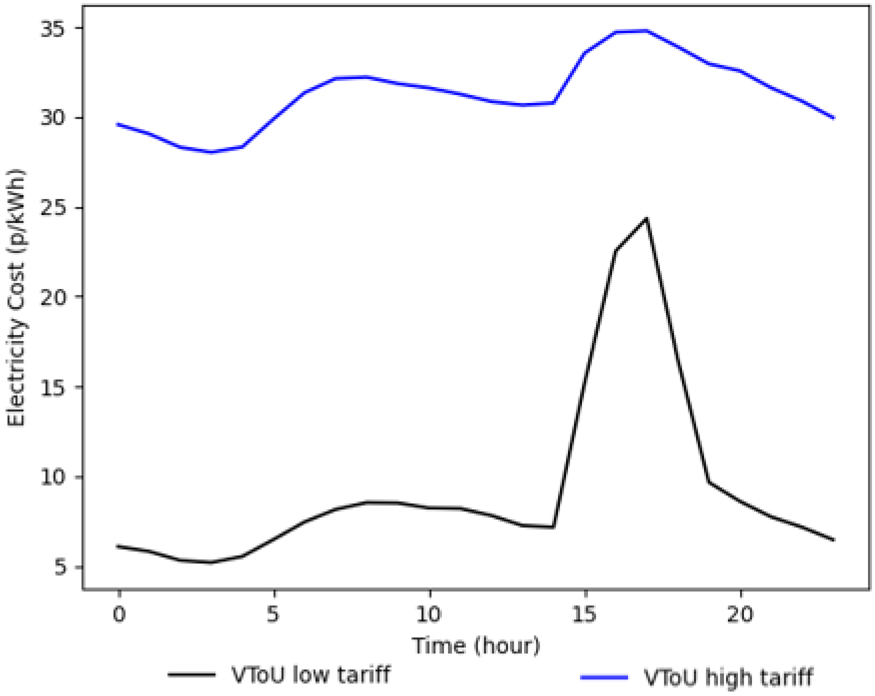

Figure 3-4 Average profiles for the high and low Variable Time of Use (VToU) tariffs

All other technologies have constant fuel costs which are shown alongside the emissions for each fuel source in Table 3-8. H_2 costs are the most challenging to estimate as it is not currently available for domestic heating, costs are taken from Speirs et al.'s range of costs, which is also comparable with analysis from Baldino et al. and aligns against the cost of its prime energy fuel cost (i.e. natural gas and electricity costs used in the model) [30], [50].

	Fuel Cost p/kWh	Emissions gCO_2e/kWh
Grid Electricity [23]	Table 3-7	212
Natural gas [23], [73]	2.1 (with a day rate of 17.85p/day)	183
Biomass [132] [12]	4.11	90
Grey H_2 [30], [50] [17]	4.9	382
Blue H_2 [30], [50] [17]	9.3	60
Electrolysed H_2 [30], [50] [17]	15.2	$1.87 \times grid\ emissions$

Table 3-8 Fuel costs used in the framework.

As well as direct electrified technologies being sourced from the grid, in this study Electrolysed H_2 is also sourced using grid electricity and so has its associated emissions. Target emissions for the years 2035 and 2050 are calculated by scaling the baseline gas and petrol emissions in this simulation by the ratio of how those overall energy sectors should reduce as proposed in the sixth carbon budget. Embodied emissions targets are scaled by the industry sector targets. Although grid electricity is an input to the model it is also scaled in the same way, starting from 0.212kgCO_2e/kWh, the carbon budget for 2035 is for this to be reduced to 17.6% so to 0.0373kgCO_2e/kWh, and for 2050 to 1.8% at 0.0038kgCO_2e/kWh [133].

3.7 Case Study Inputs

The framework created offers the ability to be easily adopted for any home and set of consumer demands, by adjusting the dwelling inputs and locations for heating demands. Case studies are used in the study to demonstrate the functionality of the framework and answer the research questions using average, low, and high demand UK dwellings at a central England location of Coventry (2027 heating degree days with a 15.5°C base temperature), with two occupants, using a thermostat temperature of 20.0°C, and a maximum TES size of 0.5m^3 considered. To see how the spatiotemporal variations change the optimum low-carbon heating technology, simulations are completed for every 0.5x0.5° longitude and latitude across the UK, which is 111km longitude by approximately 80km latitude in the UK.

The initial study uses average UK dwelling thermal efficiency with a U-value of 1.85W/m^2K and floor area of 87m^2 in Coventry, [25], [134]–[136]. The breakdown of the different simulated hourly heating demands is shown in Figure 3-5 for this average demand dwelling. Figure 3-5 (a) shows the average heating demands across the year broken down by the on/off heating profile and a constant temperature heating profile and domestic hot water demand all against the ambient temperature. Figure 3-5 (b) shows the same data for the first two days of the year.

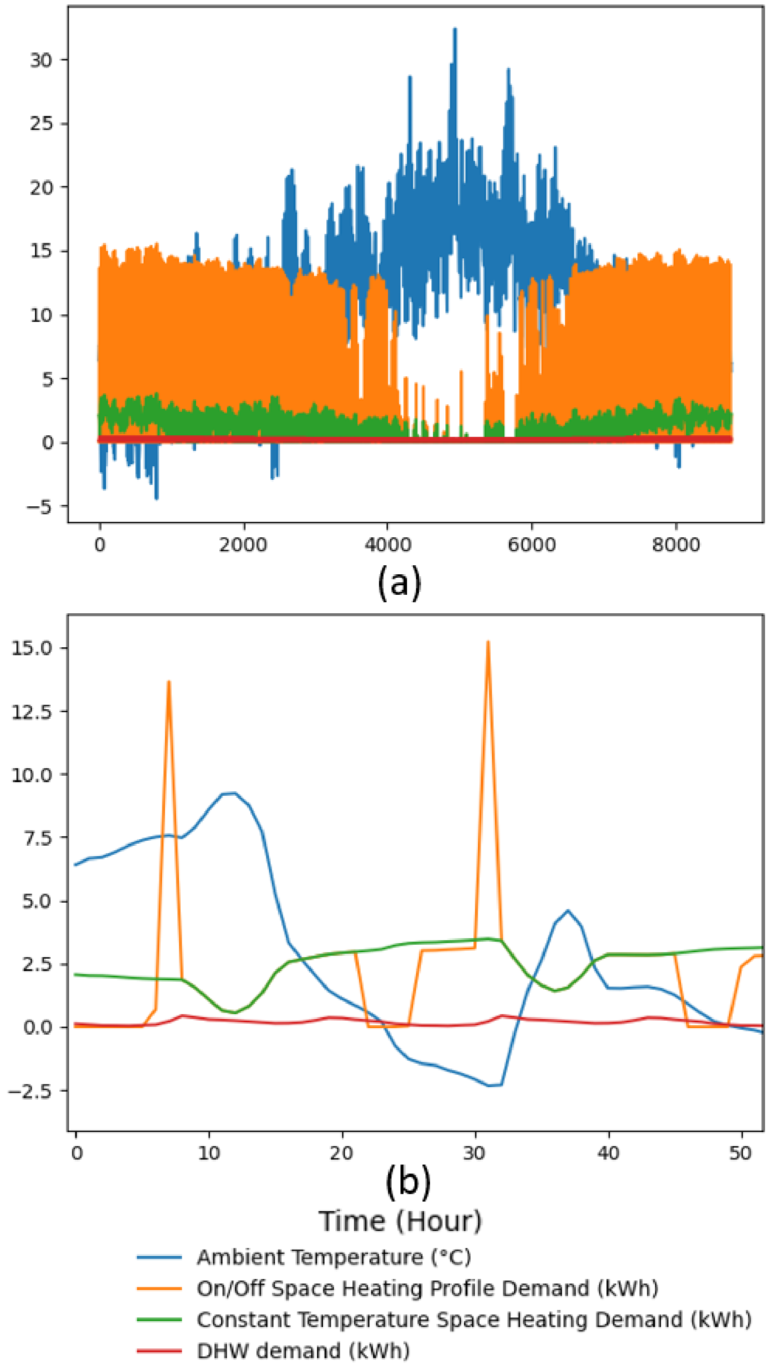

Figure 3-5 Hourly heating demand simulations for an average dwelling in central England (a) across the year and (b) for the first two days of the year. Using both the on/off heating profile for boilers and a constant temperature profile for optimum heat pump operation.

The on/off heating profile which is typically used for gas boilers has a heating demand of 10,168kWh/year, the constant temperature heat pump profile heating demand is 10,749kWh/year and the domestic hot water heating demand is 1,460kWh/year. Although Figure 3-5 (a) only emphasises the higher heating demand spikes from the on/off heating profile, as can be seen by (b) this is only for a short time, which is when the temperature of the dwelling is required to be increased. Allowing cooler temperatures at night with the on/off profile, reduces the night demand and shifts it to early mornings, allowing a period of no heating when the thermostat temperature is reduced. Then to maintain a 2°C cooler temperature at night-time is also lower demand as can be seen between 26-30 hours in Figure 3-5 (b). Overall allowing for slightly lower heating demands using the on/off profile. However, it is important to note that as the on/off heating demand requires more heating power from the heater and radiators it would also require higher radiator flow temperatures to elevate the temperature of the dwelling compared to simply maintaining its temperature. This increase in flow temperature requirement comes at the detriment of decreasing heat pump and boiler efficiencies as shown in equations (26) and (27), which can result in the on/off profile actually requiring more input energy to the heater than the constant temperature profile. In addition, the continuous profile shifts more heating demand to off-peak times when electricity is lower value, meaning potentially less electricity used and higher utilisation of off-peak electricity. As discussed, the domestic hot water demand remains approximately constant over the year and in Winter is dwarfed by the space heating demands.

Using these average dwelling inputs, the framework simulates an annual gas boiler gas demand of 12,920kWh, with the on/off heating profile combined with the domestic hot water demand and a gas boiler efficiency of 90%. This validates the framework as the heating demand for the average dwelling inputs falls in 50th percentile gas heating demand range of 12,000-14,000kWh, from UK smart gas meter data as shown in Figure 3-6, and with an annual figure of 13,000kWh from Barnes [14].

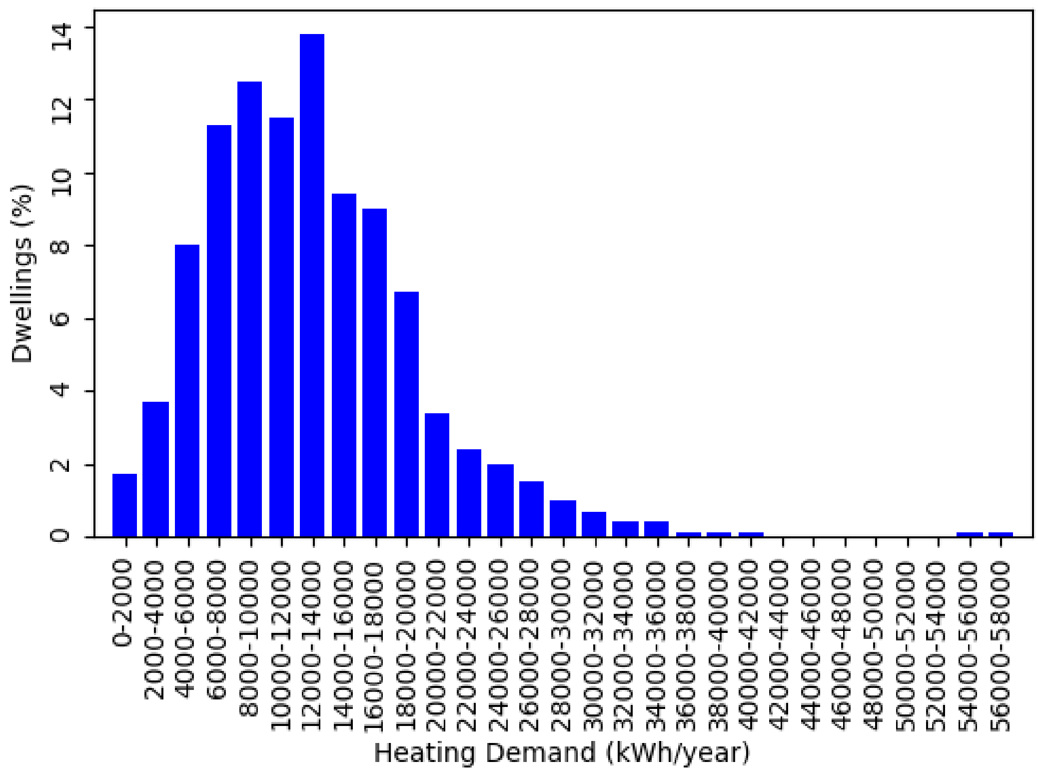

Figure 3-6 UK dwelling annual heating demands from gas meter data, from 2017-2018 from a sample of 1770 dwellings [137].

Five dwelling properties are used in the simulations: very small; small; average; large; and very large dwellings. All remain at the average thermal efficiency and have the house size adjusted to meet the 10th, 25th, 75th and 90th percentile dwelling heating demands aligned from Figure 3-6 data at the Coventry location. Resulting in houses sizes of 31m^2, 52 m^2, 87 m^2, 114 m^2 and, 147m^2 for the very low, low, average, high, and very high demand dwellings respectively.

3.8 Summary

This Chapter has explained the novel methodology that has been created for this research. This new framework balances flexibility of the input variables, with multiple demands holistically, with a sufficient level of detail of the simulation to allow a thorough understanding of the landscape of decarbonisation of consumer demands and to ensure the cost optimum combination of technologies, sizes and tariffs is found.

The detail of the hourly resolution simulations is explained for each of the consumer energy demands of heating, transportation, household baseload and cooking demands, which are then combined to create the total demands for that hour. The demands are then met, using the technologies and their size which are considered under that simulation iteration. The framework completes simulations for each combination of technologies, sizes, and tariffs to then allow a thorough comparison of results and to ensure that the true optimum lifetime cost solution can be found when considering the OpEx and CapEx alongside analysis of the environmental performance of each system.

Chapter 4 Domestic Heating Economics and Emissions

An understanding of heating technologies from the consumers' perspective is critical to ensure low-carbon technologies are adopted for reducing their current associated emissions. Existing studies from the consumers' perspective do not compare and optimise the full range and combinations of potential heating systems. There is little consideration of how spatiotemporal and dwelling variations combined alter the economic and environmental effectiveness of technologies. This Chapter uses the new comprehensive framework, that was explained in Chapter 3, to answer the first research question by capturing the range of heating technologies and their viability for any specific dwelling's traits and climate from customers' perspective which is missing from current studies. The model optimises combinations of prime heaters, energy sources, ancillary solar technologies and sizes, TES sizes and tariffs with hourly heating simulation across a year and compares their OpEx, CapEx, and lifetime costs alongside emissions to realise the true preferential heating systems for customers, which could be used by various stakeholders. Using the UK as a case study, the results show electrified heating is generally the optimum lifetime cost solution, mainly from ASHP coupled with PV. However, DEH becomes more economically viable as dwelling demands reduce from smaller dwellings or warmer climates, as shorter durations of the ownership are considered, or with CapEx constraints from lower income households. Understanding this is of high importance, as without correctly targeted incentives, a larger uptake of DEH may occur, which will burden the electrical network and generation to a greater extent than more efficient heat pumps.

This Chapter is largely based upon the published work "Heating economics evaluated against emissions: an analysis of low-carbon heating systems with spatiotemporal and dwelling variations" published in *Energy and Buildings* by the authors, M. Ryland and W. He [138].

4.1 Heating System Simulations

Building on the heating demands shown for the average UK dwelling in Coventry location from Figure 3-5, the simulations are complete using the array of technologies, sizes, and tariffs. The hourly electrical demands for the average UK dwelling and solar generation alongside TES state of charge (in kWh of thermal energy) is shown in Figure 4-1 using ASHP, a large 0.5m^3 TES and 20m^2 PV using the Eco7 tariff. These parameters are used in this example to aid explanation of the energy flows. Figure 4-1 (a) shows values across the full year, showing that the ASHP significantly reduces its demand in Summer, at the middle of the year, which is also when PV generation is the greatest, and TES state of charge never drops to lower levels.

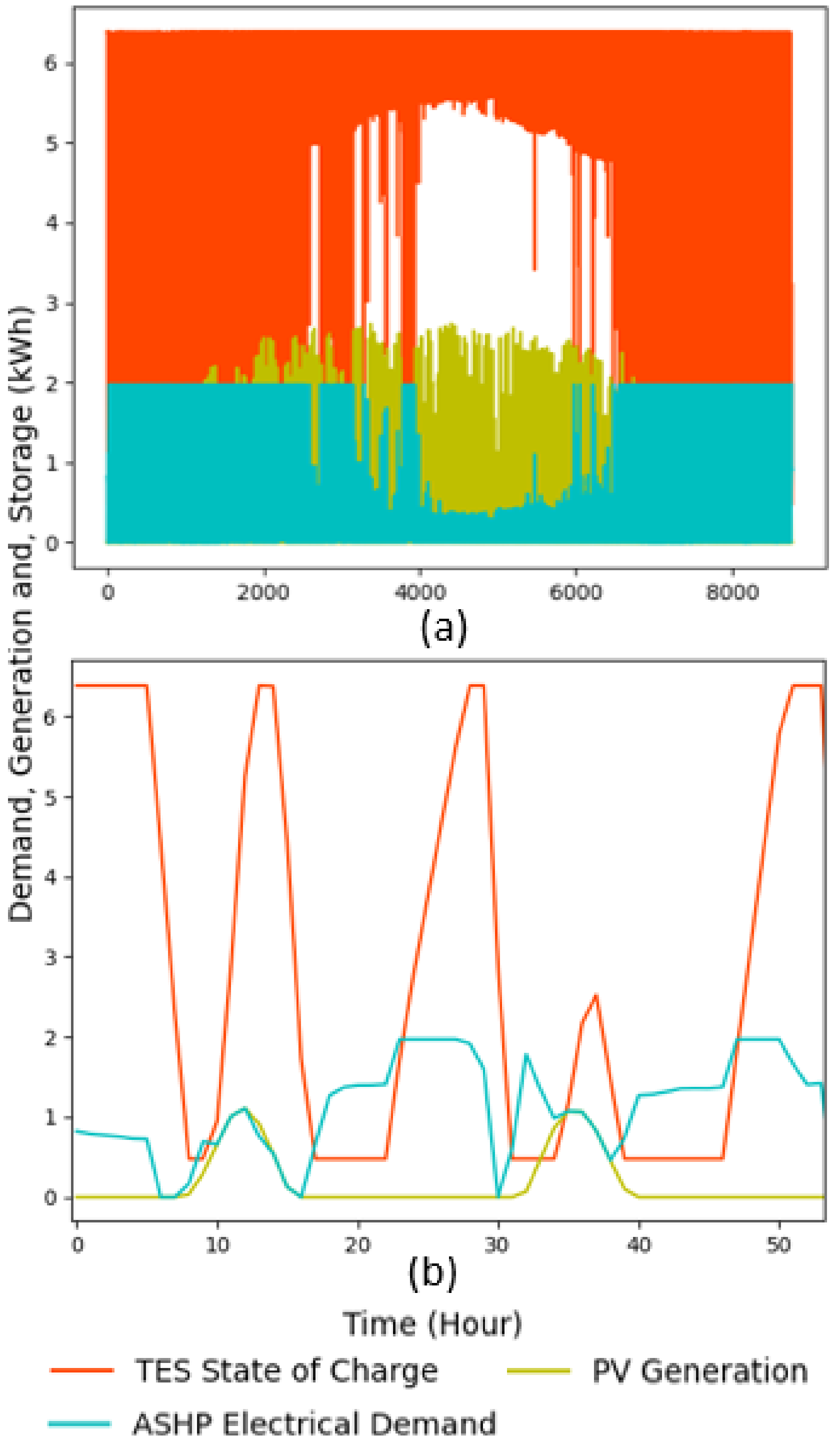

Figure 4-1 Air Source Heat Pump (ASHP) with 0.5m³ Thermal Energy Storage (TES) and 20m² Photovoltaic (PV) on Eco7 tariff simulations for an average dwelling in central England (a) across the year and (b) for the first two days of the year.

Looking closer at the data as shown in Figure 4-1 (b) for the first two days of the year, a greater understanding of the simulations can be gained. During the hours of off-peak electricity in the night the ASHP is at its full power to charge the TES up to its full capacity. Then when the tariff rate changes to peak rates at 07:00 each morning, the thermal demand is met as much as possible by the TES, often allowing the ASHP to have no demand for a few hours. Using the TES charge straight away at peak rate times reduces the losses from the TES which would be greater from storing it at longer durations. In addition, although it is not quantified here and of little benefit to consumers on the Eco7 tariff that only pay one rate across the remaining 17 hours of the day, this approach reduces the morning peak demand often seen at the UK level [12].

The daily variation in PV generation is also visible and during this time of generation the ASHP electrical load attempts to use any self-generated electricity as it follows PV generation. As shown by the first two days this can allow the charging of the TES, if the PV generation coupled with the ASHP COP at that time allows for more thermal supply than the space heating and domestic hot water demands of the household at that time. It can be seen in the first day this allowed a full charge of the TES, unlike the second day where only a small additional charge was gained by the TES. This is due to the first day being quite mild for a January day compared to the second day which was much cooler, as previously shown in Figure 3-5 (b).

Outside of the times when there is low-cost off-peak electricity or PV generation, the ASHP electrical demand follows the thermal demand of the dwelling, with slight variations due to the hourly variations in the ambient temperature and solar gains which alters the thermal demand and the COP of the ASHP simultaneously (solar irradiance not considered to changing the COP). In addition to the ASHP using a constant temperature profile benefiting the longevity and reduced power of the ASHP compared to boilers, it causes a shift in demands away from the morning peak when the gas boiler demand is high and towards the night-time when electricity costs can be lower.

4.2 Tariffs and Ancillary Technology Sizing

Simulations using the developed framework now move on to compare the outputs of heating technology combinations, sizes, and tariffs for the average UK dwelling in central England location of Coventry.

The tariff selection is the only variable to only alter OpEx, not CapEx, and can therefore has a more straightforward analysis, although the comparison of tariffs does depend on which technologies are used. In this Chapter only the more stable, pre-energy crisis, tariffs were used which had significantly lower rates than those found during the energy crisis. Figure 4-2 shows how the four tariffs considered alter the OpEx for the average dwelling when using DEH or ASHP and with small $0.1m^3$ and large $0.5m^3$ TES. The OpEx is broken down by the standing charge, electricity used in pounds during the peak rate times, and electricity used in pounds during the off-peak rate times. For the flat tariff, as there is only one rate this is all labelled peak rate, therefore leading to no benefit of having large TES as there is no off-peak times to shift energy from, when there are no ancillary solar technologies.

The annual standing rate only has a small variation across the tariffs, proportional to the input day rates. Depending on the technologies under consideration the standing rate can be nearly negligible if with the higher OpEx DEH or can become a substantial percentage when coupled with more efficient heat pumps especially if they are coupled with PV due to very low OpEx as will be shown in section 4.3.

Looking firstly at the DEH with smaller $0.1m^3$ TES sizes, shows the general trends found with the pre-energy crisis tariffs. The Eco7 results in the highest cost, then the flat tariff, then EV, followed by the VToU being the most favourable. This order follows the average rate of electricity across the day for each tariff, with the VToU being the lowest average rate across the day. The variation in results found with the same hardware from only changing the tariffs is very significant, with the difference between the flat and the VToU tariffs making £389 a year saving, showing it is an essential factor to consider for electrified heating. With the small TES capacity only a small proportion of off-peak electricity is used from the Eco7 and EV tariffs, especially as DEH system has a lower thermostat set point during these hours. With the definition given for peak and off-peak rates with the VToU tariff, that the off-peak are the values that are less than its average rate across the year, higher amounts of off-peak electricity are used with the VToU compared to the other tariffs.

Coupling DEH alongside the larger capacity $0.5m^3$ TES allows greater percentage of energy to come from off-peak times, which allows the overall reduction in OpEx. Although it allows all multi-rate tariffs to reduce, this is not significant enough to change the position of the tariffs. The largest reduction in OpEx from using larger TES alongside DEH comes from the EV tariff, due to its larger difference in peak to off-peak rates, which allows for an annual reduction of £144. Whereas for the lowest OpEx tariff, the VToU, it only reduces £94.

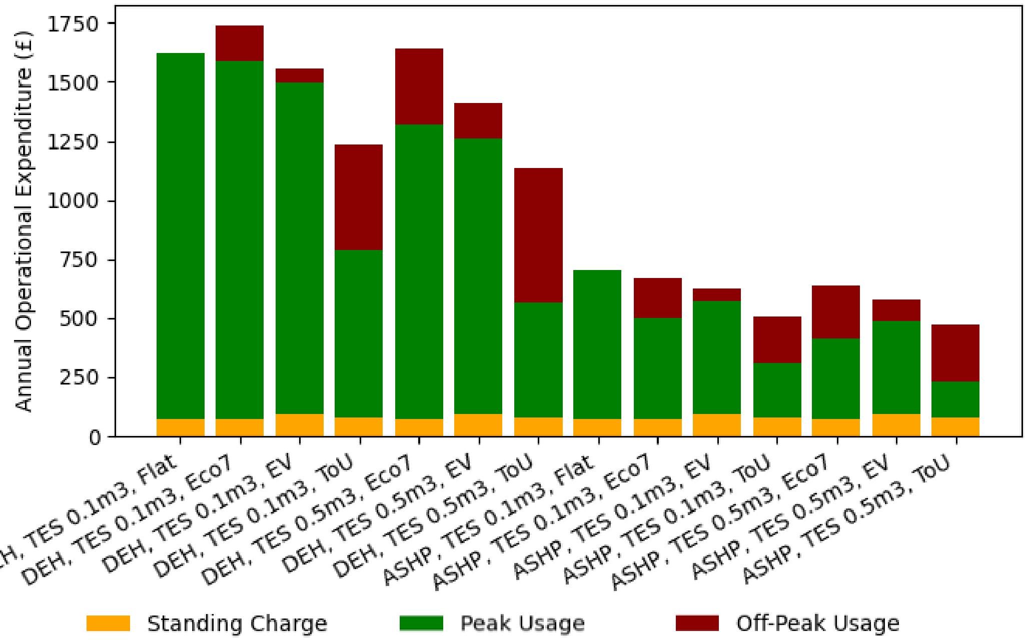

Figure 4-2 OpEx tariff comparison for an average dwelling in central England. Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH), Electric Vehicle (EV), Time of Use (ToU), Thermal Energy Storage (TES).

For the ASHP the tariff trends remain similar to what was found with DEH, but with significantly different magnitudes. Overall, the OpEx is typically less than half the value for ASHP compared to DEH, even though the standing charge cost does not change. As mentioned when reviewing Figure 3-5 (b), using the ASHP constant temperature profile allows higher proportions of low-rate electricity to be used, even without larger capacity TES. This changes the position between the flat rate and the Eco7 tariff, with Eco7 tariff now lower OpEx. The addition of larger TES capacity does also reduce OpEx, but alongside ASHP has a reduced absolute difference, with the largest decrease of £49 a year with the EV tariff, approximately a third of the reduction found with DEH.

Unlike with tariffs, the selection of hardware not only alters the OpEx, but also requires CapEx investment which should be considered to give the full costs of low-carbon systems for consumers. Figure 4-3 shows the compromise between reducing OpEx and increasing CapEx with larger TES sizes for both DEH and ASHP. The data used is for the VToU tariff which results in the lowest cost, although other tariffs do result in larger decreases in OpEx from higher capacity TES these are not part of the optimum lowest cost solution.

DEH annual OpEx decreases from £1231 by £94, which is an 8% reduction, from using larger capacity TES. For ASHP although the percentage reduction from larger TES is very similar at 7%, the absolute reduction is £37 significantly less from the nominally lower OpEx of ASHP compared to DEH. Both technologies benefit from TES in this manner, but it must be offset against the additional £831 CapEx from the larger TES. Due to the limited power of DEH and ASHP compared to combination boilers, both electrified heating technologies do require some use of TES, and therefore the minimum TES CapEx is used as the baseline comparison point.

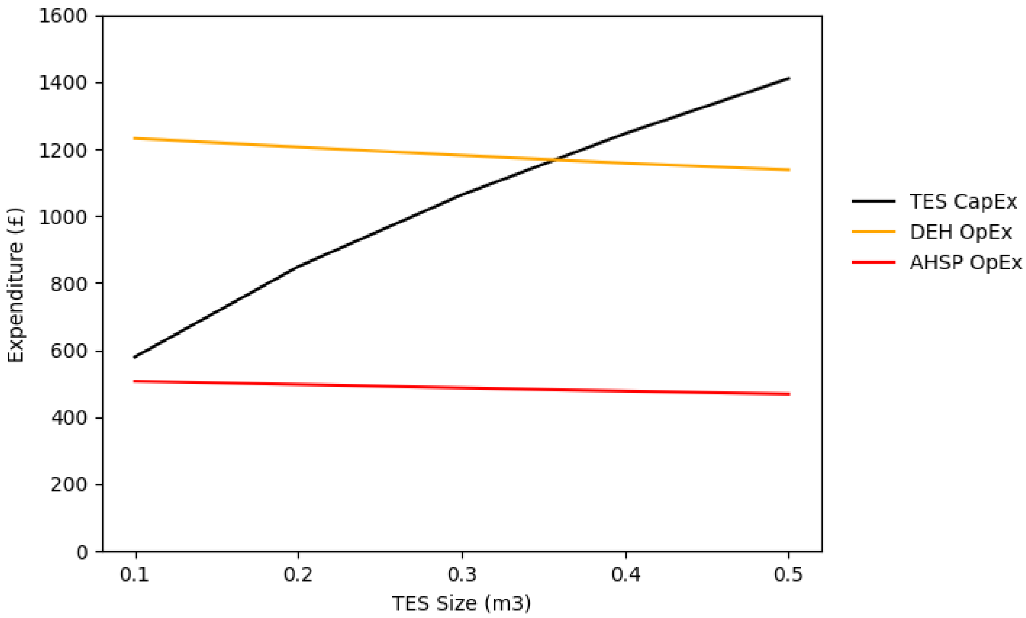

Figure 4-3 OpEx and CapEx changes from Thermal Energy Storage (TES) size for an average dwelling in central England. Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH).

Figure 4-4 introduces solar technologies alongside DEH and ASHP, showing the system OpEx reductions with increased solar technology sizing. For this comparison all systems are using the VToU tariff and a constant TES size of $0.3m^3$ is used, even if it is not the optimum sizing, to fix all other variables and allow capacity for the locally generated energy to be stored. For the DEH coupled with PV, it shows a strong trend of decreasing OpEx with increased sizing, where PV generated electricity is firstly used to try to reduce the associated cost of heating, then any surplus after the TES is fully charged is exported. With the VToU tariff the export rate at 5.5p/kWh is over half the average cost of electricity at 9.3p/kWh, before taking into consideration that when there is larger solar irradiance in the middle of the day is not aligned at the main evening peak which is the highest cost time, or with the second highest cost time from the morning peak. This reasonable export values creates a near linear decrease in OpEx with larger PV sizes even with limited storage capacity.

On the other hand, for solar thermal technologies coupled with DEH, there are more noticeable decreasing OpEx benefits with increased sizing. At lower sizes, solar technologies superior efficiency over PV with DEH allow solar technologies to result in lower OpEx. When the sizes are increased however the surplus solar thermal generation, especially in Summer when there is lower space heating demand, is wasted. Leading to solar technologies plateauing out at high sizes as more energy is wasted. At the larger sizes above 12m^2 it results in PV becoming lower OpEx than flat plate collectors. Evacuated tube technologies, which come with higher CapEx, perform better than FP technologies across the range of sizes. This is down to evacuated tube working more efficiently in scenarios where there are colder ambient conditions such as the heating season in the UK and when the sink temperature is higher which is more beneficial for conventional radiators and domestic hot water demands which are higher than underfloor heating system requirements. In addition, the higher efficiency at higher sink temperatures allows evacuated tube technologies to charge TES to higher temperatures, further improving its energy storage capacity.

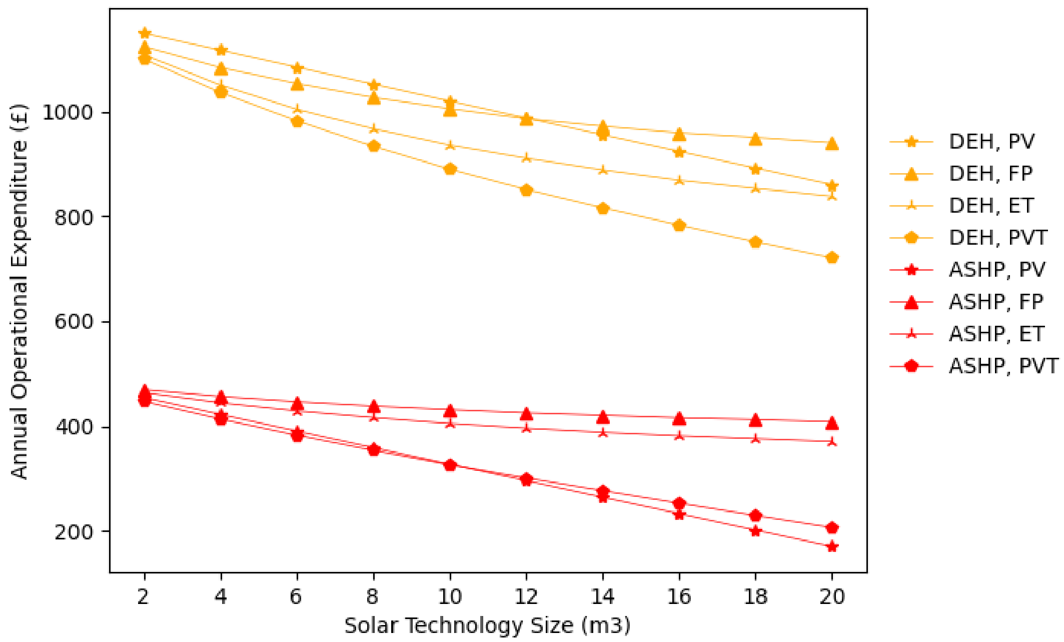

Figure 4-4 OpEx with solar technologies and their sizes for an average dwelling in central England with 0.3m^3 Thermal Energy Storage (TES). Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH), Evacuated Tube (ET), Flat Plate (FP), Photovoltaic (PV), Photovoltaic/Thermal (PVT).

DEH with PVT, which combines both aspects of PV and flat plate solar thermal generation, performs the best at reducing OpEx. The electrical energy generated can be used and exported in the same manner as PV was, although at a slightly lower electrical efficiency for PVT in the mild UK climate. The additional function of generating thermal energy directly then gives PVT overall the best system efficiency when alongside DEH, but this benefit does start to slightly reduce at higher sizes as found with evacuated tube and flat plate collectors, as the solar thermal aspect does lead to waste generation in Summer, albeit to a lesser extent for PVT.

When then comparing solar technologies coupled alongside the more efficient ASHP, the shape of the curves remains the same but with PV and PVT consistently being lower OpEx than flat plate and evacuated tube. Again, as found with TES and tariffs, the nominally lower OpEx of ASHP compared to DEH make improvements from solar thermal technologies lead to lower absolute reductions in OpEx. Resulting in both solar thermal technologies levelling off even more with increased sizes. However, for PV and PVT not only does the ability to export the home generated energy keep the OpEx reduction closer to linear with increasing sizes, the coupling with high COP ASHP makes them a better match than solar thermal technologies across the full range of sizes. This highly efficient use of electrical energy also is evidence in the fact that PV, with its slightly higher electrical efficiency, starts to outperform PVT at high solar technology sizes.

4.3 Comparison of Low-Carbon Heating Systems

The systems with their optimum tariffs, TES sizes, and solar technology sizes are shown with their OpEx and CapEx in Figure 4-5 when analysed from the consumers' perspective. Optimised TES and solar technology sizes are labelled in the legend.

For the electrified heating technologies, the optimum, lowest annual cost, tariff is consistently using the VToU tariff, as this was very competitive on average cost across the day, pre-energy crisis. The continuous thermostat setpoint/operation of heat pumps complements the use of VToU, night and EV off-peak tariffs as typical space heating demands increase when ambient are coldest, at night-time, which is also when electricity is typically lowest cost. The tariffs with the lowest rate at any point of the day become more favourable as the dwelling demand reduces with larger TES sizes, conversely in high demand dwellings and smaller TES sizes, the lowest average cost of electricity across the day becomes more beneficial. All tariffs used in Figure 4-5 therefore use the VToU tariff.

Although TES capacity was allowed to be selected up to 0.5m^3, this maximum available size was only selected as the optimum for DEH, where it is preferred over the 20-years for all ancillary solar technology options. For all heat pump configurations, the minimum TES size is selected of 0.1m^3. Due to the OpEx with heat pumps being relatively low, decreasing it further with larger TES capacities makes a small absolute decrease in OpEx, which is not sufficient to overcome the additional CapEx required for larger TES capacities over their lifetime. Although slightly higher TES capacities are selected when using flatter TES CapEx against capacity as used by Renaldi et al., showing the economic viability for TES with heat pumps is very sensitive to the TES CapEx [41]. The opposite case is found with DEH from its nominal higher OpEx, where larger capacity TES are selected as the increase in CapEx is small relative to OpEx over 20-years. As this study is only from the consumers' perspective it does not take into consideration whole energy system benefits, which for TES could be to aid reduction of peak electricity demand. If this is to be encouraged further TES incentives, or a larger hourly variation in electricity prices, may be needed to promote the use of TES for the larger energy system management benefits.

When optimising the size of the solar technologies in the Coventry England location, consistent trends are found. PV is always sized to the maximum, with any electrified heating, due to the value of using and exporting the generated electricity over the technology's lifetime outweighing the investment cost. In addition to OpEx benefits still strongly increasing with larger PV size, the CapEx structure of PV starts to level off, as there is little increase in invertor, wiring, and scaffolding costs with larger PV size installation, leading to better £/kWp at increased PV sizes. When alongside heat pumps, the minimum solar thermal and PVT sizing is selected as OpEx reduction is a lower absolute value. Additionally, CapEx of solar thermal and PVT does not decrease as much as PV with increased size, due to higher collector cost and the additional plumbing requirement for each collector, making solar thermal not financially viable from NPC point of view alongside heat pumps. However, when alongside DEH slightly larger solar thermal / PVT sizing is selected, due to the nominal higher OpEx of DEH making solar thermal technologies more effective at reducing overall costs.

Heat pump combinations can achieve comparable OpEx to the current natural gas boiler, but at noticeably higher CapEx values which limits the amount of the population that will be able to invest in this technology. DEH on the other hand is similar CapEx to gas boilers so can be considered more affordable investment, but at a large increase in OpEx. The distance on the x-axis from the gas boilers quantifies a value for incentives that may be required to promote each technology over the incumbent boiler. For technologies that are higher up the y-axis than the gas boiler this difference needs to be discounted and summed over the lifetime to quantify a mechanism to make these technologies competitive with gas. Generally, with higher investments of GSHP over DEH, or solar technologies a reduction in OpEx is found, although there are slight variations in the cost effectiveness of different solar options depending on the prime heating technology.

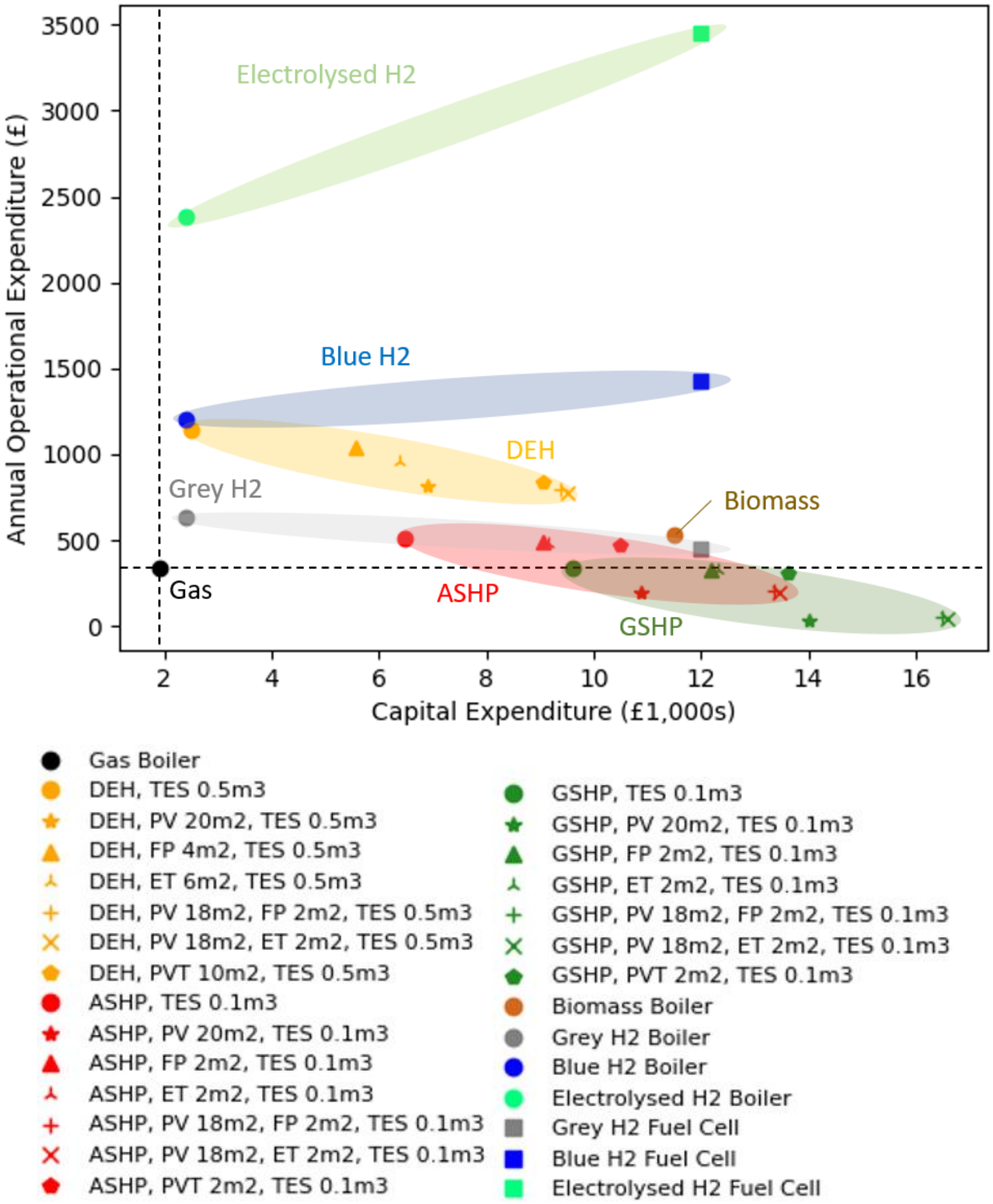

Figure 4-5 OpEx against CapEx for heating technologies with optimised tariffs, TES sizes, and solar technology sizes, in an average UK dwelling. Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH), Evacuated Tube (ET), Flat Plate (FP), Ground Source Heat Pump (GSHP), Photovoltaic (PV), Photovoltaic/Thermal (PVT), Thermal Energy Storage (TES),

H_2 boilers' CapEx is slightly higher than natural gas boilers but using the hypothetical H_2 gas grid costs the increase in OpEx is found to be significant for Blue H_2 and over a factor of four times larger for Electrolysed H_2, with only Grey H_2 being comparable to gas. H_2 FC CapEx is a magnitude higher than H_2 boiler CapEx and OpEx difference from H_2 boilers to FC greatly depends on the cost of H_2 compared to the electricity cost. Where high-cost H_2, from Electrolysed H_2 makes a FC less viable compared to a H_2 boiler. The certainty of the H_2 costs remains low and is dependent on the fuel price estimates from the literature, however the trends in differences between H_2 costs and its fuel source, of fossil fuels or electricity, are likely to remain without policy intervention or high amounts of excess renewable energy generation which would otherwise be curtailed.

To clarify the optimum heating technology when there are trade-offs between CapEx and OpEx, NPC is used to determine the lowest 20-year lifetime cost technology system for the consumer. NPC is shown in Figure 4-6 x-axis and the y-axis shows the equivalent emissions for the heating technologies where there is a significant range in heating emissions due to the production methods of electricity and H_2, technology efficiencies and the embodied emissions. Evacuated tube solar thermal collectors are not shown in the image due to their NPC and emissions proximity to flat plate solar thermal collectors in this image, Grey H_2 and Electrolysed H_2 FC are also not shown in (c) to aid image clarity.

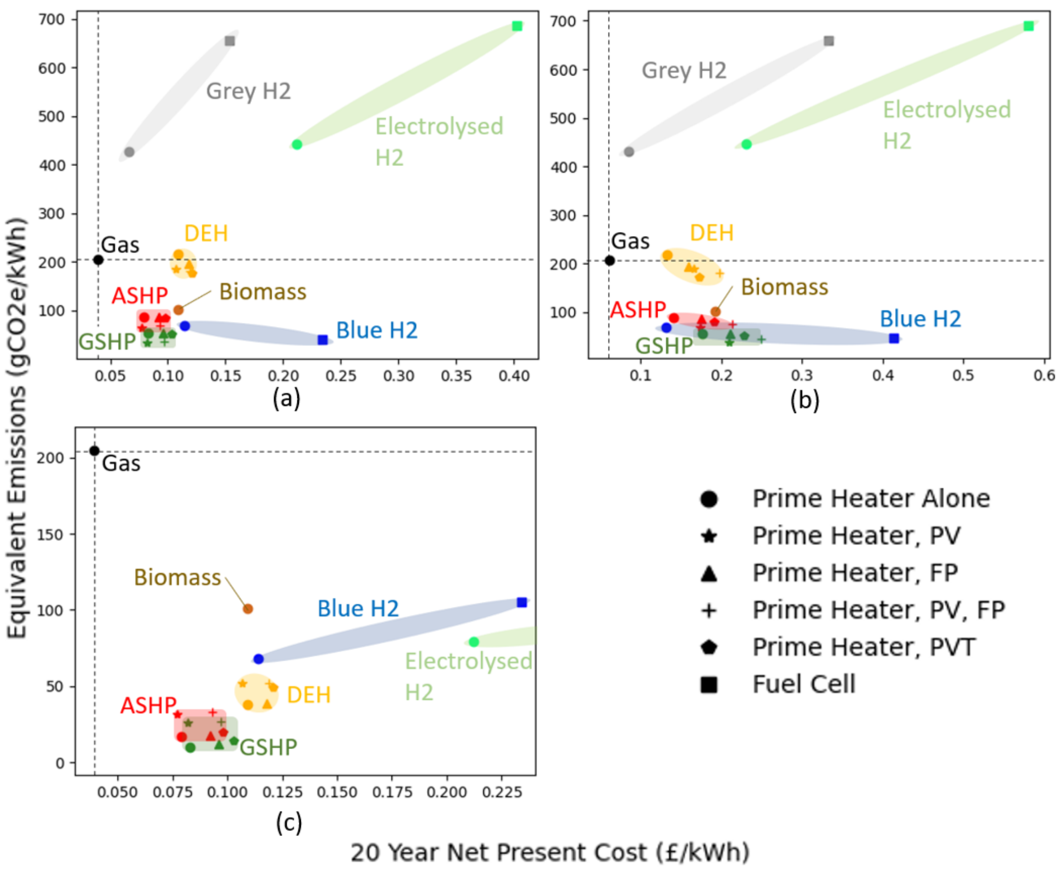

Figure 4-6 Emissions and life-time costs for heating technologies. For (a) the average demand UK dwelling in Coventry, (b) the 10th percentile very low demand UK dwelling in Coventry, and (c) the average demand UK dwelling in Coventry with 2035 target grid emissions. Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH), Flat Plate (FP), Ground Source Heat Pump (GSHP), Photovoltaic (PV), Photovoltaic/Thermal (PVT), Thermal Energy Storage (TES),

Comparing across the electrified heating technologies for the average dwelling (a), with the increased CapEx and improved efficiencies, tends to result in lower NPC, with heat pumps being slightly lower lifetime cost than DEH, but the highest investment of GSHP is not worthwhile for the average demand dwelling as ASHP is slightly lower cost. PV is the only solar technology that reduces lifetime cost from electrified heating. Emissions across electrified heating follows similar trends to OpEx, that higher efficiency technologies use less primary energy and therefore reduce emissions further. In the same manner to how solar technologies affected the electrified heating OpEx, the emissions reduction from PV is higher with more efficient heat pumps, with PV coupled with GSHP allowing very low emissions due to excess generated electricity being exported and therefore its related emissions. Solar thermal collectors can potentially increase emissions for GSHP due to its high COP and the comparison of grid emissions vs embodied emissions of solar thermal collectors. Whereas solar thermal can reduce the emissions from the lower efficiency DEH.

Biomass results are between ASHP and DEH groups, with similar OpEx and emissions to ASHP. However, the high CapEx of an automatically fed biomass boiler increases NPC in-line with the upper range of electrified heating technologies. Although lower CapEx options are available which are manually fed, these options are less comparable to the other heating systems which do not require manual operation. Biomass boilers also produce local emissions which are harmful to health, which none of the other technologies other than the baseline gas boiler produce. The simulated CO_2e emissions from biomass using the input values can result with reasonable results for biomass compared to current technologies and grid emissions, however these significantly vary for biomass depending on the type of trees used, their location for how effectively the absorb CO_2, what the landscape they are replacing was, and the emissions in transporting the solid fuel.

Across the range of H_2 production methods, other than Grey H_2 boilers, the NPC for H_2 boilers and FC are the highest compared to other technologies due to the higher OpEx. FC are then significantly higher 20-year cost due to the shorter lifetime of the FC at only 10 years coupled with the high CapEx. Although Grey H_2 boilers are economically competitive, there is a significant rise in emissions relative to natural gas boilers, due to the extra processing inefficiencies and the lack of carbon capture and storage. Adding efficient, ideal, carbon capture and storage allows the theoretical Blue H_2 boilers to be at the lower range of emissions compared to other technologies, and without a high CapEx for the user, albeit with a high OpEx and NPC in-line with the highest electrified heating options. In addition to Electrolysed H_2 having a high NPC from its high OpEx, the emissions are also the highest, due to the emissions from grid electricity generation coupled with a low system efficiency for Electrolysed H_2 compared to electrified heating.

Figure 4-6 (b) shows the very low demand dwelling results. The lower annual heating demand reduces OpEx of the heating technologies and therefore puts more reliance on the CapEx in the lifetime costs. This shifts the optimum heating technology to Blue H_2 boilers and closely followed by DEH, when excluding Grey H_2 due to its inability to reduce emissions relative to the baseline. The use of ancillary technologies is also less viable as the CapEx of solar systems does not decrease linearly to size.

To demonstrate how potential future reduced grid emissions may affect the emissions of heating technologies Figure 4-6 plots the results for the average UK dwelling with grid emissions reduced to a targeted 2035 level. In turn this reduces the emissions from electrified heating options and Electrolysed H_2. In this scenario heat pumps are now more noticeably the lowest emitting technologies with DEH slightly higher but now lower than Biomass and Blue H_2. With future grid generated electricity being so low on emissions, the embodied emissions from solar technologies manufactured today (when divided across the lifetime of the technology) do not give an environmental advantage alongside electrified heating. Emissions from Electrolysed H_2 are also decreased to be on par with Blue H_2; as also found by Ueckerdt et al. electricity generation needs to have high amounts of renewable energy for Electrolysed H_2 emissions to be competitive [11].

From reviewing the lowest cost technology over 20 years for the average and very low demand dwellings showed differences in the cost optimal solution. To expand on this Figure 4-7 shows the histogram of annual heating demands by percentage of UK dwellings on the left axis, against the optimum cost technology over different timescales on the right axis. When comparing across 20 years approximately only the lower 13% of dwellings were suitable for DEH, for analysis at shorter durations significantly more dwellings optimise with DEH for the consumers with its lower CapEx. There is a similar trade off at higher demand dwellings and over longer timescales between ASHP and GSHP. A key point to highlight is that both breakeven lines level out at higher demands, this is due to the increased CapEx required for more thermally powerful heaters in higher heating demand dwellings. The increased CapEx is especially apparent for GSHP due to the installation of larger underground heat exchangers being a more substantial part of the cost.

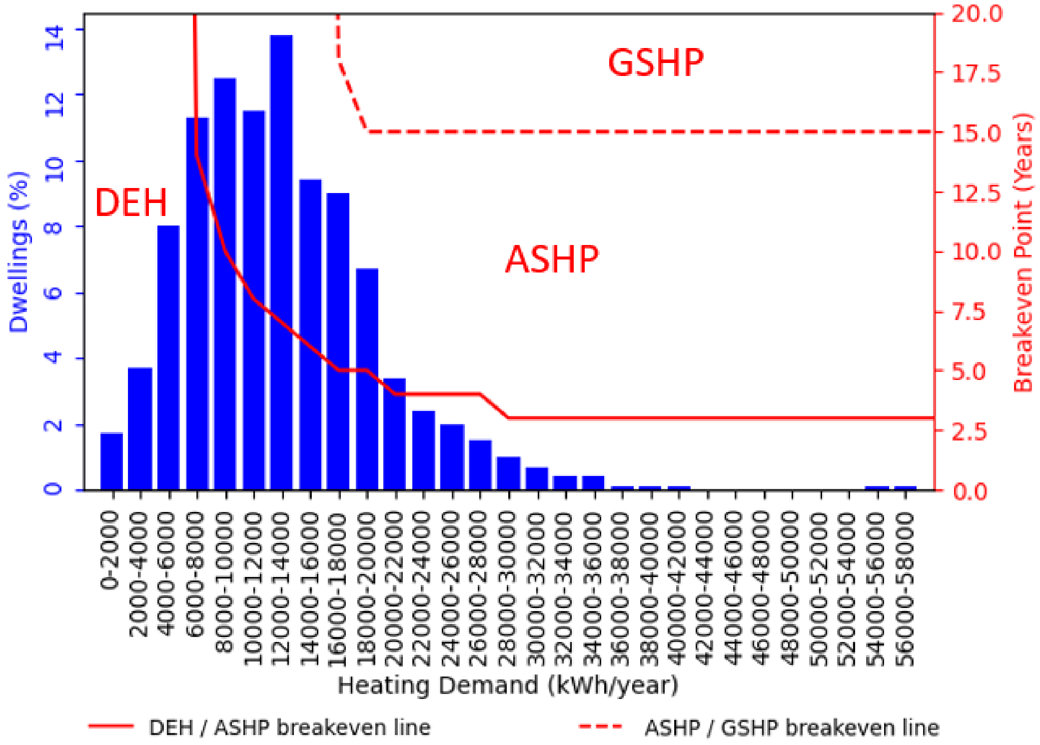

Figure 4-7 Optimal cost heating technology. Breakeven durations against dwelling heating demands, compared to the percent of UK dwellings at the different ranges of heating demands. Data from 2017-2018 from a sample of 1770 dwellings. Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH), Ground Source Heat Pump (GSHP).

Results shown can be used to identify incentives that may be required for each heating technology to make it economically viable compared to incumbent fossil fuel heaters. The x-axis of Figure 4-5 demonstrating CapEx grants or technology cost reductions that may be required to reduce the gap to the gas boiler, and the y-axis differences showing the OpEx that could be discounted over the lifetime of the products or to quantify efficiency improvements required. The analysis finds electrified heating is generally the lowest cost and lowest emissions. Figure 4-6 shows the emissions reduction potential of technologies, as the electricity grid may become decarbonised. Where solar technologies can have a positive impact with the current grid state of play but reduce their effectiveness with lower grid emissions. Although Blue H_2, when commercially available, can reduce emissions straight away, Electrolysed H_2 is only effective as the grid becomes significantly decarbonised.

4.4 Effect of Spatiotemporal Variations on the Optimum Heating Technology

For determining how spatiotemporal variations can change the optimum heating system, maps are created to show the low-carbon heating technology combinations with the lowest 20-year NPC (excluding natural gas and Grey H_2 due to inability to reduce emissions) at each 0.5x0.5° longitude and latitude across the UK. Figure 4-8 shows five maps each with different dwelling demands: (a) a very small dwelling; (b) a small demand dwelling; (c) an average dwelling; (d) a large dwelling, and (e) a very large demand dwelling. The heating degree days for the previously used central England location of Coventry are 2027, the lowest and highest values across the UK locations used, with the weather dataset used, are 1554 and 2840 respectively, all using a base temperature of 15.5°C. The optimum heating technology across the UK and for all different dwelling properties is predominantly electrified heating system, sometimes with the prime heater alone and sometimes coupled with PV.

In the average dwelling, (c), ASHP is mainly the optimum technology, where coupling with PV is preferred in England and Wales, but generally not in Scotland or Northern Ireland where there is less solar irradiance. GSHP does become preferable in the average home in the most inland and highest altitude areas where colder Winter temperatures increase heat demands and reduce ASHP efficiency.

As dwelling heating demand increases for the large (d) and very large (e) dwellings more locations optimise with GSHP, from the inland and northern locations towards coastal and south areas where Winters are milder. With the increased heat demand also comes more coupling of PV as more generated electricity can be used and PV cost per installed capacity reduces with larger arrays possible on larger rooftop area of the larger dwellings.

Conversely, with 20-year analysis, in the small demand dwellings (b) in nearly every UK location ASHP becomes preferable but without PV. The only exception being some locations in the Southwest of England, with very mild Winters, where DEH becomes beneficial due to the low heating demand. Reducing demand to the very small dwelling (a) shows more varied results, as DEH becomes more prominent, but then in the warmest locations Blue H_2 is also competitive due to its slightly lower CapEx than DEH. However, even in a very small dwelling when it is positioned in the coldest UK locations ASHP remains the preferred option.

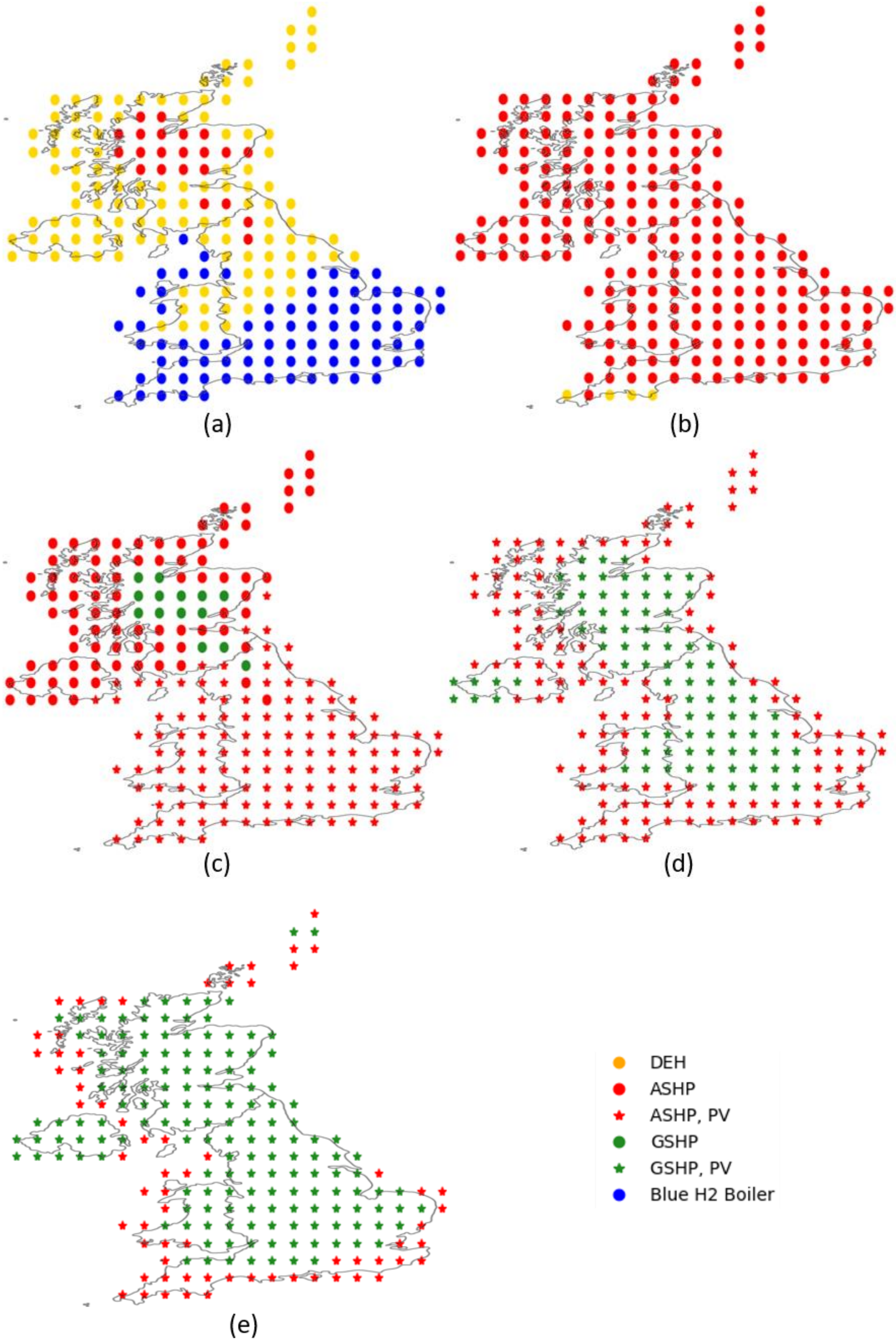

Figure 4-8 Optimal cost heating technology maps for different size dwellings, where the size is based on percentile heating demands when in central England, Coventry, location (a) very small lower 10th percentile dwelling, (b) small lower 25th percentile dwelling, (c) 50th percentile dwelling, (d) large upper 75th percentile dwelling, and (e) very large upper 90th percentile dwelling. Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH), Ground Source Heat Pump (GSHP), Photovoltaic (PV).

Joining all the analysis together creates the technology landscape for low-carbon heating, showing how there is no single ideal technology and that it changes based on many factors. Based on lowest 20-year NPC methodology of low-carbon technologies only, the average demand dwelling optimises with ASHP, then ranks GSHP next, followed by DEH. For very low demand dwellings this changes to Blue H_2 boilers, then DEH, followed by ASHP, and for high demand dwellings the preferred heater is GSHP, then ASHP and DEH. If optimising by lifetime emissions GSHP is the lowest for all demands considered, followed by Blue H_2 then ASHP. However, as the electrical grid emissions reduce ASHP and DEH emissions become lower than Blue H_2 emissions.

Optimum technologies shown in Figure 4-8 are dependent on the inputs used in the framework. The most sensitive variable to altering the results is the cost of energy, where higher costs encourage more efficient technologies to be preferred and lower cost electricity makes lower CapEx DEH more economically favourable. Another key variable is the CapEx for the heat pumps and in particular for GSHP where cost variations can be substantial percentage of the NPC. Higher CapEx of heat pumps causes more locations and dwellings to optimise over the 20-years with the lower CapEx DEH.

The spatiotemporal analysis for different dwelling variants shows some key take-away messages, electrified heating is generally economically preferrable among all low-carbon heating technologies considered, and the optimum technologies are dependent on the dwelling's properties and its location. The addition of PV to an electrified heating system can be favourable over the lifetime but is dependent on the location, the dwellings heating demand, and the maximum size array that can be fitted.

4.5 Summary

This Chapter answers the first research question to determine how spatiotemporal and dwelling variations alter the position of the different low-carbon heating systems. It analyses a range of different dwellings in central England and then across every 0.5° longitude by 0.5° latitude location in the UK. To find ASHP are generally the preferred solution, but there are many scenarios where for lower demand dwellings and importantly over shorter timescales than the technologies lifetime that DEH is preferred. This higher than expected consumer preference of DEH, that is not captured in the current research, needs to be reduced to prevent exacerbation of the concerns around meeting the electrical demands from low-carbon heating.

Here a novel versatile framework is presented that fills gaps in current studies, allowing greater understanding of the diverse range of low-carbon heating technologies and their potential when integrated and optimised with different energy sources, ancillaries, and tariffs. Highlighting both their economic and environmental performances from the consumers' perspective. Taking the consumers' perspective is critical for understanding what technologies may be taken up, instead of what technologies are desired for the network or at a national level. The framework also demonstrates how the viability of heating systems changes for different spatiotemporal and dwelling parameters, allowing consumers, network operators, and policy makers to determine the optimum NPC low-carbon heating technology system and to quantify what incentives may be required to select more efficient high investment technologies.

Each heating technology combination, with its optimised solar technology size, TES size, and tariffs is compared in terms of OpEx, CapEx, NPC, and emissions by completing heating simulations across the year at hourly resolution. A key trade-off is found between OpEx and CapEx: when optimised by 20-year NPC this highlights that high CapEx is required for an optimal solution of heat pumps in most dwellings, which is likely a limiting factor for many users. With decarbonisation of the electricity grid, electrified heating also reduces its emissions, and the coupling of solar technologies becomes less valuable in terms of emissions. Electrolysed H_2 can produce low emissions but requires nearly complete grid decarbonisation to be competitive with Blue H_2 on emissions. All low-carbon heating technologies struggle against the economic competitiveness of current fossil fuel boilers which have low OpEx and CapEx. The OpEx or CapEx differences from a low-carbon heating technology to the baseline in the results can help to target technical improvements required by new technologies or incentives required to encourage uptake.

The versatility of the framework shows the effect of the changes in spatiotemporal and dwelling properties on the heating technologies. Most scenarios analysed found electrified heating as the optimum low-carbon heating technology. Average homes typically optimise with ASHP and high demand homes to prefer GHSP over 20-years. However, for lower demand dwellings, especially in more costal and southern locations DEH and Blue H_2 boilers become optimum. The effectiveness of different heating technologies even across the small climate variations in the UK emphasises the importance of considering spatiotemporal and dwelling variations.

Alongside this, when analysis is completed over shorter timescales DEH also becomes a more preferential option for increasing heating demands. Not only may the high CapEx of heat pumps be a restricting factor for many consumers especially low-income households, but also the timescales needed for heat pumps to breakeven over DEH may far outweigh how long consumers are willing to wait to reap the benefits of their investment. In parallel, as thermal efficiency of dwellings improves from retrofitting and new housing standards, and global warming continues, dwelling heating demands should reduce, and DEH will become more competitive against heat pumps. This viability of DEH over ASHP for consumers has not been realised in current studies, which is a critical insight for larger network implications. The increased demand from DEH over ASHP would require substantially more electrical network capacity and generation, where ASHP uptake is already of concern for networks as highlighted by Love et al [12], and so mass uptake of DEH would not be desirable on larger regional and national levels. Careful consideration needs to be given to incentives in low-carbon technologies, as whilst reducing electricity costs alone relative to gas costs will benefit electrified heating and reduce the risk of fuel poverty in low-carbon heated dwellings, the lower electricity costs also shift towards DEH being preferred over ASHP.

Chapter 5 Holistic Analysis of Consumer Demands

Consumer emissions account for around a third of all emissions globally. The consumers' perspective on low-carbon technologies is critical to gain an understanding of technologies that will likely be taken up, as technologies for any energy demands need to be financially viable for many consumers to justify adopting them. A holistic consideration of demands and technologies is critical due to the high amount of interaction between demands and technologies and their competing use of energy storage, utilisation of rooftop PV generation and preferred tariff structure. Presented here is a comprehensive holistic approach that includes electrification and hydrogen options to understand the trade-offs in technologies and tariffs for consumers in their energy decarbonisation pathways which is missing from the technology specific analysis in the literature.

Chapter 4 first used the novel framework focusing on the heating aspects alone, in this Chapter all of the demand features of the holistic framework, that were defined in Chapter 3, are used together. Considering all consumer demands simultaneously through combinations of different low-carbon technologies over a 20-year lifetime, linked with conventional and emerging electricity tariff structures. In this Chapter, using the UK as a case study, the results find that electrification is more cost-effective than hydrogen for most consumers to reduce their energy emissions and that the lowest 20-year low-carbon solution of ASHP, EV, and PV may have slightly (9%) higher lifetime cost to the gas boiler and petrol car baseline but can achieve 54% emission reduction using the grid electricity mix and energy tariffs in 2020. In terms of technologies, EV and solar PV are the only evaluated technologies that have the potential to reduce customer's 20-year energy costs, 8% and 0.2% respectively, alongside emissions reductions, of 28% and 2% respectively. Energy storage technologies, though significantly benefit the grid by unlocking demand-side flexibility, were not economic beneficial to customers until the tariff increase due to the energy crisis. Designing the average day rate of a tariff is most important for adopting electrified heating, on the other hand energy storage use requires low off-peak rates, where the Chapter quantifies the minimum required difference in tariff peak to off-peak rates to allow energy storage financial justification. This learning can be used to help incentivise consumers to adopt these technologies, allowing greater system benefits.

This Chapter is largely based upon the published work "Holistic Analysis of Consumer Energy Decarbonisation Options and Tariff Effects" published in *Applied Energy* by the authors, M. Ryland and W. He.

5.1 Overview of Complete Low-Carbon Systems

In this Chapter, average, low, and high demand UK dwellings are considered at the central England location, where the average demand dwelling simulates with the same annual heating demand as the median UK home. The baseload, cooking, and transportation demands are also set to the average demands. Each hour in the simulations all the demands are combined, any self-generated energy is simulated, and the demands are met by the technologies under consideration for that simulation. TES and BES are used to shift energy from off-peak times and using solar technologies where applicable to meet as much of the consumer demands at peak times as possible, for the tariff under consideration. Results of the key system configurations are shown to demonstrate the effect of variables on the OpEx, CapEx, NPC, and emissions from the consumer's perspective to show what technologies they would likely adopt.

Figure 5-1 shows the result for an average dwelling comparing the OpEx and CapEx. The position of the current baseline fossil fuel combination of the gas boiler, gas cooking, and petrol car are shown with black dashed lines. Results are grouped in ellipses by the prime energy source for both heating, cooking, and transport within electric and H_2 groups, then a third group is formed of the baseline petrol car with a gas boiler, ASHP and electric cooking, and Blue H_2 boiler and cooking option to show the step changes in results from domestic and transport technologies separately.

An increase in investment to have zero tailpipe/local emissions technologies sometimes also leads to a reduction in OpEx, but not always. Low-carbon cars do find a co-benefit of reduced OpEx, from a petrol car at £1065 a year to £178 for EV and £330 using Blue H_2 in a FC car. Within the electrified prime heaters and ancillary technologies show the same trend, that the high CapEx technologies generally improves system efficiency and therefore reduce heating OpEx, from £1155 a year for DEH, to £430 for ASHP, and £265 for a GSHP. However, the baseline heater is the main outlier, being the natural gas boiler, which has the lowest CapEx and OpEx of £272. The multi-vector approach demonstrates that although reducing emissions from transport does require higher investment than low-carbon heating systems, low-carbon cars do come with the additional benefit of reduced OpEx.

The high CapEx which is required for nearly all low-carbon technologies is likely a limiting factor for many consumers, especially those on low-income. This limiting factor for heaters could restrict many consumers to DEH or H_2 boilers, which generally come with higher OpEx. However, for transportation there are no lower options that are comparable to fossil fuelled cars, leaving no options for low-income consumers.

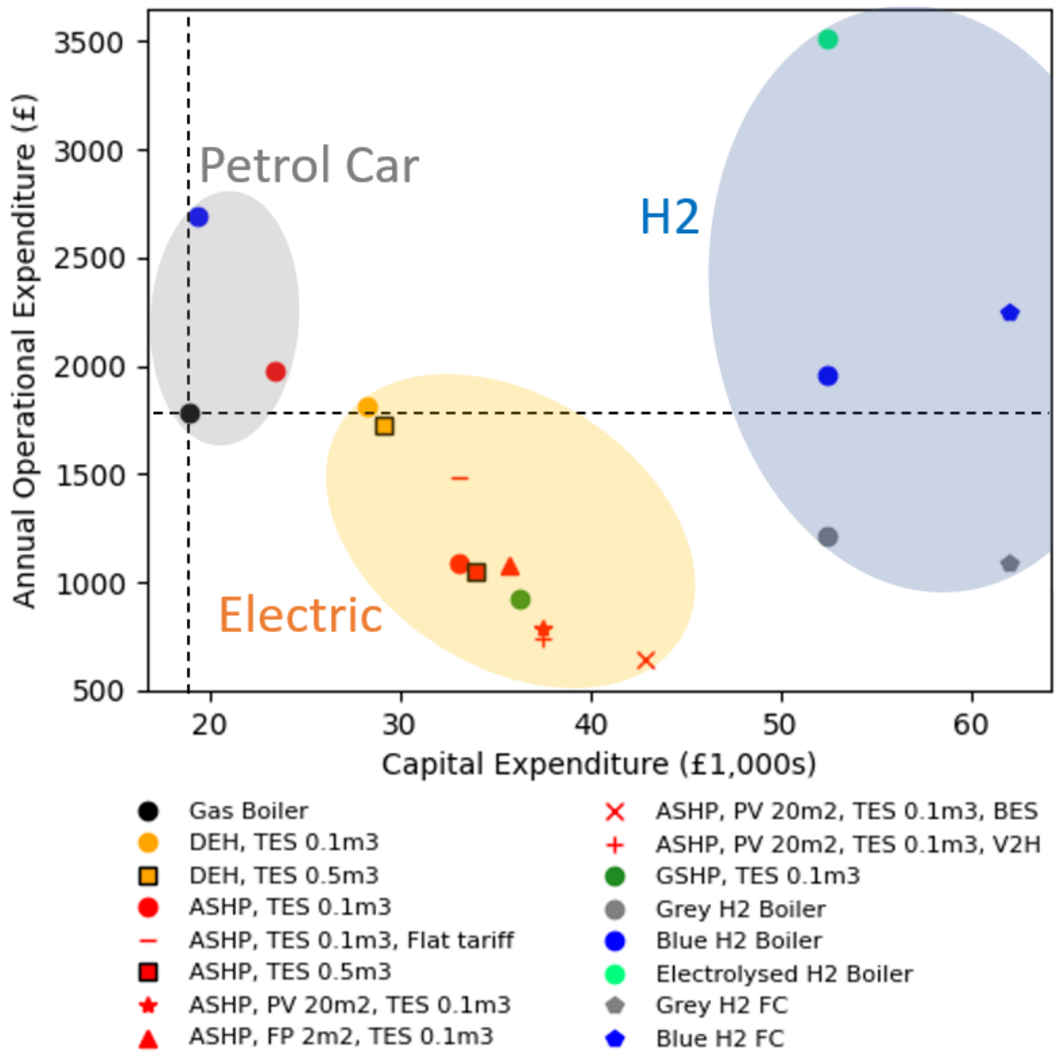

Figure 5-1 CapEx against OpEx of all consumer demands for an average dwelling and key system configurations to highlight effects of variables. All systems using the optimum VToU tariff unless stated otherwise. Ellipses are used to group technologies. Electrified groups collate results with electrified heating, cooking, and transport and the H_2 group collates options using H_2 fuels to meet all demands other than baseload. The petrol car group has the gas and petrol baseline as well as petrol car with heating using an ASHP and a Blue H_2 boiler to show step changes from individual parameters. Air Source Heat Pump (ASHP), Battery Energy Storage (BES), Direct Electrical Heating (DEH), Flat Plate (FP), Fuel Cell (FC), Ground Source Heat Pump (GSHP), Photovoltaic (PV), Thermal Energy Storage (TES), Vehicle to Home (V2H),

Although multiple tariffs were analysed from the low energy period of 2020 for these results, as found when solely looking at heating demands in Chapter 4, in nearly all technology combinations the optimum tariff was the VToU tariff and so is used in each results shown unless stated otherwise; the significance the tariff has on the OpEx can be seen by looking at the single result shown with the flat rate tariff (generally this tariff gave the most expensive results) which resulted in a 37% higher OpEx with the same hardware. This difference from tariffs is greater than found from heating alone, the additional difference is predominantly from transportation. Making the tariff one of the most critical variables for EV and other electrified energy costs. It was found that the average day rate of the tariff is the principal factor in the tariff design for incentivising the switch from gas to electrified heaters and cooking.

To understand the trade-off between CapEx and OpEx for the variables, Figure 5-2 introduces the NPC for the systems which is plotted against the equivalent annual emissions, that includes operational direct and indirect emissions for all demands and a yearly equivalent of the embodied emissions for the heating, transportation, energy storage, and solar technologies hardware.

Using NPC, the results show that the high investment required for EV can result in lower lifetime costs compared to the baseline, however the same cannot be said for H_2 cars and low-carbon heating technologies. The natural gas boiler remains the lowest lifetime cost solution for heating. For the average home, the next most competitive solution is an ASHP, closely followed by a GSHP. The high OpEx of DEH causes a high NPC for the average demand dwelling.

With the high efficiency of ASHP and GSHP comes a 57% and 74% emissions benefits respectively over gas with the current electrical grid mix. DEH with its lower CapEx, has a lower efficiency than heat pumps and comparative emissions to the gas boiler, but will improve with the decarbonisation of the electrical grid, as the rest of the direct and indirectly electrified options will.

For the H_2 solutions, improvements in emissions differs for heating and transport, and depends on the manufacturing method of the H_2. Due to H_2 not currently being produced at scale, there is significant uncertainty around its costs, but the general trends are likely to remain without Government and policy interventions. As Grey H_2 is sourced here from steam methane reforming of natural gas without carbon capture and storage, it is logical that using it in a H_2 boiler gives slightly higher OpEx and significantly higher emissions than gas boilers, yet despite the lack of carbon capture its use in cars can result in lower emissions than a petrol car. Adding a highly effective carbon capture and storage process onto Grey H_2 gives the potential for Blue H_2 which increases the OpEx due to more manufacturing processes, inefficiencies, and industry capital requirement, but has a significant impact on emissions for both transport and heating, resulting in the lowest emitting technology. Electrolysis of water to make Electrolysed H_2 then picks up the associated emissions from the electricity production, which for this study uses the electricity emissions from the grid mix. As per the comparison between Grey H_2 and natural gas, the use of Electrolysed H_2 compared to direct electrification of heat has the downside of additional processing requirements which causes higher OpEx and emissions than direct electrification. Using current electrical grid emissions this causes Electrolysed H_2 to also have higher emissions than gas boilers. Another option for heating with H_2 is the use of FC, although they have a lower thermal efficiency than boilers, due to self-use and exporting of the electricity generated they can result in comparable OpEx and emissions to H_2 boilers depending on the H_2 source, however, the shorter life and higher CapEx of FC compared to boilers creates higher NPC.

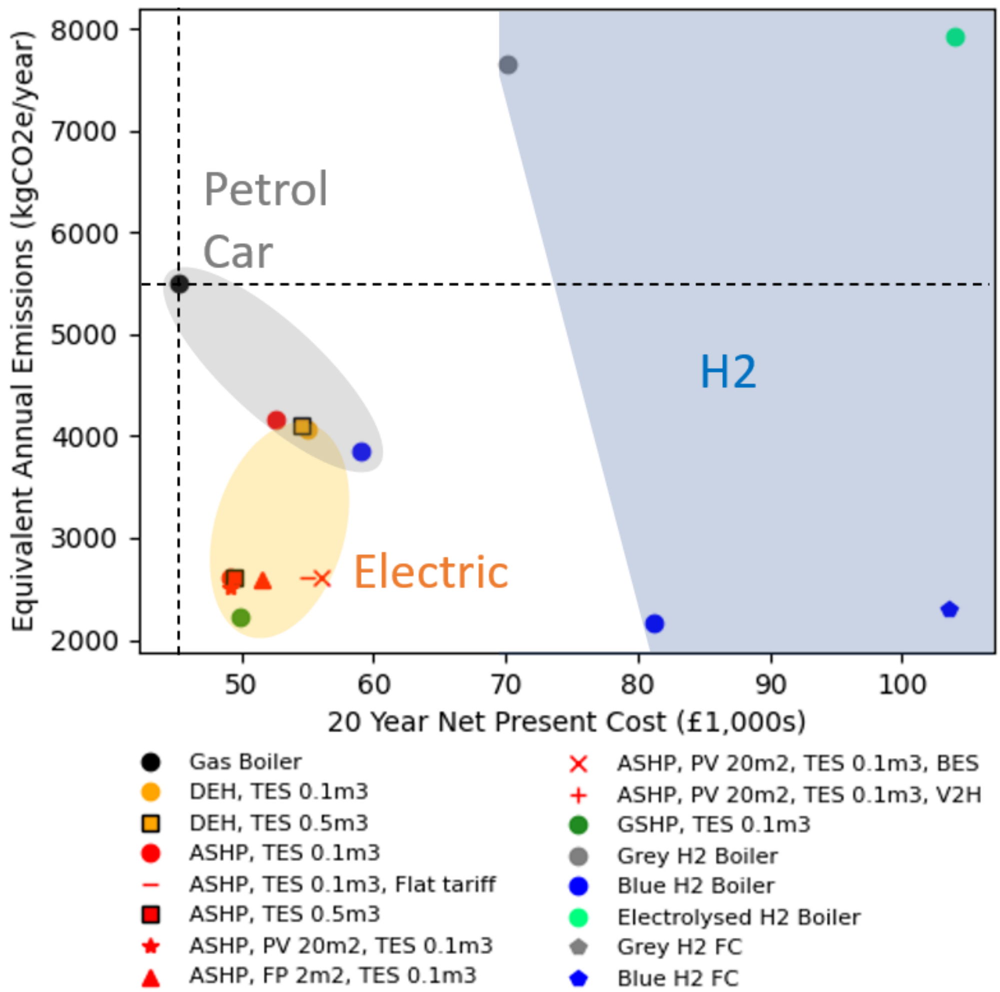

Figure 5-2 20-year NPC against equivalent annual emissions of all consumer demands for an average dwelling and key system configurations. All systems using the optimum VToU tariff unless stated otherwise. Air Source Heat Pump (ASHP), Battery Energy Storage (BES), Direct Electrical Heating (DEH), Flat Plate (FP), Fuel Cell (FC), Ground Source Heat Pump (GSHP), Photovoltaic (PV), Thermal Energy Storage (TES), Vehicle to Home (V2H), Reviewing the ancillary technologies shown within the electric group, generally shows limited economic and environmental benefits with the simulation inputs, although there are some outliers. The addition of PV to an electrified system can give OpEx and emissions benefits, with limited additional benefits of PV with electrified transport using the vehicle away from home pattern in this framework. However, if the EV is at home more during the middle of the day this would allow further use of PV to charge the EV. Solar thermal collectors are not found to be an economically viable addition to a prime heater, other than with DEH as previous found in Chapter 4, and adding the other consumer demands gives no extra benefit as solar thermal collectors can only meet heating demands.

The use of TES can reduce OpEx for electrified heaters which have varying hourly tariff rates, but the OpEx is only reduced sufficiently when alongside the nominally higher OpEx DEH, where it can overcome the additional CapEx required for larger TES, when using the low tariff rates. For the more efficient heat pumps with the difference in peak vs off-peak tariffs rates, the use of TES is not viable over its lifetime. As with solar thermal collectors, the inclusion of the complete consumer demands has no bearing on TES.

The full potential of BES and V2H found in the results is only possible due to the holistic approach considering all demands simultaneously. Yet with their current CapEx and the low-rate tariffs it is also found that the use of BES and V2H with the EV: OpEx reductions do not cover the CapEx cost of the BES over its 10-year life and are less than the degradation cost to an EV from using this secondary function of its battery. With the use of V2H functionality on an EV which was also used on weekday commutes and weekend journeys, this limits the potential of V2H compared to a stationary BES which, has a smaller capacity and charge rate, but the BES is available all the time. There may however be small further benefits for energy storage alongside PV if finer resolution simulations were complete, as this would lead to higher fluctuations in energy generation which demands may not be able to match as closely such as heat pumps, allowing BES or V2H to fill in smaller mismatches in supply and demands. This would not be the case however for DEH which can alter demands very quickly.

Bringing all variables together results with the lowest 20-year NPC low-carbon solution for an average dwelling using a combination of ASHP, EV and PV with the minimum TES size and VToU tariff. This has an NPC at £49,091 and emits an equivalent of 2508 kgCO_2e/year, this is less than a 10% increase in cost over 20-years for less than half of the emission of the baseline with an NPC of £45,205 and 5509 kgCO_2e/year.

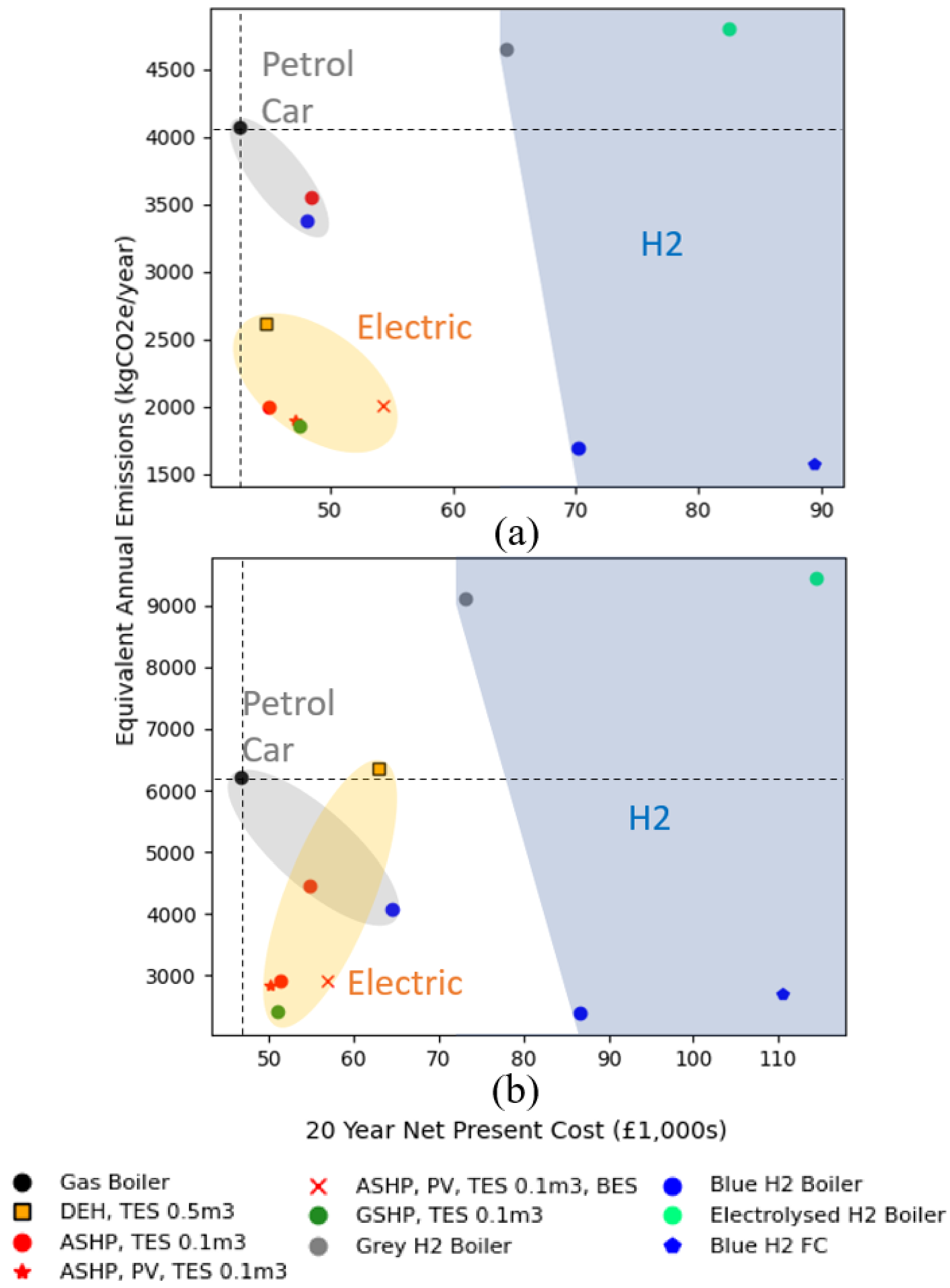

Figure 5-3 20-year NPC against equivalent annual emissions of consumer demands for (a) low demand dwelling and (b) high demand dwelling, with key system configurations. All systems using the optimum VToU tariff. PV systems optimised to their maximum sizes of 6m^2 on the small low demand dwelling and 28m^2 on the large high demand dwelling. Air Source Heat Pump (ASHP), Battery Energy Storage (BES), Direct Electrical Heating (DEH), Fuel Cell (FC), Ground Source Heat Pump (GSHP), Photovoltaic (PV), Thermal Energy Storage (TES),

Utilising the multi-vector framework, it is possible to see how the performance of the technology systems alter with varying demands, Figure 5-3 uses (a) a low demand dwelling and (b) a high demand dwelling with the same transport demands as the average dwelling. Altering the ratio of heating demand to transport demand does not change the position of any of the transport technologies from the previous findings, but it does adjust the distribution of car to heater significance in the results. Finding that, unlike with the average demands that transportation had the greater potential for emissions reduction, with the higher heat demand dwelling it is possible for the consumer to reduce more emissions by changing their heating method instead of changing their car.

A noticeable difference comes from the position of different prime heaters with changes in demands. Although in the average demand dwelling the ASHP was the lowest (low-carbon) NPC option, with a reducing demand the high CapEx of a heat pump is not warranted, and so DEH and Blue H_2 boilers become the optimum cost solution. Conversely, with higher demand dwellings, GSHP with their improved winter efficiency are economically preferred over ASHP. The increased demand and maximum size from the larger high demand dwelling also further benefits the use of self-generated electricity from PV, and vice versa, as it is more valuable to self-consume than export and importantly costs per area of PV installation decreases with size.

5.2 Breakdown by Demands

Figure 5-4 (a) takes some of the key system configurations for the average demand dwelling and breaks down the OpEx by demand. Where PV and FC are used the generated electricity is firstly considered as being used by the baseload, then surplus would be used by electrified cooking, then heating, and finally transport where applicable. Any surplus generation that remains after meeting all the demands is shown by the negative export OpEx.

Comparing the gas and petrol baseline to ASHP & EV both using the VToU tariff shows the constant baseload, over 50% higher heating cost with ASHP, transport reduced to a tenth of the cost with EV, and a tenfold increase in cooking cost is found with electrified cooking. This cooking difference is due to comparative efficiencies between gas and electric cooking, but with VToU tariff costs during typical cooking times being significantly higher than the flat gas rates. The use of the flat tariff does help reduce this cooking cost from electrified ovens and hobs, but at the more significant detriment of increased baseload, heating and transport costs which far outweigh the benefits to cooking. Demonstrating the significance of tariff trade-offs for demands, which is only possible with the holistic methodology, and that an overall balance must be found.

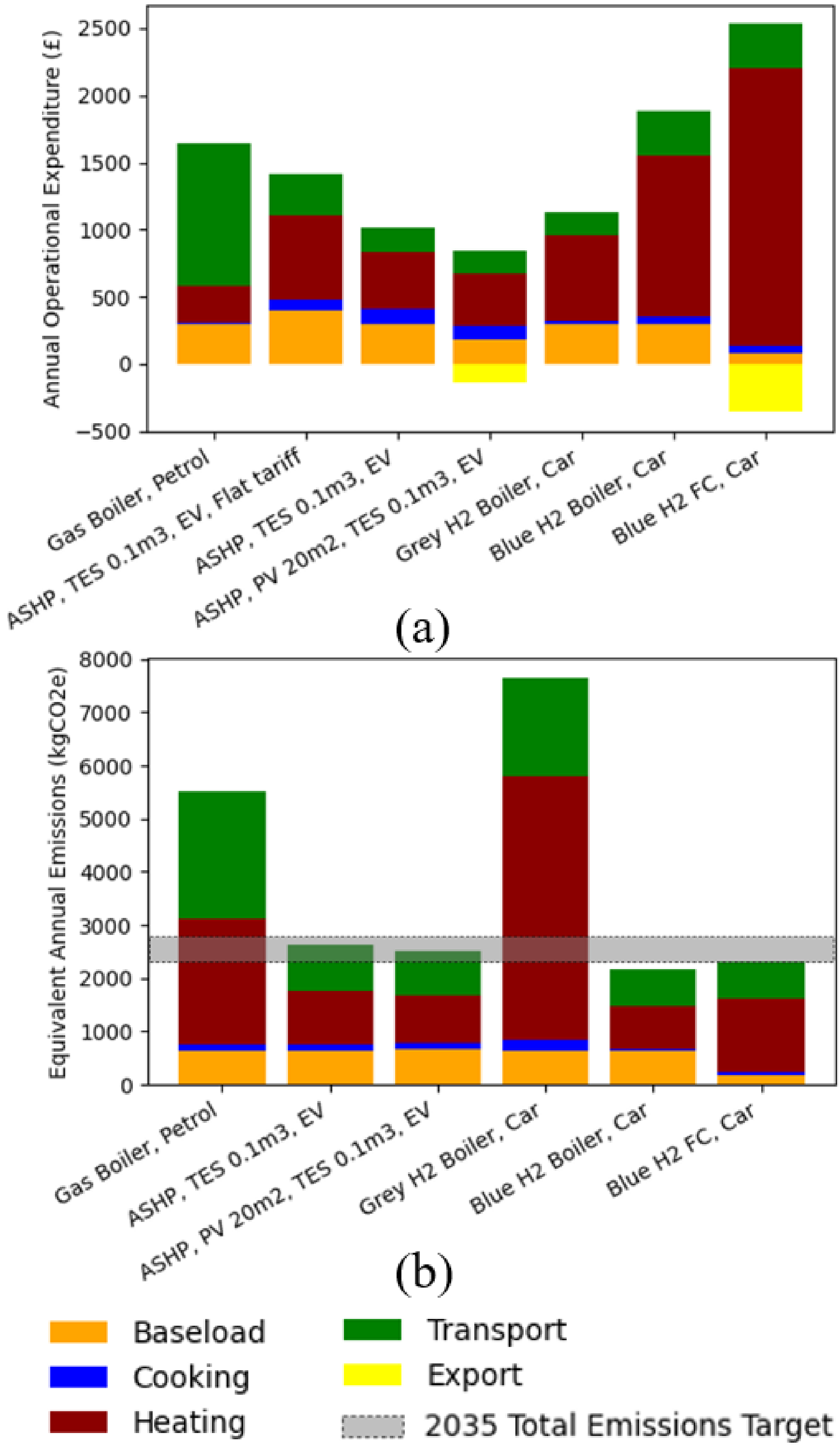

Figure 5-4 Average UK dwelling breakdown of key systems by (a) OpEx and (b) equivalent annual emissions. All systems using the optimum VToU tariff unless stated otherwise. Embodied emissions for technologies are included in the relevant demand sector, where PV is included under baseload and FC in heating. Air Source Heat Pump (ASHP), Fuel Cell (FC), Photovoltaic (PV), Thermal Energy Storage (TES),

When including PV with the ASHP & EV system there is a noticeable reduction in baseload OpEx, but only a slight decrease in costs for cooking and heating due to the hourly and seasonal mismatch in peak generation and demands respectively, and due to PV prioritised towards baseload first. This is different to the PV benefit to heating found in Chapter 4 as PV energy was fully dedicated towards heating, showing the effect of which demands are considered priority. The addition of the exporting benefit of PV is then an additional benefit which helps to ensure economic viability of the technology.

Reviewing the breakdown of H_2 solutions, the H_2 car can be competitive in OpEx against a petrol car and even an EV, but the cost of H_2 heating is much less viable. In particular for H_2 FC, which despite generating electricity in a more useful manner than PV to reduce baseload demands further and the benefit from more exports, the lower thermal efficiency of FC makes them less suited to buildings which have higher ratios of heating to electricity demands.

Figure 5-4 (b) uses a similar methodology to break down the equivalent annual emissions by demand for key configurations, where emissions include operational and an annual proportion of the embodied emissions. Each technology's embodied emissions go into the relevant demand, where PV is included in the baseload category and FC in heating category.

The multi-vector analysis shows that as with OpEx, the emissions change from the baseline to ASHP & EV significantly comes from the transport sector, with no changes from baseload and minor changes from cooking with current grid emissions, but in emissions there are improvements in the heating demand by using the ASHP. Although the PV gave good OpEx benefit to the baseload demand, due to the embodied emissions from PV being allocated into the baseload demand, this leads to an overall increase in emissions from the baseload. However, the inclusion of PV still leads to a net system decrease in emissions. A factor that is not included in this analysis is the contribution from the exporting electricity to reducing the emissions of the electrical network, if this is included further emissions benefits can be associated with PV and FC, irrelevant of self-consumption levels.

As stated, the emissions reduction from H_2 is highly dependent on the source, where only the theoretical Blue H_2 can currently give a reduction in emissions relative to gas boilers. A comparison of current emissions is also made against potential 2035 targets, which demonstrates that heat pumps using current grid generation mix and Blue H_2 could fall within these targets already, but other technologies will struggle. Which raises key concerns given the lifetime of heaters and cars and that they are still being produced.

5.3 The Effects of Tariffs on Technology Viability

From the analysis completed so far in the study, the use of the low-rate tariffs from 2020 have found there is very limited economic benefit for consumers to adopt energy storage, except for with the nominally higher OpEx of DEH. However, in the energy crisis fuel costs dramatically increased. With consumers using energy storage to shift demands this has additional wider benefits to the networks and low-carbon energy generation, and therefore has reason to be encouraged for the greater benefit. Although other work has been completed focusing on how to reduce CapEx of energy storage, this study will turn the approach around and quantify the tariff structure required to make current technologies viable today. Analysis is now completed using the same tariff types from 2020 but at the higher tariff rates from 2022, as quantified in section 3.6, to determine how this alters the position of energy storage.

Figure 5-5 uses the system of an ASHP, PV, and EV for an average demand dwelling to compare different energy storage OpEx and NPC for the collection of low tariffs and high tariffs. For most of the low tariff systems the optimum tariff was the day ahead VToU tariff, except for when using BES when the EV tariff becomes slightly more favourable due to its consistently lowest night rate. The benefit of this consistent low rate for the EV tariff becomes even more favourable for the high tariffs as it is then always the preferred tariff even with no energy storage. As the ASHP operates at a constant indoor temperature it has highest heating demand, and therefore electrical demand, when the outdoor temperature is coldest, which typically aligns with the EV tariff off-peak times, helping to reduce OpEx. Additionally, the EV OpEx reduces significantly if there is any option across the day for a short time of low-rate electricity. Demonstrating, that to incentivise energy storage and EV adoption, the critical tariff factor is how low the off-peak rates are to minimise cost of charging storage, not the overall average day rate of electricity.

As determined previously with the ASHP and the low tariffs, no types of energy storage are found to be viable over 20-years, although larger TES and V2H nearly breakeven. When looking at the high rate tariffs the conclusion changes and all forms of energy storage payback over their lifetime. TES and BES are equally beneficial over the long term, but do not have as significant improvements as the V2H due to its large capacity and no additional CapEx requirement, even if it is only available for this secondary function when at home and it accelerates the EV battery degradation.

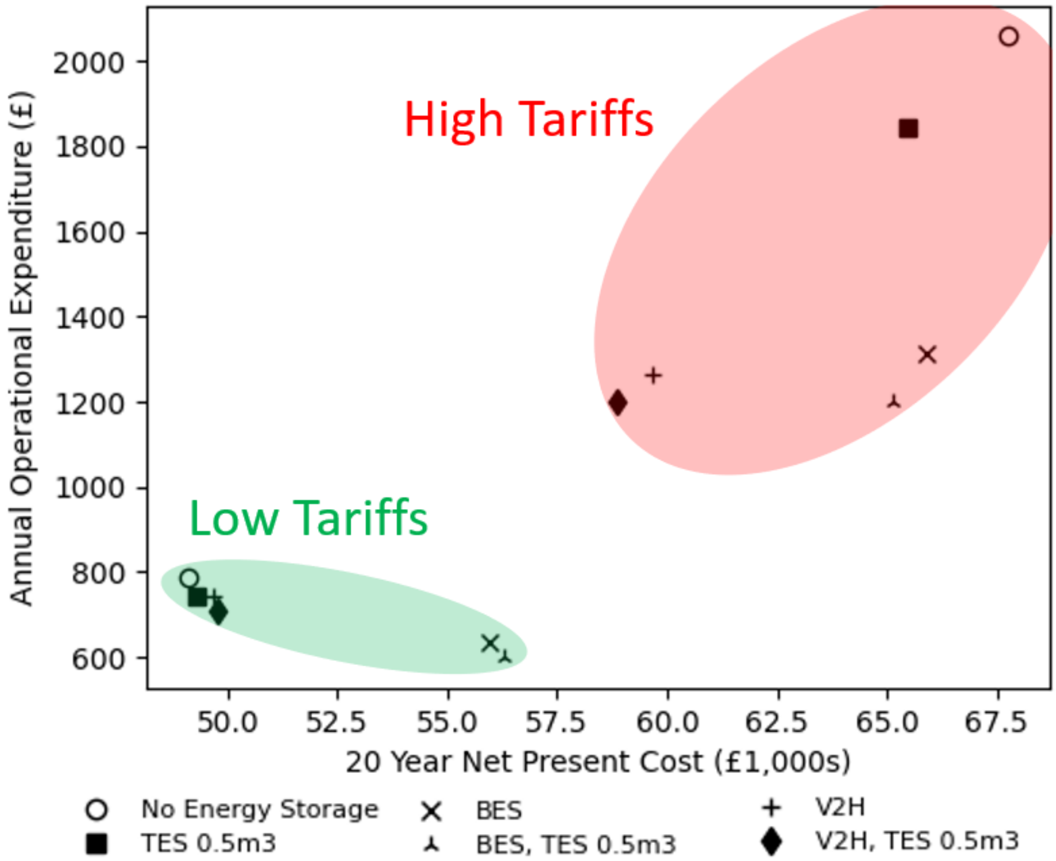

Figure 5-5 Energy storage sensitivity to tariffs showing OpEx against 20-year NPC using low tariffs and high tariffs for an average demand dwelling. System constants are the use of an Air Source Heat Pump, 20m² Photovoltaic, and electric vehicle. Battery Energy Storage (BES), Thermal Energy Storage (TES), Vehicle to Home (V2H),

Although when higher average day rates of tariffs occur this could be considered as beneficial for energy storage adoption, the additional OpEx and NPC requirements for consumers are not. Other, likely more favourable, methods of increasing energy storage viability are by looking on the tariff structures with the difference between peak and off-peak rates rather than the average tariff rates.

Figure 5-6 shows results of the key energy storage technologies for the same ASHP, PV and EV configuration of the average demand dwelling, where the EV style tariff, with four off-peak hours, is used at different peak to off-peak differences always averaging 20p/kWh across the day, which is between the low and high tariffs shown in Figure 5-5. Keeping the same average tariff rate approximately ensures that this tariff is still as viable for energy generators, suppliers, and the transmission network. This tariff is selected as a small window of a low-cost rate is highly beneficial to energy storage. Which is contrary to the general trends of the VToU tariff which typically has a low average day rate and only a few hours of the day which are high cost, making it relatively easy for most demands (other than cooking) to be shifted away from the peak when it is only a few hours long.

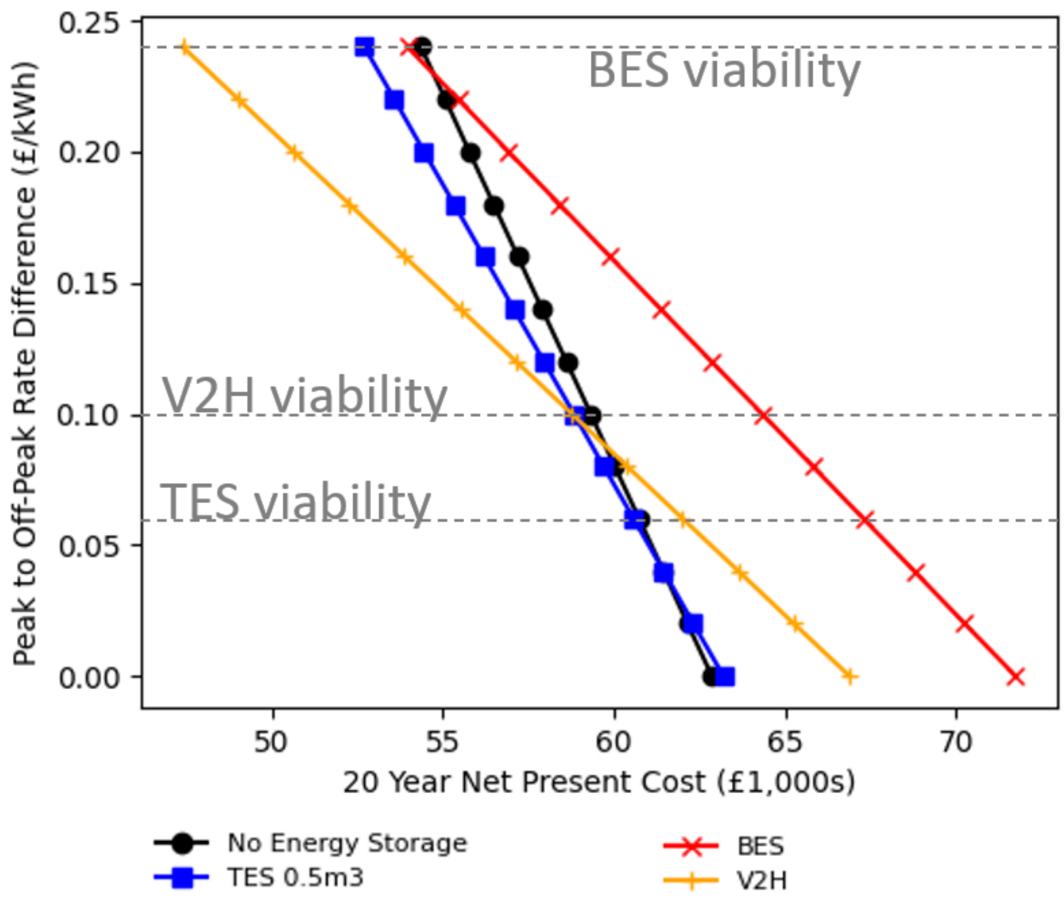

Figure 5-6 Energy storage viability from tariff structure differences for an average demand dwelling. An EV style, night-time 4 hours off-peak tariff is used, where the average day rate is kept constant at 20p/kWh. System constants are the use of an Air Source Heat Pump, 20m² photovoltaic, and electric vehicle. Battery Energy Storage (BES), Vehicle to Homes (V2H).

As the peak to off-peak difference tends to zero i.e., a flat tariff, there is little lifetime benefit of any energy storage even with PV, due to sufficient exporting revenue only allowing a slight reduction in OpEx from energy storage. TES is the first to become viable due to its relatively low CapEx only requiring a peak to off-peak difference of 6p/kWh, however even at higher rate differences it is limited in its potentially due to its low energy capacity and ability to only meet heating demands. V2H is the next to become viable at 10p/kWh, as the rate difference must overcome the value of degradation to the battery, but with an increasing rate difference significant NPC benefit can be realised with its high capacity and versatility of the electrical energy storage alongside heat pumps, baseload, and electrified cooking. BES is the energy storage technology which requires the highest rate difference to become viable at 24p/kWh, due to its additional CapEx and short lifetime. However, like V2H, the gradient of the BES line shows strong increase in benefits with the rate difference increase, especially if rate differences were to increase greater than the values plotted, which requires either higher average rates or negative off-peak rates to occur. When comparing the trajectories of V2H and BES it is clear to see that in all scenarios V2H is always more viable than BES primarily due to the additional CapEx of a dedicated BES.

5.4 Prospective Future of Technologies

Analysis is complete for future scenarios in 2035 and 2050 where the electricity grid input for the framework is reduced and target bands are set from the UK's sixth carbon budget [133]. The operational emissions calculated in the simulations include direct and indirect emissions, as electrified and H_2 technologies have negligible direct operating emissions. The targets are only for direct emissions, as indirect emissions would already be covered under the power and industry sector, not the buildings and transport sector. This allows the simple conclusion that any electrified or H_2 technologies can meet net zero targets for the building and transport sector.

Figure *5-7* (a) shows the emissions for 2035 and how electrified and Electrolysed H_2 operating emissions are reduced alongside the electrical network decarbonisation. This level of grid decarbonisation allows Electrolysed H_2 to be competitive against Blue H_2 in emissions reduction, but both H_2 sources create more emissions than electrified systems. With this scenario the embodied emissions, which are still using current day values, start to become the dominant source of emissions, as embodied emissions are shown as being distributed across each year but are crucially dependant on the time of manufacture. If the products are manufactured in 2035 it is expected their embodied emissions would then reduce approximately in-line with decarbonisation of the electrical network due to energy intensive manufacturing methods, and partially in relation to decarbonisation of the transport sector which transport the materials and products.

Figure *5-7* (b) goes on to show the operational emissions from 2050 'net zero' scenario for technologies which can reduce their emissions in-line with the electrical network. The small amount of indirect electricity generation emissions (which are offset from natural and engineered carbon capture and storage in the carbon budget) now clearly show the ratio of technology efficiency differences between Electrolysed H_2 cars, boilers, and FC against DEH, ASHP, GSHP and EV. The many variables and assumptions required for 2050 embodied emissions could easily dwarf any of these operation emissions, depending on the year of manufacture and how decarbonised manufacturing sector is at that time and location.

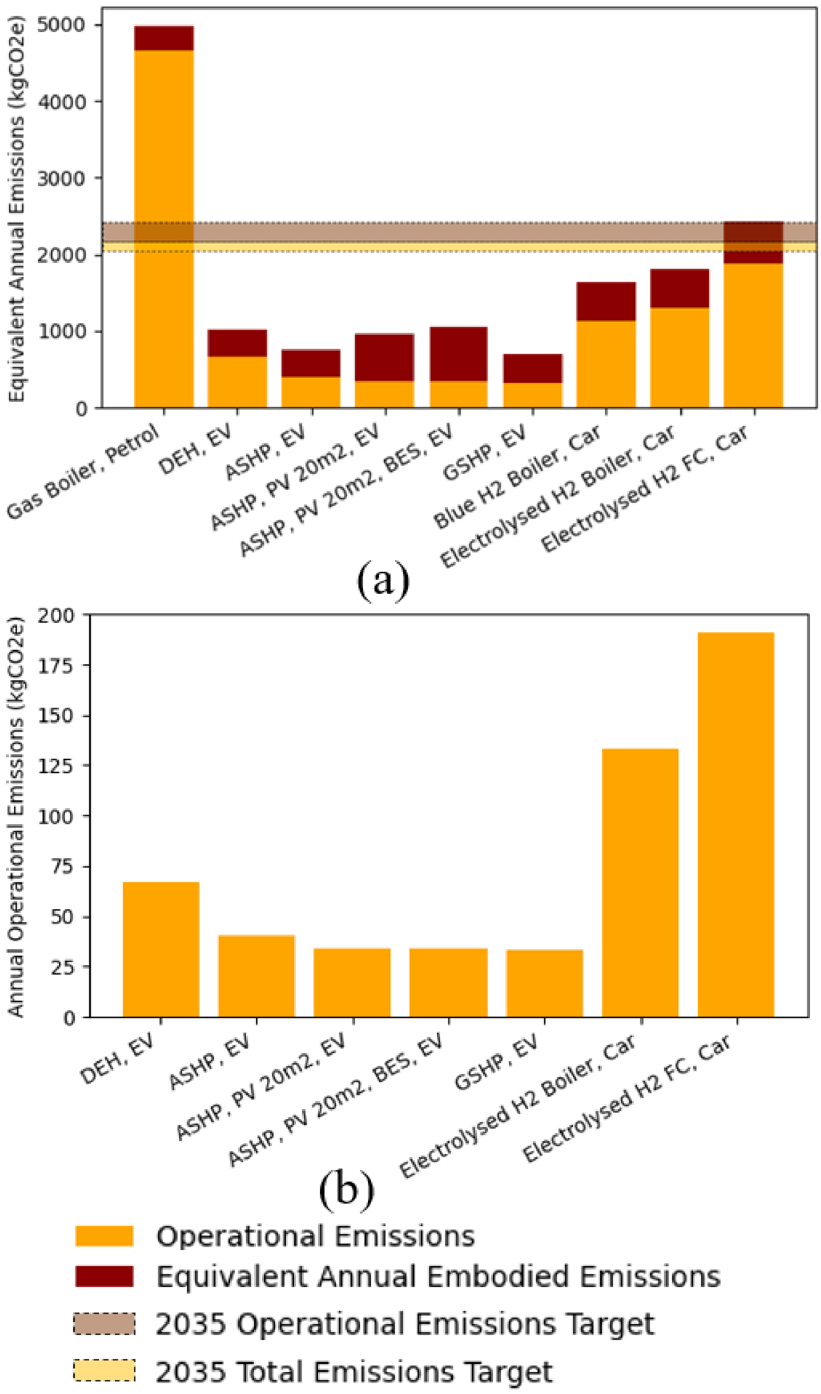

Figure 5-7 Equivalent annual consumer emissions in (a) 2035 and (b) 2050, using the relevant year's electricity generation emissions, broken down by operational and embodied emissions for an average dwelling. Air Source Heat Pump (ASHP), Battery Energy Storage (BES), Direct Electrical Heating (DEH), Fuel Cell (FC), Ground Source Heat Pump (GSHP), Photovoltaic (PV).

5.5 Summary

This Chapter quantifies the answer to the second research question which is to determine the tariff structures required to incentivise energy storage with the currently available energy storage technology range and costs. Which is contrary to current research which is focused on the technology improvement. This research highlights how energy storage has become viable with the increase in energy costs using current tariffs. It also finds that a difference of 6, 10 and 24p/kWh between off-peak and peak electricity costs is required for TES, V2H and BES to be viable. Demonstrating how TES can be one of the most affordable energy storage technologies, but V2H has the most potential due to greater storage capacity and flexibility to meet more demands.

This study has created a new consumer centric framework to fill the gap between other research areas, which focus specifically on single demands or specific systems, to access the full range of technological solutions while considering their interactions, and trade-offs in preferred tariffs, to meet all consumer demands. Giving a new insight into what technology combinations are likely to be taken up by consumers, which can differ from network preferences of higher efficiency heating technologies and adoption of energy storage. The versatile framework allows the investigation of how changes in tariff rates and structures can influence the technologies for consumers.

The study generally finds electrification overall is the most attractive option financially for consumers to decarbonise. Only EV and PV are found to reduce emissions and lifetime costs, with 8% NPC and 28% emissions reduction for EV and 0.2% NPC and 2% emissions for PV relative to the baseline for average demands. The multi-vector approach allows the comparison of different demands and their associated costs and emissions for consumers, which allows the conclusion that EV is the most cost-effective way for a consumer to reduce their emissions. However high CapEx of EV and heat pumps is likely a restricting factor, especially for low-income consumers, and may lead to more homes preferring DEH particularly for lower demand homes. As with Pratchett's boot theory, this inability for lower-income consumers to afford high CapEx better quality products, which in this case have lower OpEx, further increases the divide and perpetuates fuel poverty.

The tariff structures with the lowest average day rate across the day, which is typically the VToU tariff, are best positioned to aid the transition from gas boilers to electrified heating technologies, even with the compromise of increasing other costs like electrified cooking, and therefore should be more widely encouraged to decarbonise heating.

With the low tariff rates initially analysed energy storage is generally not found to be viable as they offer insufficient OpEx reduction for their CapEx. As tariffs have increased from the energy crisis the case has changed, and all energy storage become viable although at the detriment of significantly higher OpEx for consumers. The difference in peak to off-peak rates needs to be at least 6p/kWh for TES to be viable, 10p/kWh for V2H and 24p/kWh for BES. As the rate difference increases electric energy storage case becomes significantly stronger due to its flexibility, but V2H remains prominent over dedicated BES, as BES requires additional CapEx. Alongside the energy storage benefit from increasing the difference in peak to off-peak, this also has added incentive for adoption of EVs. The case for V2H is also likely to get stronger if dwellings with multiple occupants have multiple EV, meaning energy storage is available for more demand times. Tariff designs can play a crucial role in encouraging energy storage, with the key being how low the off-peak rates are, this strategy can be adopted to give greater system benefits. The energy supplier and system operators would then also need to be considered in the tariff design.

As electrical grid networks become decarbonised in the future, Electrolysed H_2 and direct electrification become preferential as they could offer negligible direct and indirect operational emissions compared to other methods. The embodied emissions become a larger percentage of the total emissions and time of manufacture is a crucial factor on the overall emissions. Additionally, if domestically generated energy cannot be exported as freely as it can now, and is instead curtailed, the use of energy storage for prosumers will become more viable. Energy storage, smart charging, and vehicle to grid can also aid electrical networks if operated in a smart manner, and so tariffs and policy incentives need to carefully encourage consumers to use these technologies. The results for this study can be used to help specifically target incentives to encourage the uptake of specific technologies or groups of technologies and focus on consumer financial support in a direction which also is beneficial to low-income homes to reduce fuel poverty.

Chapter 6 Domestic Thermal Energy Storage Parameters

TES is required to allow low-carbon heating to meet the mismatch in supply and demand from renewable generation, yet domestic TES has received low levels of adoption, mainly limited to hot water tanks. Current reviews and studies primarily focus on the comparison of storage materials neglecting the performances at a system level and analysis studies tend to solely look at hot water tanks, missing the key technology developments in thermal storage systems which are under development. The current research overlooks TES at a material level, but it is an essential enabling technology to decarbonise heating systems. Therefore, this Chapter investigates performance and cost variations of TES from material-level to system-level analysis and assesses impacts of emerging heat storage technologies.

This Chapter focuses on the third research question, which TES parameters are most valuable to be developed to improve their viability. Firstly, by accessing data from a thorough literature review of TES materials and TES systems. Then by using the framework explained in Chapter 3 this Chapter builds on the broader heating analysis from Chapter 4 which covered many heating technologies. By focusing on the two most feasible technologies across the range of dwelling heating demands as found in Chapter 4, of DEH and ASHP, to simulate and identifying how different TES parameters improve the system performance for different dwelling demands when coupled with the two key heating technologies.

By simulating different types of TES materials and varied system integration options, a significant reduction in energy densities and increase in specific costs of TES systems were found compared to the material-level analysis. DEH has much greater potential to integrate with TES from its high operating temperature with TES compared to heat pumps or solar thermal which are constrained to lower temperatures. TES properties are simulated in various scenarios in a domestic heating techno-economic framework. It is found that for heat pumps there is economically-limited potential for TES, even if very high energy densities are possible. In addition, the priority for TES coupling with heat pumps is low capital cost, although high tariff rates due to the energy-crisis do improve economic viability of TES. On the other hand, with DEH, high energy density is the most valuable parameter for TES, as it allows significant quantity of demand to be shifted to very low-tariff times, in particular for low demand dwellings where negligible amounts of peak electricity could be required for heating.

Here, emerging domestic TES technologies and concepts are examined and their integration with renewable and electrification heater options, while also exploring the impact of power system decarbonisation on emissions of future domestic heating. In particular, focusing on the trade-offs between costs and emissions that consumers face in selecting a low-carbon alternative. Although cost is not the sole influence on consumer purchasing decisions, low-carbon heating and TES will only achieve a dominant market share if they are affordable to most of the population. Addressing these issues by comprehensively examining TES technologies and concepts, covering all prominent options: SHS, LHS, and TCS. Taking a step back from the existing thorough material analysis which focuses on how specific materials differ, instead focusing on the integration of the technologies at a system level and applying them to domestic heating applications from the consumer's perspective.

This Chapter covers the range of technology readiness level from existing TES technologies of hot water storage tanks and electric storage heaters, emerging TES technologies such as high temperature SHS and LHS which are just starting the commercialisation process, and potential future technologies from theoretical improvements to determine what parameters are most valuable for TES. A hot water tank TES is added into a domestic heating simulation framework, where 0.1 to 0.5m^3 sizes are analysed. Additionally theoretical changes to TES parameters of energy densities, CapEx, storage temperature and insulation value are investigated. This enables an understanding of which aspects are useful for TES rather than examining specific materials/systems, which has already been done in existing TES studies. A default temperature of 51°C is used for the TES storage temperature, but higher temperatures of up to 500°C are considered in the simulations, and up to 1500°C in initial material and system comparisons.

This Chapter is largely based upon the published work "Domestic Thermal Energy Storage Applications: What Parameters should they focus on?" published in *Journal of Energy Storage* by the authors, M. Ryland and W. He.

6.1 Analysis of TES Applications: from Materials to Systems

First an analysis of existing and emerging TES materials and TES systems will be undertaken from a comprehensive review of the literature, covering the full spectrum SHS, LHS, and TCS. Comparisons of the TES will be made at a material level and system level to compare how this alters the position of the technologies, instead of purely focusing on the material level as current studies tends to. The system level analysis will include manufacturers data on traditional hot water tanks and electrical storage heaters as current TES technologies, as well as emerging commercial products that target high efficiency and storage densities that are using SHS at higher temperatures with high quality insulation [68], [69], and LHS systems using salt as the phase change material designed for domestic heating application with melt temperatures setup to efficiently store energy around the domestic demand temperatures [70]. Analysis will also be broken down showing how the TES technologies alter in their performance depending on if they are coupled with the prominent low-carbon heating technology of an ASHP with its limited operating temperatures, or with the more flexible and lower CapEx DEH which is better suited to lower-demand dwellings and can achieve higher temperatures.

6.2 TES Integration into Domestic Heating Framework

The study will then go on to look at how TES can integrate into a domestic heating application with hourly simulations across a year for a dwellings demand met by TES that is heated with DEH or ASHP, comparing economics and environmental factors. This study will then look at how changing parameters of TES alters the system viability, to demonstrate which parameters are most valuable to reducing costs of TES. A consumer centric mathematical model to simulate domestic heating across the year at an hourly resolution is used as introduced in previous work [138], [139].

The framework holistically considers each combination of heating technologies, ancillary solar and TES sizes, and tariffs to meet the heating demands from the dwelling. The CapEx and the single years' OpEx are then used to calculate the 20-year NPC. The OpEx, CapEx, NPC, and emissions values are used for technology comparisons. Emissions include operational emissions and embodied emissions, to give an equivalent annual emission. Inputs to the model are: dwelling location; number of occupants; desired thermostat temperature; dwelling floor area, and annual space heating demand, the latter two can be found on the dwelling's energy performance certificate in many countries. To demonstrate the sensitivity of TES parameters a case study is complete in the UK for multiple scenarios.

The heating model is described in detail in Chapter 3, where the thermal efficiency of the dwelling is back-calculated from the input data, then a higher resolution space heating demand can be calculated using calculations and assumptions from Standard Assessment Procedure [100] and Building Research Establishment Domestic Energy Model [99] and using location specific reanalysis weather dataset from Renewable Ninja [103]. Heat pumps are set to operate at a constant indoor temperature throughout the day, due to their low thermal power, and other heating devices set the target thermostat temperature from 07:00-22:00. Hot water demand is determined from Building Research Establishment Domestic Energy Model and geographical cold water temperatures and hourly ratios of daily demand from Energy Saving Trust [104]. TES is simulated as stratified hot water tanks at sizes from 0.1-0.5m^3 in 0.1m^3 steps.

The framework created offers the ability to be easily adopted for any home and set of personal demands, by adjusting the dwelling inputs and locations for heating demands and in scaling the typical baseload electricity and transport demands. Case studies are used in the study to show how TES and low-carbon heating are suited in different dwellings, low and high demand UK dwellings are considered at the central England location of Coventry, with two occupants, using a thermostat temperature of 20.0°C, and a maximum TES size of 0.5m^3 considered. All dwellings use an average thermal efficiency of 1.85W/m^2K, then dwelling size is adjusted to match different percentiles of UK homes heating demands. Resulting in the average demand dwelling set to 87m^2, lower 10th percentile demand to 31m^2, lower 25th percentile demand to 52m^2, and high 75th percentile demand at 114m^2.

To promote the shifting of energy to consumers, which is the main function of TES and other energy storage, variable rate tariffs are used as these create low electricity rates at times of lower demand. A range of different tariffs are considered, the flat rate tariff is the only tariff which does not promote shifting demands due to a constant rate across the day. Night off-peak tariff is a traditional two rate tariff, with seven hours of low-cost electricity at typical low demand times in the night, but a higher day rate than the flat tariff. A more modern version of this is the EV off-peak tariff, which has a shorter four-hour window of very low rates. Finally, day ahead, VToU tariff is also considered, which has a different rate for each hour of the day and changes every day depending on supply and demands. This study then also considers the comparison of these tariffs at the pre-energy crisis low rates from 2020 to the current high costs tariffs from 2022 to determine how the tariff changes alter the position of TES. The tariffs selected are the lowest rate tariffs of that structure available across the year 2020 and 2022, as any consumer is likely to select the lowest rate tariff available to them. Apart from the VToU tariff which uses data with the changing rate for each half hour across the two years.

For this study variable GB electricity grid emissions are used from the year 2020, which averaged 181gCO_2e/kWh across the year, unlike in the previous Chapters where a fixed grid emissions value was used [61]. Where reduced grid emissions scenarios were input into the framework this was completed by subtracting or adding a fixed value, in 25gCO_2e/kWh increments, to each hourly value. Values were limited to a minimum value of zero emissions at each time step.

6.3 Thermal Storage Materials and Heat Store Designs

A survey has been completed of the literature [64], [65], [145]–[151], [66], [67], [70], [140]–[144] to gather data on existing and under development SHS, LHS and TCS materials that could potentially be used in a domestic TES application, to show the full technology landscape of TES. Figure 6-1 (a) shows a range of materials down to a temperature of 30°C, as less than this yields little value for domestic heating, comparing two important parameters: energy density and specific cost. However, as found in previous studies, many other factors need to be considered when selecting TES materials including: discharging rate; charging rate; discharging efficiency; charging efficiency; storage efficiency; corrosivity; acidity; toxicity; life duration, and technology readiness level [64], [65], [145]–[151], [66], [67], [70], [140]–[144].

For SHS the upper material temperature limit is used to calculate the values, importantly these high potential temperatures allow relatively good densities and specific costs for SHS, but do not emphasise that with the higher temperatures comes more storage losses (with the same insulation). SHS materials are also grouped by their sub-categories and some of the best performing materials for energy density and specific costs of key sub-categories are labelled. For SHS oils and salts, there are only small differences in densities within their groups, cost also remain similar, with the exception of vegetable oils which give comparable costs to the salt group but at lower densities. The metals and earth materials groups have varied performance across their groups, with some materials able to withstand very high temperatures and high densities. This results in some of the best energy densities, and, due to their low cost, they are the clear preferred TES materials for these parameters.

LHS data focuses on potential energy storage available from phase changing: the materials can achieve reasonable densities just relying on the latent heat from the phase change. Although LHS can allow further improvements in energy densities if the materials continue to be elevated up to their maximum workable temperatures, this also comes with the downside of more heat loss and lower storage efficiencies as with SHS. In addition, the larger temperature change alongside the phase change may cause further degradation of the LHS materials. For the LHS sub-categories, the paraffins, fatty acids, alcohols, and salt hydrates all have comparable energy densities, but with vast ranges in costs depending on the abundance of the material. Hydroxides in LHS improve on energy densities, but not as significantly as some metals and other salt materials.

As TCS is at the development stages, mass production costs are unclear, the potential range of production costs and energy densities of TCS are shown by the transparent green box using data gathered from the thorough literature review, and TCS technologies are positioned at the upper cost value of this due to not being commercially available. The energy density for TCS is shown using the energy from the material's chemical reaction. The materials under consideration from the literature are predominantly using adsorption reactions instead of absorption reactions. This has very varied results for TCS but does have many options with very high energy densities. The additional benefit of LHS and TCS, not show, being lower temperatures and therefore higher storage efficiencies than some of the high SHS. With temperature constraints, and disadvantages, removed it becomes clear that SHS generally is the most cost and space effective compromise.

In addition to higher operating temperatures of TES materials making high storage efficiencies more challenging, they also restrict the type of heater used, which is pertinent for decarbonising heating. Figure 6-1 (b) shows how the potential low-carbon heaters perform depending on their output temperature, with thermal power on the left axis with solid lines and efficiency on the right axis with dashed lines. Solar thermal and ASHP show decreases in efficiency and therefore thermal power output with higher sink temperatures. Although DEH has a relative low efficiency at lower sink temperatures compared to the heat pumps, it remains nearly 100% efficient at higher temperatures. Making DEH the only suitable method to couple with the higher temperatures required by some TES.

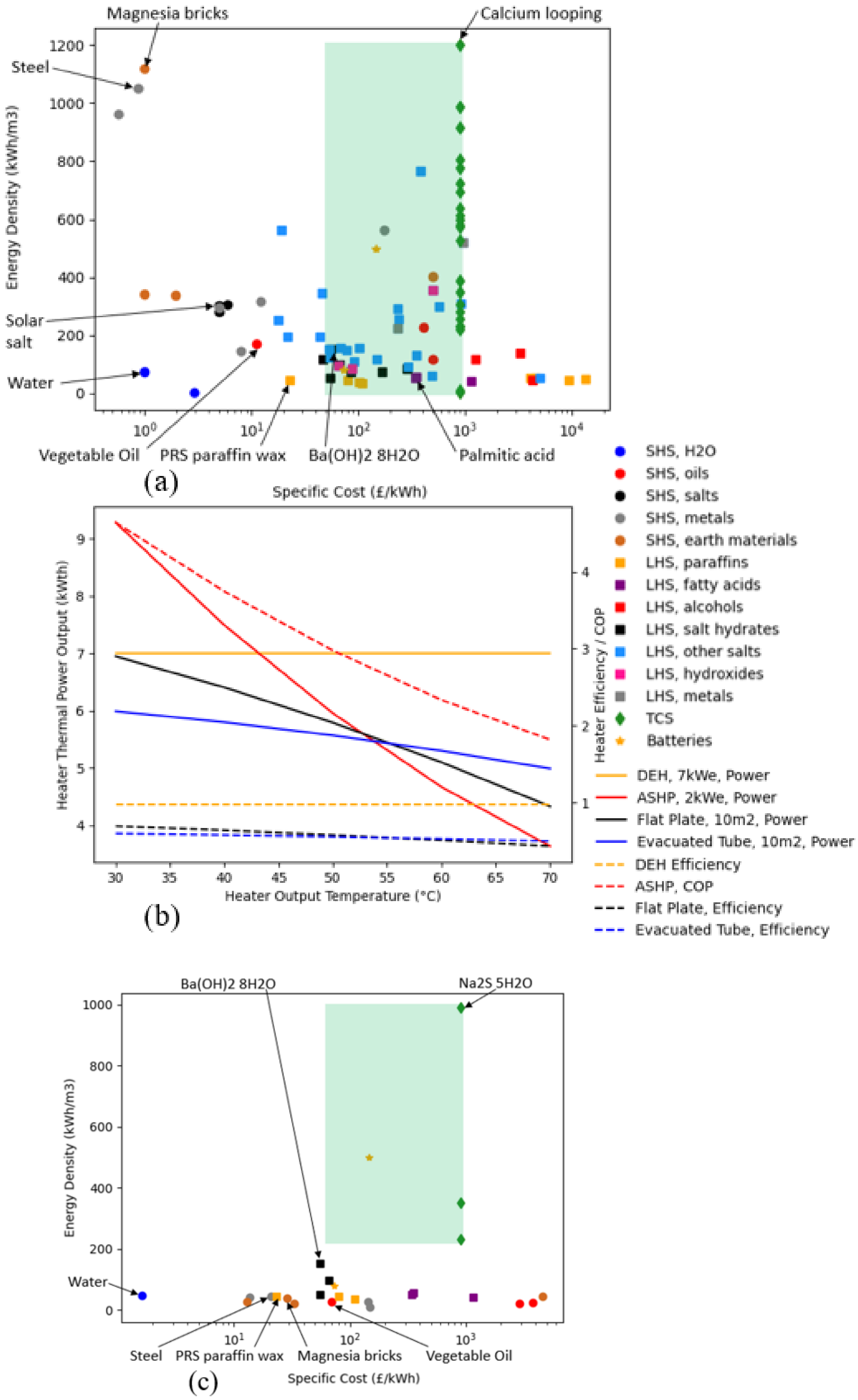

Figure 6-1 (a) and (c) Thermal Energy Storage materials energy densities against specific material costs. Energy storage using (a) the maximum material temperature and (c) using an upper temperature of 70°C, both down to 30°C. The shaded green box shows the range of potential of commercial TCS. (b) Shows low-carbon heater thermal power output and efficiencies against increasing output temperature. Data in the Appendix. Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH), Sensible Heat Storage (SHS), Latent Heat Storage (LHS), Thermochemical Storage (TCS).

Many current studies on TES focus on the potential of the materials, at their upper temperature limits showing what is possible for different TES materials and how the different categories of SHS, LHS and TCS typically differ, as shown in Figure 6-1 (a), however by considering the limitations of the low-carbon heaters gives a more complete picture. This temperature constraint from heat pumps and solar thermal collectors restrains the performance of the TES, making it an important aspect to consider when analysing TES applied to domestic heating.

By adapting the data in Figure 6-1 (a) to show how TES materials can perform when restricted to sensible upper values for ASHP and solar thermal of 70°C Figure 6-1 (c) is created. SHS now has significantly lower values as the upper temperatures are limited, reducing the capacity and energy densities of these systems. LHS and TCS removes any material that melts / reacts above the 70°C limit, significantly reducing the number of options, leaving much lower energy densities for LHS and with the remaining TCS now significantly higher energy densities than other thermal storage materials. With this limit also imposed, Li-ion batteries become much more favourable forms of energy storage, especially if considering being coupled with ASHP that operate at higher efficiencies.

As prior studies tend to focus on TES materials, they can miss the performance changes that occur when considering the full thermal storage system. Figure 6-2 shows how different TES systems can perform against each other using thermal store data from manufacturers, with (a) using the maximum TES system operating temperature and (b) limiting temperatures to 70°C. The system level data analysis is taken from manufacturers, shown in the Appendix, when including their whole installation, not simply just the storage material. This higher level differs from the material level as the upper temperatures of the system may be limited lower than the maximum possible temperature achievable by the material. It also includes the increase in volume and cost requirements from the heat exchangers, insulation, and other ancillary parts, which lowers the energy densities and increases the specific costs compared to at the material level.

These are important factors as this is not the same fixed values for all types of TES i.e., higher storage temperatures require more advanced insulation materials. As discussed, getting the maximum performance from many of the TES systems as shown in Figure 6-2 (a) is only possible with DEH. At the maximum TES system temperature scenario, as found in the material level, SHS remains the most advantageous technology, but with a reduced cost benefit compared to at the material level. At the system level the cost benefit of water for storage is limited as it is comparative to storage radiators and is only slightly lower specific cost than new high temperature SHS technologies which all come with higher energy densities. LHS has acceptable energy densities put at higher costs, but not as high as batteries, as shown in Figure 6-2. However, batteries are positioned using their stored electrical energy to calculate both energy density and specific costs, unlike the TES technologies which are used in thermal energy. The thermal equivalent of energy storage for batteries depends on which heater it is coupled with: if this is coupled with DEH this is near identical to the electrical values shown as DEH efficiency is close to 100%. If electrical batteries are coupled with ASHP the battery performance would be 3.5 times better with a typical ASHP COP of 3.5, making it the second lowest specific cost in Figure 6-2 (b) after hot water tanks but with an energy density over seven times better than any TES.

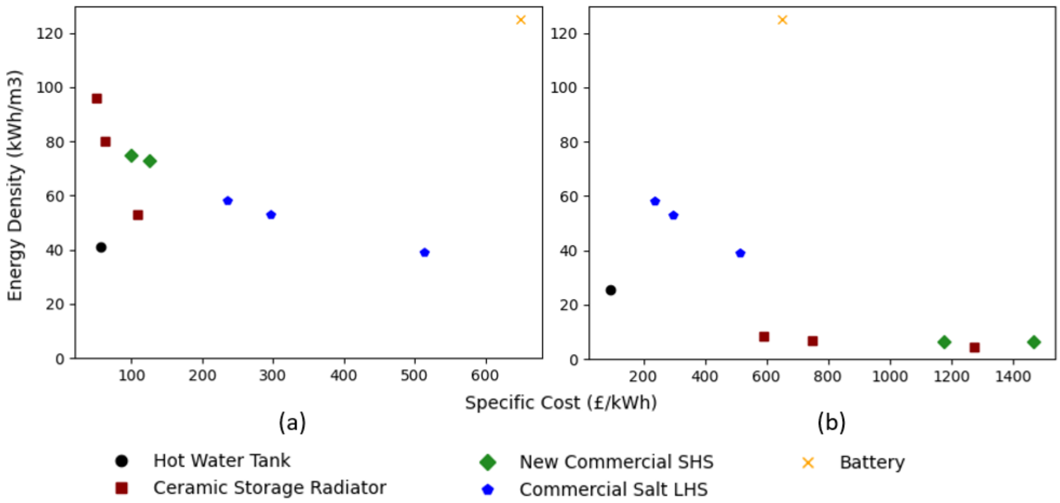

Figure 6-2 Manufacturers data for TES system energy densities against specific system energy costs (a) using their maximum system operating temperatures (b) only heating up to 70°C to remain suitable for heat pumps and solar thermal technologies. Data provided in Appendix. Sensible Heat Storage (SHS), Latent Heat Storage (LHS).

Figure 6-2 (b) using the limited temperatures causes a few key changes to energy storage system landscape. SHS energy densities and costs are reduced, so much so that water tanks are the only feasible option as the high temperature SHS technologies are limited when coupled with ASHP or solar thermal. The reduction in performance of SHS makes LHS and batteries much more competitive, with LHS only slightly higher specific costs but with good energy density improvements over water tanks.

These new insights show how important it is to consider the system level for domestic TES, where consumers have limited space, capital to invest and TES may be coupled with different types of heaters. As the system level shows the significant increase in specific costs and decrease in energy densities compared to the material level. It highlights that if the commonly favoured low-carbon heater of ASHP is to be used, that the simple hot water tank remains competitive although LHS can have a strong future in this market if costs can reduce, therefore integrating the right technologies for the specific application is important.

6.4 Integration of Thermal Storage Parameters to Heating Framework

To better understand how TES operates in domestic applications and which TES parameters are most effective to improving its performance, various TES and heating demand scenarios are simulated at an hourly resolution across the year in framework explained in the methodology Chapter 3. With multiple tariffs available for consumers considered in the framework it is worth emphasising that, other than flat tariffs, the tariffs that have varying costs across the day generally have lower costs at the times when the associated emissions from grid generated electricity is also lower, as demonstrated in Figure 6-3. This highlights that if TES is targeting reducing consumers OpEx by shifting demand to off-peak times of the day with electrified heating this has the added benefit of reducing emissions and improving utilisation of variable renewable energy generation and reduce peak demands on networks. The positive effect of TES to reduce emission will be enhanced with the progress of the power system decarbonisation.

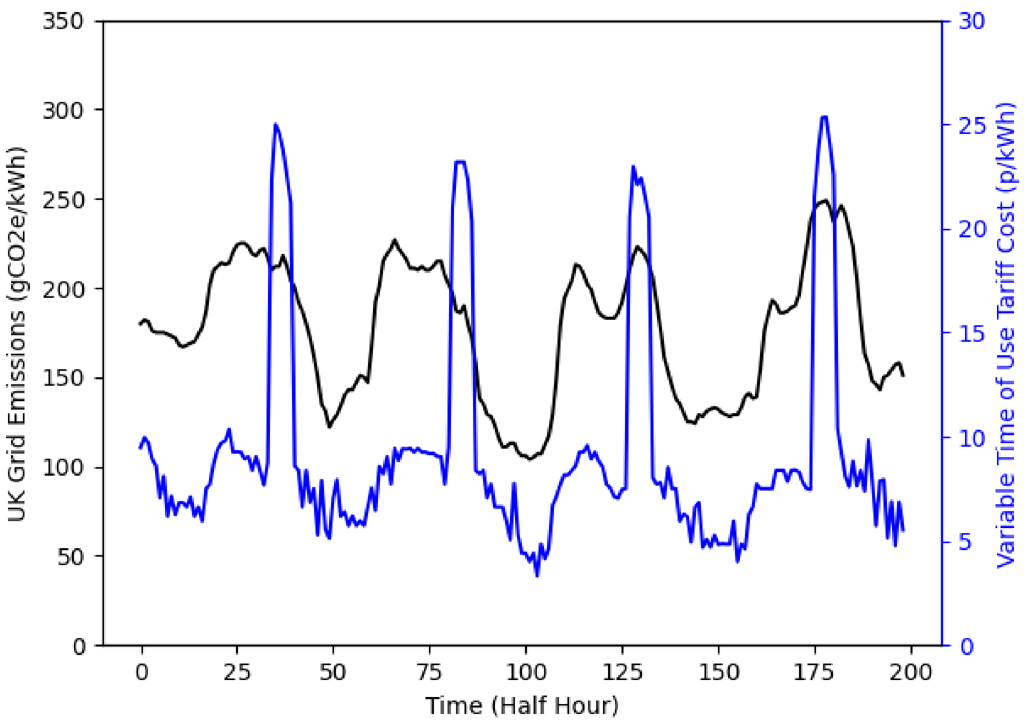

Figure 6-3 Variation in British electrical grid emissions compared to a variable time of use tariff, for the first four days of 2020 [60], [61].

ASHP and DEH are simulated alongside the commonly used domestic TES of hot water tanks and variations for representing other TES scenarios, the heater parameters used in this Chapter are detailed in the Appendix A. Then, the results are compared to the fossil fuel baseline of natural gas boilers in Figure 6-4 in their systems OpEx and 20-year NPC. Tariffs used are the lower rate tariffs from 2020 (pre-energy crisis) and results shown use the EV style tariff, with 4 hours of very low cost electricity in the night, as this tariff structure is shown to be the most beneficial for energy storage as found in section 5.3.

With the electrified heaters different TES scenarios are presented, a minimal 0.1m^3 TES, a large 0.5m^3 TES, a 0.5m^3 TES with high (x10) and low (÷10) specific heat capacities/energy densities to simulate how significant improvements to energy densities would alter TES viability, compared to the current technologies which can approach 2.5 times hot water tank energy densities shown in Figure 6-2. Scenarios are also included for a 0.5m^3 TES with high (x10) and low (÷10) TES CapEx, where high CapEx is comparable with more recent TES technologies and low CapEx could be an ideal cost scenario. These hypothetical changes to key parameters can help identify what direction domestic TES should develop.

Firstly, looking at Figure 6-4 (a) for the average UK dwelling heating demand, the ASHP is more viable across the 20-years over DEH, although neither can compete with the gas boiler economically. With the ASHP the addition of larger TES and changing TES parameters has a small impact over an ASHP with a minimal TES, other than high CapEx TES which significantly increases the NPC of the system. This is primarily due to the lower OpEx from using an ASHP, meaning any improvements in reducing its OpEx using TES make a small absolute different and therefore do not payback the increased CapEx of TES over its lifetime. In addition, the most cost-effective charging time for TES is using the night-time off-peak times, which is accompanied by cooler temperatures and therefore lower ASHP efficiencies, which typically give ASHP lower charging power than DEH. Showing TES struggles to improve the economics of the relatively lower OpEx ASHP, and that lower CapEx TES is the most useful direction for TES coupled with and ASHP.

However, alongside DEH the potential for TES is much greater. Although low CapEx TES has similar overall advantages as with ASHP, the higher energy density has a much stronger impact. The high energy storage capacity of the high energy densities scenarios with the large 0.5m^3 TES coupled with the faster charging DEH, can better take advantage of off-peak electricity rates, and make a larger absolute difference due to the nominally higher OpEx of DEH compared to ASHP. Although this best-case TES scenario for DEH can result in similar peak electricity usage and NPC to ASHP, the lower efficiency of DEH still results in over double the equivalent annual emissions to the ASHP system.

Figure 6-4 (b) introduces a higher demand dwelling which has been correlated to the upper 75th percentile UK dwelling heating demand. The scene remains similar for the high demand dwelling as with the average demand dwelling, but with further increase in DEH relative to ASHP due to the higher OpEx representing more of the overall NPC than the CapEx, where ASHP CapEx is higher than DEH.

Lower heating demand dwellings are shown in Figure 6-4 (c) and (d) representing the lower 10th and 25th percentile respectively. In lower demand, with lower OpEx, DEH becomes more favourable, and with the high energy density TES, DEH is even the optimum cost overall low-carbon solution. However, although this is now the optimum solution the benefit of high energy density reduces compared to low CapEx TES alongside reduced demand. The ability of DEH with high-capacity TES in the low demand dwelling shows great flexibility potential for being able to shift demands, as only £2 of the £331 annual bill is from peak electricity usage (98% reduction as £91 a year was from the fixed daily standing charge).

In comparing the emissions of the key combinations of heaters and TES parameters in Figure 6-4 reveals similar trends to OpEx, as Figure 6-3 highlights the link between tariff rates and electrical grid emissions. Emissions fall in-line with demand, so reducing heating demands is one of the largest ways to reduce associated emissions. The difference between ASHP and DEH efficiencies (typically 3.5) is greater than the variation in electrical grid emissions and therefore concludes ASHP has lower associated emissions than DEH in all TES scenarios, even if ASHP use electricity at times of higher emissions. Increasing the energy density and therefore capacity of the TES allows a decrease in emissions, however this is less than the OpEx reduction as the variation in the EV tariff peak vs off-peak rates is greater than the variation in electrical grid emissions.

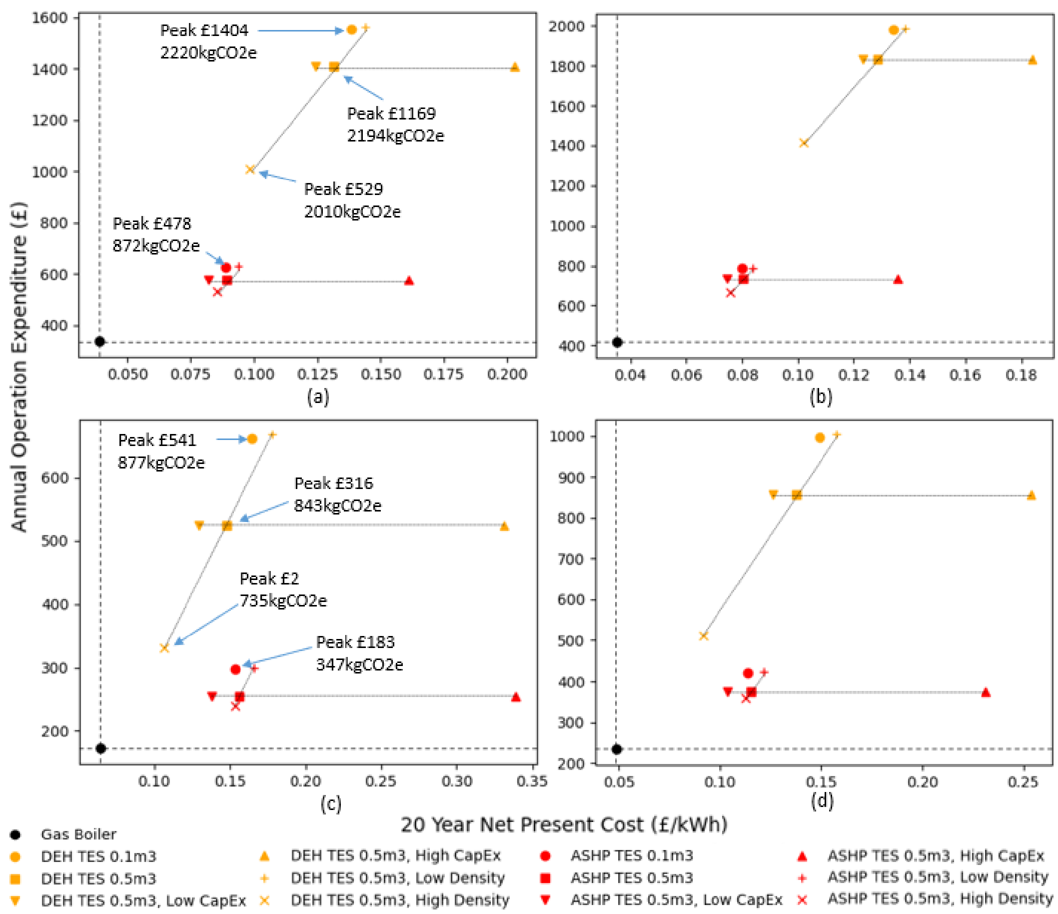

Figure 6-4 OpEx and NPC for Direct Electrical Heating (DEH) and Air Source Heat Pump (ASHP) with various Thermal Energy Storage (TES) scenarios for (a) 50th percentile, average dwelling (b) upper 75th percentile dwelling, (c) lower 10th percentile dwelling, and (d) lower 25th percentile dwelling. Text labels for key results show peak electricity used over a year and equivalent annual emissions.

A key factor to domestic energy technologies viability are the tariff rates, to understand how the increased cost of energy from the energy crisis has altered the position of the TES parameters, Figure 6-5 uses the same tariff styles but from 2022 for (a) 10th percentile and (b) 25th percentile dwellings. As found with the higher demand dwellings, the higher OpEx, now from higher tariff rates, benefits the more efficient ASHP over DEH. However, as the demand remains low a high percentage of the electricity used can be from off-peak times for the high energy density TES with the fast-charging DEH, keeping the high energy density TES with DEH as the overall optimum NPC solution.

Although gas and electricity costs have both increased, the ratio between gas and electricity has reduced. On top of this, the off-peak electricity rate for the EV tariff only has a small absolute increase of 2.5p/kWh. Combining these points gives a significant economic improvement in electrified technologies relative to gas boilers, but gas remains the lowest NPC and very competitive on OpEx. ASHP has similar OpEx to gas and DEH with high density TES, which has a very strong potential using large quantities of the off-peak electricity allows competitive OpEx alongside its low CapEx.

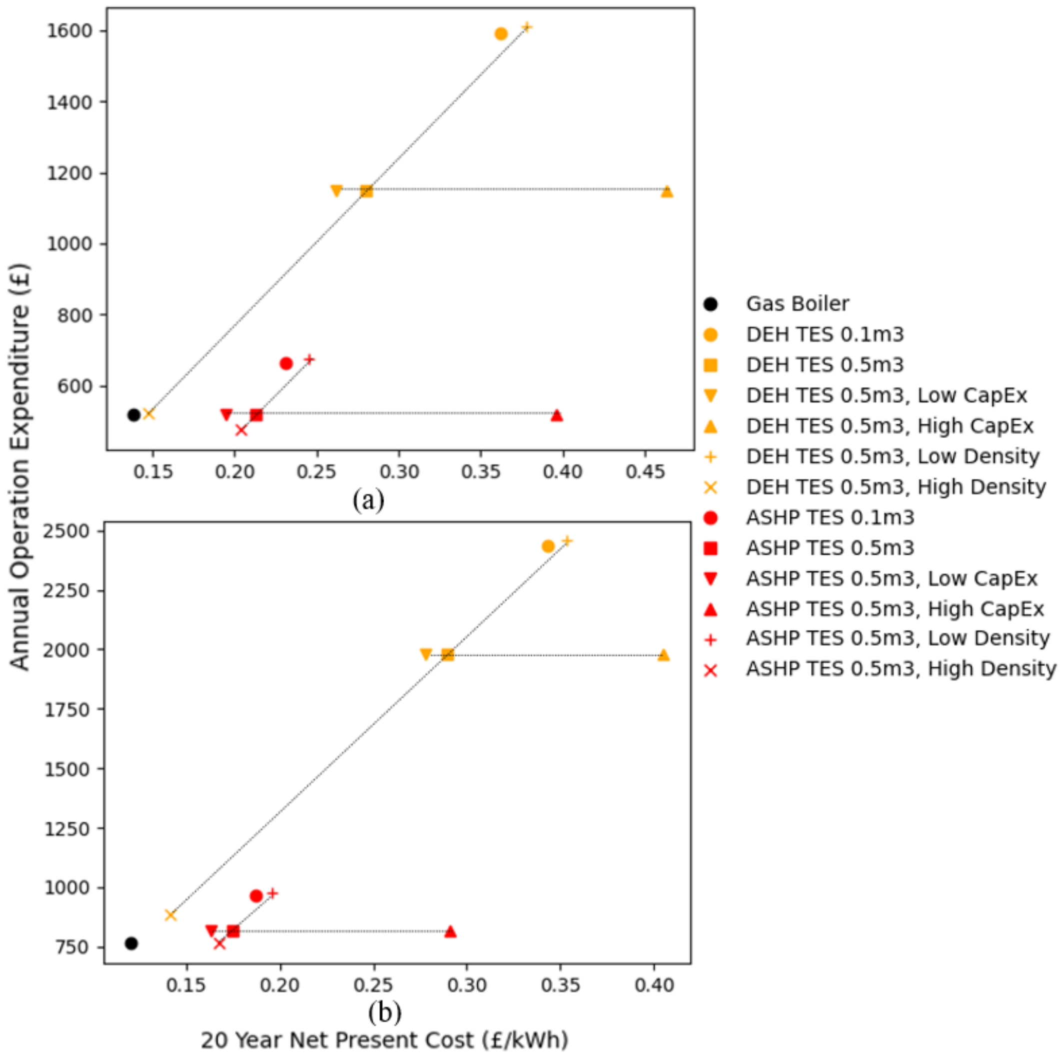

Figure 6-5 Operational and 20-year costs for Direct Electrical Heating (DEH) and Air Source Heat Pump (ASHP) with various Thermal Energy Storage (TES) scenarios with 2022 high tariffs rates for (a) lower 10th percentile dwelling and (b) lower 25th percentile dwelling.

As discussed, the high energy density can bring benefits to the OpEx of electrified heating systems, so far in framework this has been considered by using a theoretical material with higher specific heat capacities. As introduced in section 6.3, high energy densities can also be achieved by SHS operating at higher temperatures. Although this makes storage efficiency more challenging as heat is lost through from the TES.

Figure 6-6 looks at how the thermal storage efficiency of the TES (the U value), which is of particular importance when operating at the higher temperatures to retain the stored energy, alters the system performance. Now shifting the focus to the environmental aspects of the system for an average demand dwelling, showing how the input variables can impact the equivalent annual emissions, even if both OpEx and emissions benefit in the same way of being able to shift demands from peak times to off-peak times efficiently. This plots the equivalent annual emissions from the system at different TES U values against different average grid emissions, all grid emissions used the varying hourly profile based on 2020 data as explained in the section 6.2. The default value in the framework had average 2020 electrical grid emissions at 181gCO_2e/kWh and a TES U value of 1.3W/m^{2}K. Figure 6-6 uses a large, 0.5m^3, hot water tank Figure 6-6 with (a) using DEH and an upper (hypothetical) TES limit of 500°C to simulate values close to new commercial SHS technologies considered in section 6.3 which are well suited to low-demand dwellings and (b) remains at the 51°C temperature and is coupled with an ASHP which is economically a preferred solution for the average demand dwelling.

Logically, as grid emissions are reduced the equivalent heating emissions from electrified technologies reduce proportionately. Because the difference of energy efficiency for heating between DEH and ASHP, heating emissions vary significantly as shown in Figure 6-6. For example, with the average grid emission of 150 gCO_2e/kWh, the heating emission of DEH can be three times of the emission of TES coupled ASHP. However, if electrical grid is deeply decarbonised (average emission lower than 25 gCO_2e/kWh), both DEH and ASHP (coupled with TES) can deliver low-carbon heating at a similar emission level (i.e., <30 gCO_2e/kWh).

For DEH although the high temperature allows high energy storage densities, at the higher U values there are more losses and so there is little benefit until around 0.8 W/m^{2}K, below this point the heat can better be retained to use off-peak low emissions grid electricity more efficiently. As the average grid emissions reduce although the percentage of heating emissions still reduces with the U value, the absolute difference decreases, however this is very dependent to how future grid emissions vary on an hour-by-hour basis. On the other hand, TES coupled with ASHP shows that the U value makes very little difference to heating emissions, due to the lower temperature limits of ASHP making TES low capacity and losses remain very low even at higher U values compared to overall heating demands.

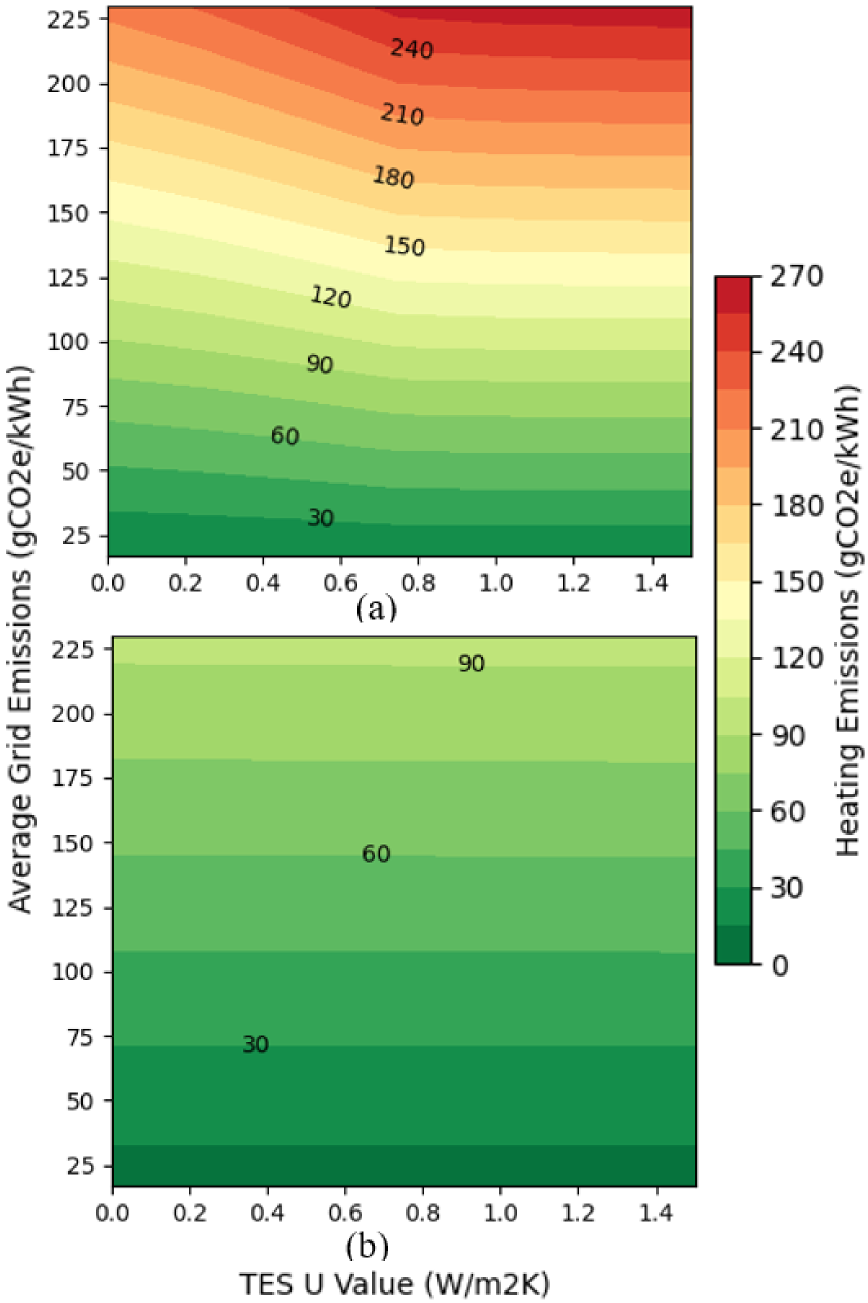

Figure 6-6 Specific heating emissions in gCO_2e/kWh for the average demand dwelling with varying levels of average grid emissions in the y-axis against Thermal Energy Storage (TES) thermal efficiency improvements on the x-axis with a $0.5m^3$ thermal store for (a) Direct Electrical Heating (DEH) with an elevated maximum TES temperature of 500°C and (b) an ASHP at a maximum TES temperature of 51°C.

Alongside the planned reduction of grid emissions, there is also the consideration of increasing global temperatures. Figure 6-7 shows how the cost of heating may change from increasing ambient temperatures for the current average dwelling size and efficiency. This very approximately simulates global warming by adding a fixed value onto each hourly temperature value from 2019 weather datasets. The low-rate 2020 tariffs are used, with the electrified technologies using the VToU tariff. DEH is coupled with 0.5m3 TES and ASHP with 0.1m3, as they are both typically the optimum size TES. With the increasing ambient temperatures, the OpEx for all technologies decreases, which then also reduces NPC. The position of the three key technologies does not change, with gas remaining the lowest cost, but absolute differences are reduced. It is worth noting that alongside this reduced heating demands comes increased cooling demands which are not considered here, which may become a new of a requirement in locations, such as the UK, which currently do not use a lot of air conditioning.

Comparing ASHP to gas, initially with 2019 weather ASHP is £170, 50%, higher OpEx, but this reduces to £93, 39%, with 4°C global warming. There are multiple factors as to why the competitiveness of gas is reduced. All technologies start to plateau out at increased ambient temperatures, although space heating demands reduce from less heat loss, the hot water demand is not affected, while maintaining the same cold water inlet temperature and desired hot water temperature. Domestic hot water demands, and additionally the standing charge which has not changed, will limit how low the OpEx can then go. On top of the ambient temperatures reducing heating demands for ASHP it also has the benefit of improving the COP, therefore helping to decrease its costs relative to gas boilers.

As found when lower demand dwellings were considered from smaller dwellings and from spatiotemporal changes, with the reduced demand and OpEx it puts more ownness onto the CapEx of the technologies as a more major contributor towards the NPC. This can be seen by a decrease between ASHP and DEH on NPC as temperatures increase.

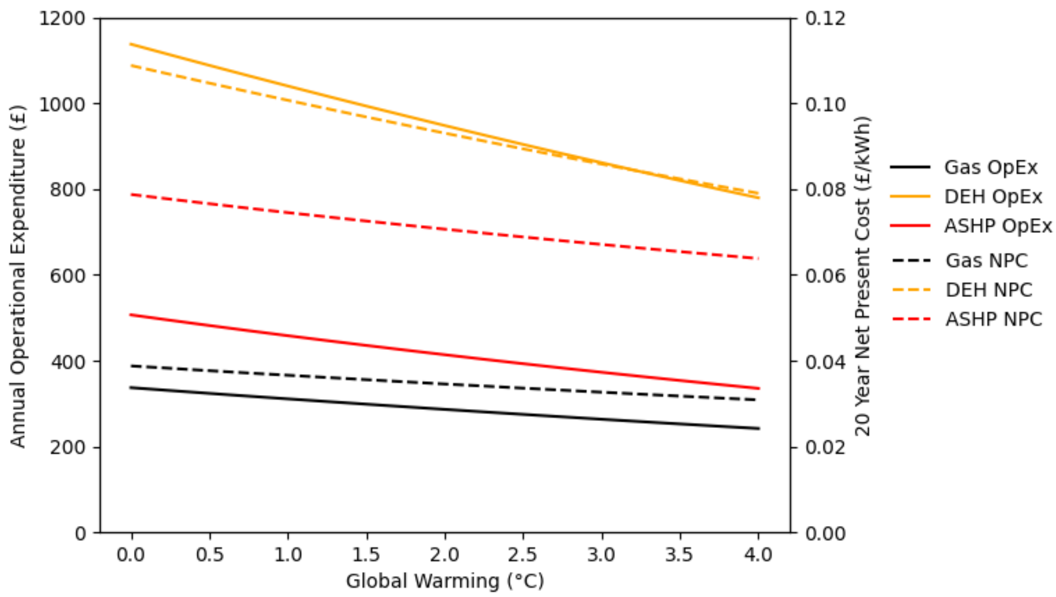

Figure 6-7 Global warming effect on cost of heating, with the current variable time of use tariff. Air Source Heat Pump (ASHP), Direct Electrical Heating (DEH), Net Present Cost (NPC).

To better visualise the greater system benefits of TES coupled with electrified heating systems Figure 6-8 shows the first two days of the simulation for DEH in the lower 25th percentile home, which has been found to have a good potential for shifting demand and reducing peak electricity usage. Figure 6-8 (a) without any TES and (b) with a 0.5m^3 hot water tank TES.

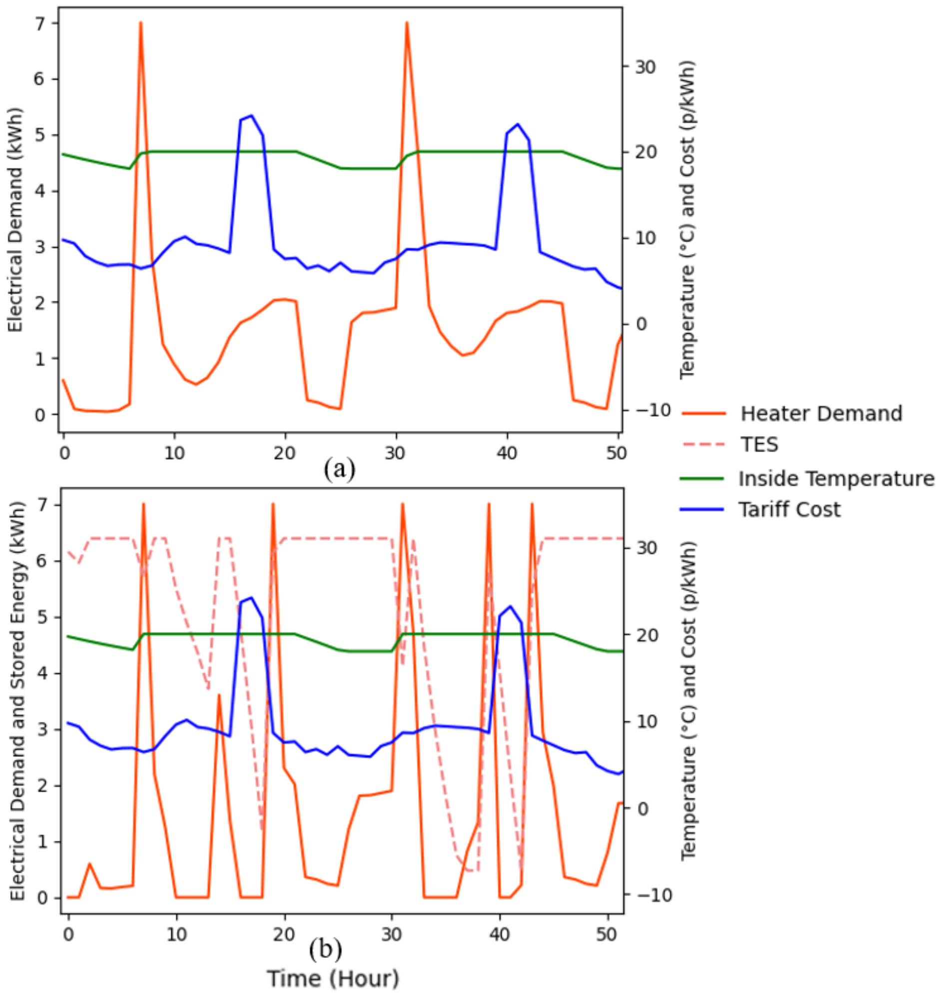

Figure 6-8 DEH demands against variable time of use tariff costs for the lower 25th percentile dwelling demand with (a) no Thermal Energy Storage (TES), and (b) with a 0.5m³ TES.

Without the TES the heating supply must instantaneously follow the heating demand to balance out building heating losses, domestic hot water demands, and increases in desired thermostat temperatures. Any following of off-peak electricity use here is purely coincidental as the system has little control. In reality DEH is likely to struggle to meet instantaneous heating demands without some TES. When then including TES, although similar trends occur of following increasing thermostat set points, the TES can significantly reduce peak electricity use and recharge when prices reduce again while still meeting the household demands. This affect is stronger with the lower demand dwelling as even with current TES technologies the capacity is significant enough to have an impact for low demand dwellings.

6.5 Summary

This Chapter answers the final research question to identify which TES parameters are most valuable to improve the viability of TES. As current research is dominated by improving energy densities. Using a range of dwelling demands and high and low cost tariffs the research finds TES has limited potential to improve economic viability with ASHP for consumers, due to the temperature limitations heat pumps, making low CapEx the most critical parameter for TES, however LHS is the technology that can couple best with heat pumps if a phase change temperature around 50°C can be used to meet demands while maintaining high efficiency. On the other hand, TES can bring significant benefits to DEH, in particular with SHS which can achieve high temperatures and therefore have low cost high energy storage densities. Indicating high temperature SHS with DEH is of most interest for domestic TES.

The data and simulations shown in this Chapter demonstrate the benefits of TES and importantly which areas of improvement can result in improved economic and environmental viability of TES in domestic applications, and therefore increase its adoption by consumers. TES can bring wider system benefits from shifting of demand, leading to reduction in peak electricity use which eases the burden along the electrical network and generation demands. This flexibility can also allow the increased utilisation of variable renewable energy generation, whether regionally or decentralised at the dwelling, allowing further reduction in emissions.

An important comparison of TES at a system level is considered as well as at a material level, which emphasis why system approach needs to be considered as the addition of ancillary parts alongside the storage material significantly alters the specific costs and energy densities. The study also quantifies how TES requirements change from DEH to ASHP. Giving clear conclusions that ASHP and solar thermal low-carbon heating technologies with limited output temperatures can benefit well alongside LHS that have a suitable melting temperature around 50°C to provide useful heat to the home while maintaining high heater efficiencies. On the other hand, DEH, which maintains its efficiency at higher temperatures and has high charging power and flexibility couples best with high temperature SHS.

Various scenarios simulated in the Chapter allow a clear clarification of what parameters are the most valuable for TES concepts to improve their economic viability, finding low CapEx is the most important factor for domestic TES, as also found in a review by Alva et al [64]. The study specifies low CapEx TES is a much more dominant factor for ASHP compared to DEH. Our work further concludes that at the pre-energy crisis low tariffs, larger TES does not reduce its OpEx sufficiently enough over its lifetime to payback the additional CapEx alongside ASHP, but with the high tariffs larger TES has now become cost effective. The low CapEx requirement for TES viability is why the simpler hot water tanks, with their competitive costs are the dominate technology, as other technologies are more expensive at a system level in £/kWh.

For DEH, although low CapEx is found to be valuable for TES, the most valuable parameter for TES coupled with DEH is high energy densities, allowing greater use of off-peak electricity. Yet it is important to emphasise that DEH may be selected due to its low CapEx making it the only affordable low-carbon heating technology, meaning high CapEx TES is not realistic with DEH. This high density can be achieved at low CapEx by using low-cost materials that are capable of withstanding higher temperatures. It is found that for high temperature TES alongside DEH that the U value needs to be less than $0.8W/m^2K$ to reap the advantageous of the higher storage temperatures. Space availability for TES in homes can be a restricting factor, hence why this study focuses on energy densities as high energy densities can allow sufficient energy storage capacities in smaller spaces. With smaller dwellings there is likely a smaller area available for TES and ASHP, alongside this the smaller the dwelling the lower the demand (with a fixed dwelling thermal efficiency), therefore in lower demand dwellings it was found high-capacity TES has more potential, these points together highlight a real benefit of high energy density TES with DEH in low demand dwellings. The study also finds that even in scenarios which are most preferential for TES, which are high density alongside DEH, this combination of DEH still struggles to compete with ASHP in reducing emissions in all scenarios simulated. Although this does depend on the how the grid emissions fluctuate across the day, this can conclude the heater efficiency is more important that the TES parameters.

Chapter 7 Conclusion

Due to the ever-growing threat of climate change from the combustion of fossil fuels from human activities, there is an urgent need to decarbonise all energy sectors. The domestic heating along with other consumer energy consumptions face unique challenges that it is down to the consumer's preference and ability to afford and invest in low-carbon technologies to implement their uptake. The thesis is motivated by these aspects and aids to highlight the technologies that are the most viable for consumer decarbonisation alongside tariffs and technology parameters analysis which can improve the uptake of low-carbon technologies.

A novel framework was created to simulate heating demands for a range of dwelling sizes and locations. Additionally other consumer demands were then added into the model to allow full holistic approach for more realistic integration of demands and technologies that consumers would face, especially with the use of electrification of heating, transport, the use of local generation, and energy storage. The model goes on to complete techno-economic analysis of the range of technology combinations and potential tariffs structures available to consumers for the dwelling inputs to determine what is the most economical combination of technologies and tariff across a 20-year lifetime.

This Chapter concludes how the research has answered the objectives that were set in section 1.2.

- *How does the economically optimum heating system alter with changes in dwelling demands and spatiotemporal variations?*

  Analysis was complete in Chapter 4 for a range of dwelling sizes which were correlated to 10th, 25th, 50th, 75th and 90th percentile dwelling demands in the UK in a central England location of Coventry. The study then went on to compare how location of the dwelling across the UK alters the positions of the heating and ancillary solar technologies. This analysis was complete with the range of tariff costs from the more stable pre-energy crisis period.

  The results show that for an average demand dwelling and across the majority of UK locations the lifetime cost optimal solution is an ASHP coupled with a solar PV and using a minimal TES size of 0.1m^3 and the low average cost VToU tariff. As the dwelling demand increases from larger dwellings and more northerly and inland locations GSHP becomes more viable where its high efficiency and therefore lower OpEx which can overcome the high CapEx. More coastal areas, which have milder Winters can remain optimal with ASHP as they are less susceptible to the ASHP drop off in COP with colder ambient conditions that is more prominent inland. Conversely as dwelling demand reduces due to smaller dwellings and more southerly locations DEH and Blue H_2 become preferred solutions due to their low CapEx, despite their higher OpEx than heat pumps. Solar thermal technologies struggle economically compared to solar PV due to inability to use or sell surplus energy generation, which is commonplace in summer for solar technologies. Due to the cost structure of PV with the decreasing cost per panel at increased array sizes, PV becomes more viable in larger dwellings which have more space for larger PV installations, and conversely smaller dwellings struggle to payback the CapEx for small installations.

Although it is well known that high CapEx cost may be limiting factor for heat pumps especially for low-income households, current literature draws little conclusions from this other than it prevents heat pump uptake. This study has gone on to explore how DEH can become the preferred technology from smaller dwellings and dwellings in milder locations, on top of ASHP being unaffordable for many consumers. This is particularly prominent with new building regulations and encouragement of retrofitting installation, making dwellings more efficient and climate change increasing average temperatures during heating seasons and therefore all lowering their heating demand. Additionally, the thesis completed an investigation to show that when optimising for shorter periods of time than the full 20-years typical life of heating systems, DEH also becomes the preferred. The thesis has collated an array of reasons why DEH may become preferential for many dwellings over ASHP. This higher potential popularity of DEH is critical for future planning, as DEH will require larger electrical demand than ASHP requiring more low-carbon generation and more impact onto the electrical network. Strong policy decisions and incentives set by governments need to ensure that high efficiency technologies remain the prominent option for dwellings to prevent mass uptake of less efficient DEH over ASHP.

- *Determine tariff structure changes required to incentives the use of energy storage for consumers?*

The effect of tariffs rates on consumer OpEx and cost of living is a key issue given the energy-crisis, with simple conclusions being quickly reached from the reduction in the ratio between gas and electricity prices, as they have both increased, which improves the viability of electrified heating technologies compared to gas boilers. Yet there is little discussion of how these more complex changes in tariff rates for different types of tariff structures alters the position of other low-carbon technologies, in particular energy storage. A range of four types of tariff structures are analysed, the basic flat tariff, the night-time off-peak Eco7 tariff, an EV tariff with a short four hour window of low-cost electricity and a day ahead VToU tariff. These were also then analysed at pre and post energy crisis rates.

At the stable pre-energy crisis low tariff rates, where the cost of heating and other consumer energy use was lower, the VToU tariff was the dominant preferred tariff. This was due to its low average rate across the day, with only a short three-hour window of high-cost peak electricity. With these 2020 tariff rates, and the competitive VToU tariff, no energy storage was found to be viable unless coupled with DEH which has one of the highest OpEx. At this time the only low-carbon technologies that were found to reduce lifetime costs compared to the fossil fuel baseline of a gas boiler and a petrol car were EV and PV.

When then considering the higher rate energy crisis tariffs the situation changes. The VToU tariff reacts quickly to the market price increase and becomes one of the least favourable tariffs. Instead, the EV tariff, which keeps a short window of off-peak electricity becomes preferred. With the higher rates, any opportunity for low-cost electricity is more valuable, which significantly improves the situation for all energy storage, making larger capacity TES, BES and V2H all financially viable. Albeit at the expense of significantly higher OpEx for consumers from the increased tariff rates. Building on this the thesis goes on to quantify the difference required between peak and off-peak electricity prices required to ensure energy storage viability over its lifetime, based off the EV tariff structure. Finding that TES only needs a difference of 6p/kWh, whereas V2H requires a minimum of 10p/kWh, and BES 24p/kWh. Although TES requires the lowest difference to breakeven, any increase in peak to off-peak difference makes stronger economic case for electrified technologies due to the higher versatility to supply multiple demands not only heating.

Other conclusions can be drawn with respect to energy poverty, which is more prevalent at higher tariff rates. There are increased OpEx reduction benefits for consumers that invest in technologies which are high CapEx, and therefore less likely to be affordable by those in poverty. This perpetuates the divide between the poor and the rich, as the wealthier are the only ones able to afford technologies which reduce their longer-term cost. These insights highlight to policymakers that adoption of half hourly settlement and widespread use of time of use tariffs that are tailored to specific technologies are crucial to incentivise uptake of low-carbon technologies, reduce consumer costs and reduce network peak demands.

- *Which TES parameters are most valuable to be developed to improve their viability?*

  Current analysis on TES focuses on material specific developments, which although is important alone this does not show the full picture for TES. For TES to achieve higher levels of uptake it needs to be economically effective for consumers to purchase. The thesis looks at the parameters of TES and investigates which ones are most valuable and crucially how this alters depending on what heating technology the TES is coupled with. A thorough literature review on TES was complete to collate material data and shows how the perspective SHS, LHS, and TCS changes depending on if it is coupled with DEH which is able to achieve the high temperatures required for many TES materials, to how the TES materials perform when coupled with ASHP or solar thermal collectors with their limited temperature range. Using ASHP reduces the material options for TES, especially for TCS, and shifts the focus from SHS being preferential with DEH to LHS have a strong potential with ASHP.

  Techno-economic analysis of TES systems are then complete within the heating simulation framework created in this thesis. Although TES has potential to reduce emissions by shifting heating demands to off-peak times for the average demand dwelling, for those dwellings that optimise with ASHP it is less advantageous economically. With the nominally lower OpEx of ASHP there are fewer financial improvements to be made with shifting demands to off-peak times. Instead alongside ASHP the most important TES factor is low CapEx, which can then increase the likelihood of it being taken up. Although DEH also finds low CapEx TES highly beneficial, increasing the capacity of the TES is significantly more advantageous for DEH than for ASHP, as DEH has nominally a higher OpEx.

  These learnings show that TES developments should target working alongside ASHP with LHS TES that has melt temperatures close to the heating demand temperatures of 50°C to allow maximum ASHP efficiency, but importantly need to ensure low CapEx. The most potential for domestic TES however is alongside DEH, where SHS with high temperature materials brings higher energy storage densities and can benefit lower demand dwellings where DEH is typically more favourable.

7.1 Further Work

Although the research tried to be thorough and cover a wide array of demands, technologies, and variables to improve the understanding of low-carbon technologies for consumers, there are some aspects that could be worked on to improve the breadth or depth of the research.

In addition to how the future associated emissions of technologies will change with reduction in electrical grid emissions which was analysed in the thesis, the costs for technologies are also likely to change. Predicting these changes is very challenging and not attempted within this study, as there are many unknown factors. As the current energy crisis shows, energy costs can be highly volatile, but further adoption of higher quantities of renewable power generation could reduce the costs of electricity. The CapEx of technologies for consumers are also likely to change, in relation to cost of energy required for manufacturing, but also from reducing CapEx as technologies are manufactured at larger volumes. Changes to these variables will have a strong impact on the position of the technologies presented. Further work could be done to complete sensitivity studies from CapEx reductions due to low-carbon technologies being manufactured at higher quantities.

As the study focuses on optimisation and analysis of multi-vector energy demands and a wide selection of technologies and scenarios, the breadth of the simulations has been gained by reducing the depth and detail of the heating simulations, by having relatively simple building and demand models to allow flexibility and versatility in the framework. More detailed dwelling analysis could be completed to further optimise the heating system not only from reducing the thermostat setpoint in some rooms, but also by using smarter weather compensation values for the radiator flow temperature which can allow greater heat pump efficiency.

The analysis is focused from the perspective of the consumer to show what they are likely to implement, but mass adoption of these technologies will have knock on effects for regional and national electrical/gas networks. Local networks may benefit from locally produced electricity from PV and FC as it has the potential to reduce end-of-the-line electrical network congestions, which is not quantified here. On the other hand, very high adoption may also cause an oversupply congestion and curtailment. The wide array of network challenges which would need to be overcome with either the expansion of the electrical network or adoption of the gas network for H_2 suitability to facilitate the low-carbon technologies has not been studied. As the source for Grey and Blue H_2 is a fossil fuel, this also depletes the finite resources, which can alter energy security along with other factors that are not taken into consideration. The storage benefits of H_2 are also not considered which can help to meet the mismatch in demands from variable renewable energy generation to demands from direct electrification, in particular from electrified heating. Incorporation of using H_2 for energy storage and consideration for the impact on the electrical or H_2 networks could be included into the study to show the broader impact of the technology uptake.

During development of the framework and analysis in the simulations higher TES temperatures were trialled to better utilise off-peak electricity and surplus PV energy by charging to higher temperatures. However, using the blanket approach of one target TES temperature for all of the year increased TES storage losses which is detrimental outside of the heating season (and causes more overheating challenges) and therefore was not viable as it resulted in more TES storage losses. Although the benefits of TES with the pre-energy crisis energy costs is diminished as the VToU tariff is the optimal tariff, which only typically has three expensive hours of electricity a day, making energy shifting requirements relatively small. Smartly adjusting the charge levels of TES to meet the days demands could be added to the framework. For warmer days, outside of the heating season, only sufficiently to meet domestic hot water demands. Cooler days can also adjust the temperature of the TES to optimise by balancing using off-peak electricity rates charging to higher temperatures against more TES storage losses from using higher temperatures.

Future work could also consider the compromises and trade-offs found with hybrid heat pumps with gas boilers, with low emissions of heat pumps and low OpEx of gas boilers. Although a hybrid system increases the CapEx above the already expensive heat pumps, the framework can be used to see if there is any room for optimisation beyond the current more general conclusion that has been found of heat pumps always offer improved emissions, in the UK, and gas boilers always offer reduced lifetime costs.

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Appendix A

Material Category	Material	Specific Cost (£/kWh)	Energy Density (kWh/m3)
SHS, H2O	Water	1	75
	Steam (5 Bar)	3	1
SHS, oils	Therminol VP-1	408	228
	Syltherm XLT	504	116
	Vegetable oil	11	171
SHS, salts	HITEC	5	279
	HITEC XL	6	304
	Solar salt	5	301
SHS, metals	Aluminium (500°C)	12	317
	Cast iron (1000°C)	0.56	962
	Cast steel (1000°C)	0.867	1051
	Sodium	5	295
	Sodium-potassium eutectic	7	146
	Lead-bismuth eutectic	173	564
SHS, earth materials	Basalt	498	4604
	Concrete	1	340
	Silica fire bricks	2	339
	Magnesia fire bricks	1	1121
LHS, paraffins	n-Hexadecane	4611	51
	n-Heptadecane	9455	46
	n-Octadecane	4094	53
	n-Nonadecane	13611	48
	Rubitherm RT-25	80	44
	Rubitherm RT-50	110	36
	Rubitherm RT-82	103	39
	PRS paraffin wax	23	44
LHS, fatty acids	Lauric acid	1152	41
	Palmitic acid	341	341
	Stearic acid	352	352
LHS, alcohols	Xylitol	1248	118

	D-sorbitol	4276	46
	Meso-erythritol	3285	139
LHS, salt hydrates	CaCl2 6H2O	289	83
	NaCH3COO 3H2O	55	51
	MgCl2 6H2O	86	73
	Mg(NO3)2 6H2O	168	74
	Ba(OH)2 8H2O	56	153
	Na2S2O3 5H2O	66	97
	Na2HPO4 12H2O	47	118
LHS, other salts	NaNO3	92	108
	KNO3	69	156
	Na2CO3	22	194
	K2CO3	78	150
	CaCO3	148	116
	Li2CO3	573	298
	ZnCl2	491	61
	NaCl	18	252
	KCl	44	194
	MgCl2	232	291
	LiCl	238	254
	CaCl2	53	151
	Na2SO4	54	123
	Li2SO4	5080	52
	K2SO4	102	157
	MgSO4	295	90
	CaSO4	350	131
	LiF	380	766
	NaF	19	564
	KF	919	308
	CaF2	46	345
LHS, hydroxides	NaOH	65	96
	KOH	88	85
	LiOH	497	354
LHS, metals	Copper	950	518

	Zinc	233	224
TCS	MgSO4 7H2O		917
	MgSO4 6H2O		580
	Mg(OH)2		778
	FeCO3		722
	Fe(OH)2		611
	Ca(OH)2		806
	CaCl2 2H2O		306
	CaCl2 NH3		230
	Al2(SO4) 6H2O		528
	CaSO4 2H2O		389
	MgCl2 6H2O		694
	Na2S 5H2O		989
	SrBr2 6H2O		639
	Li2SO4 H2O		256
	CuSO4 5H2O		575
	SiO2 H2O		220
	Zeolith H2O		230
	NiCl2NH3		280
	CH4 H2O		9
	NH3 H2O		1
	2H2 O2		600
	Calcium looping		1200
Batteries	Lead batteries	73	80
	Li-ion batteries	146	500

Table A-1 TES material cost and energy density, using maximum temperatures. Sources [64], [65], [145]–[151], [66], [67], [70], [140]–[144].

For the analysis of material suitability and properties for low-carbon heaters, SHS materials are limited to 70°C, whereas latent heat and thermochemical materials use the same data but only those which have suitable melt/reaction temperatures between 70-30°C.

Material Category	Material	Specific Cost (£/kWh)	Energy Density (kWh/m3)
SHS, H2O	Water	1.6	46
SHS, oils	Therminol VP-1	3777	25
	Syltherm XLT	2899	20
	Vegetable oil	70	26
SHS, metals	Aluminium	144	27
	Cast iron	14	40
	Cast steel	21	43
	Sodium-potassium eutectic	148	8
SHS, earth materials	Basalt	4604	44
	Concrete	13	26
	Silica fire bricks	33	20
	Magnesia fire bricks	29	38

Table A-2 TES materials costs and energy density using 70°C down to 30°C. Sources [64]–[67], [140], [144], [145].

TES System	Dimensions (m)	Cost (£)	Energy Capacity (kWh)
Hot water tanks	ø0.579x1.739	1063	18.6
Ceramic storage radiator	0.78x0.25x0.75	836	7.7
	0.78x0.25x0.99	983	15.54
	0.78x0.25x1.23	1162	23.1
Commercial salt LHS	0.429x0.365x0.575	1800	3.5
	0.64x0.365x0.575	2075	7
	0.87x0.365x0.575	2469	10.5
	1.05x0.365x0.575	3230	15
New commercial SHS	0.98x0.6x0.66	5000	40
	ø1.0x1.7	10000	100

Table A-3 TES system level data [68]–[70], [143], [146], [152]–[155].

Heater	Dwelling Percentile	Thermal Power (kW) COP 2-4 for ASHP	Heater CapEx (£)
DEH	All	7	1100
ASHP	10th	2.0-4.1	5659
	25th	2.5-5.0	5671
	50th	3.9-7.9	5894
	75th	5.1-10.1	6162

Table A-4 ASHP and DEH parameters used in the simulations.