Energy & Buildings 277 (2022) 112561

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

# Heating economics evaluated against emissions: An analysis of low-carbon heating systems with spatiotemporal and dwelling variations

Michael Ryland, Wei He *

*School of Engineering, University of Warwick, Coventry CV4 7AL, United Kingdom*

ARTICLE INFO

*Article history:*
Received 22 June 2022
Revised 16 September 2022
Accepted 5 October 2022
Available online 8 October 2022

*Keywords:*
Decarbonising
Low-carbon
Domestic
Residential
Heating

ABSTRACT

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 also little consideration of how spatiotemporal and dwelling variations combined alter the economic and environmental effectiveness of technologies. The novelty of this paper is the creation and use of a new comprehensive framework to capture 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, thermal energy storage sizes and tariffs with hourly heating simulation across a year and compares their operation, capital, 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 air source heat pumps coupled with photovoltaics. However, direct electrical heating becomes more economically viable as dwelling demands reduce from smaller dwellings or warmer climates, as shorter durations of the ownership are considered, or with capital cost constraints from lower income households. Understanding this is of high importance, as without correctly targeted incentives, a larger uptake of direct electrical heating may occur, which will burden the electrical network and generation to a greater extent than more efficient heat pumps.



## 1. Introduction to decarbonising domestic heat

Many countries are committing to net zero emissions to help tackle climate change, the majority targeting 2050 [1]. To achieve this goal, the building sector, which currently accounts for 37 % of global $CO_2$ emissions, will have to decarbonise. Direct emissions from this sector totalled 3Gt$CO_2$ in 2019, and 80 % of this was from heating [2]. The challenge of decarbonising heating is felt globally, although 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, but most countries globally are still heavily reliant on fossil fuels for heating [3]. However, the path to decarbonise heating is less clear than for other energy sectors.

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 highly 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 such enormous investments [4,5]. Similarly, from the end users' perspective, which this paper 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 needs to be economically competitive with incumbent fossil fuel burning (e.g., gas) boilers [6]. Achieving this cost constraint will particularly influence low-income households, where fuel poverty was already of concern for between 50 and 125 million people across Europe before the energy crisis and there is limited capital available to install the high cost heat pumps [7].

The consumer's perspective is often overlooked in academic research with more focus being put onto the overall system

* Corresponding author.

https://doi.org/10.1016/j.enbuild.2022.112561
0378-7788/

**Nomenclature**

*Abbreviations*

| | |
|---|---|
| ASHP | Air Source Heat Pump |
| CCS | Carbon Capture and Storage |
| COP | Coefficient of Performance |
| DEH | Direct Electrical Heating |
| DHW | Domestic Hot Water |
| GSHP | Ground Source Heat Pump |
| NPC | Net Present Cost |
| PV | Photovoltaic |
| PVT | Photovoltaic/Thermal |
| SAP | Standard Assessment Procedure |
| TES | Thermal Energy Storage |

*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 |
| $\delta_m$ | Monthly solar declination (°) |
| $C_d$ | Dwelling heat capacity (kWh/K) |
| $C_n$ | North facing window constant |
| $C_s$ | South facing window constant |
| $E^i_{pv}$ | PV or PVT electrical energy generation (kW) |
| $f^i_{\varphi\delta}$ | Solar height factor |
| $f_{pitch}$ | Window pitch factor |
| $G_m$ | Metabolic gains (kW) |
| $G^i_{s,n}$ | Gains from north facing windows (kW) |
| $G^i_{s,s}$ | Gains from south facing windows (kW) |
| $h_{tes}$ | TES cylinder height (m) |
| $h^i_{t,c}$ | Height ratio of thermocline |
| $I^i_{i,n}$ | Incident solar irradiance for north facing windows (W/m$^2$) |
| $I^i_{i,roof}$ | Incident solar irradiance on the dwelling roof (W/m$^2$) |
| $I^i_{i,s}$ | Incident solar irradiance for south facing windows (W/m$^2$) |
| $I^i_{h,n}$ | Horizontal solar irradiance for north facing windows (W/m$^2$) |
| $I^i_{h,s}$ | Horizontal solar irradiance for south facing windows (W/m$^2$) |
| $\varphi$ | Dwelling latitude (°) |
| $\eta^i_{pv}$ | 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) |
| $Q^i_{dhw}$ | DHW demand (kWh) |
| $Q^i_{hl}$ | Dwelling heat loss (kWh) |
| $Q^i_{sh}$ | Space heating demand (kWh) |
| $Q_{sh}$ | Yearly space heating demand (kWh) |
| $Q^i_{st}$ | Solar thermal collector energy generation (kWh) |
| $Q^i_{tes}$ | TES thermal energy capacity (kWh) |
| $Q^i_{tes,low}$ | Heat loss from lower part of TES (kWh) |
| $Q^i_{tes,up}$ | Heat loss from upper part of TES (kWh) |
| $r$ | TES cylinder radius (m) |
| $r_d$ | Discount rate |
| $R^i_{dhw,h}$ | DHW hourly ratio |
| $R_{dhw,m}$ | DHW monthly factor |
| $R^i_{h-p,n}$ | Horizontal to pitched ratio for north facing windows |
| $R^i_{h-p,s}$ | 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 100 m depth (°C) |
| $T_{hw}$ | Hot water temperature (°C) |
| $T_d$ | Desired indoor temperature (°C) |
| $T^i_{in}$ | Inside temperature (°C) |
| $T^i_{out}$ | Outside temperature (°C) |
| $T^i_{st}$ | Solar thermal collector temperature (°C) |
| $T^i_{tes,low}$ | Temperature of lower part of TES (°C) |
| $T^i_{tes,up}$ | 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 DHW for baths (L) |
| $V_o$ | Daily other volume of DHW (L) |
| $V_s$ | Daily volume of DHW for showers (L) |
| $V_t$ | Daily total DHW volume (L) |
| $V_{tes}$ | Volume of TES being simulated ($m^3$) |

analysis. Yet the consumer's perspective is critical in decarbonisation of heat, as they will be the ones that are selecting 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.

Low-carbon heating solutions generally have higher capital expenditure (CapEx) than fossil fuel boilers, alongside higher fuel costs than fossil fuels. For example in the US, electricity is in the region of five times more expensive than natural gas [8,9]; and low-carbon gas like hydrogen produced in steam reforming or electrolysis is also more expensive than gas, before taking into account the infrastructure construction cost [4]. Thus, simply replacing fossil fuel boilers with alternative low-carbon heating solutions will lead to significant heating cost increases and poses a huge challenge for domestic heating decarbonisation [10].

Current research does not give the full picture of the potential of different heating systems considering and optimising the range of parameters alongside ancillary technologies for homeowners, it also does not show how they are affected by variations in the dwellings geographical, temporal and efficiency differences. Leading to lack of clarity about how different heating systems compare depending on a dwelling's heating requirements. To mitigate the challenge, this paper develops a novel comprehensive framework to assess heating costs against associated carbon emissions among hundreds of combinations of state-of-the-art heating technologies – including the time-of-use electricity tariffs, Thermal Energy Storage (TES), various solar technologies, hydrogen productions and biomass boilers. The consumer-focused methodology finds a CapEx-OpEx (operational expenditure) balanced cost-effective heating solution tailored to individual customer's energy demand across climate zones and seasons. The versatility of the framework enables many parameters and technologies to be studied in a manner not done before, revealing which direction consumer may go once gas boilers are banned.

### 1.1. Low-carbon heating technologies

The range of heating technologies is introduced in this section before they are later be compared. A key competing technology to the gas boiler, which will be used as the baseline, 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. Direct Electrical Heating (DEH) is the simplest form, which uses resistance heating and is commonly already used in smaller dwellings in the Europe [11]. DEH can offer comparable emissions to gas with many current national 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 gas but with much higher fuel prices [12].

More sophisticated, and investment heavy, electrified heating options are heat pumps, common options being Air Source Heat Pumps (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 heat 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.

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 OpEx that can be used by electrified heating to reduce costs and emissions. Solar thermal collectors on the other hand directly generate thermal energy, but in cooler climates will 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 [13]. 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 [14].

Hydrogen for heating has recently been considered more seriously as a competitor to heat pumps for low-carbon heating [2,15,16]. Hydrogen could be used in boilers, in a similar method to natural gas boilers, or with fuel cells generating thermal and electrical energy. Although the current main method of manufacturing hydrogen is Grey Hydrogen, which converts hydrocarbon fuels into hydrogen with the by-product of $CO_2$, lower emissions methods would be required to ensure hydrogen for heating reduces emissions over gas boilers [17]. Blue Hydrogen can go one step further and uses Carbon Capture and Storage (CCS) to reduce emissions from hydrogen production, crucially though, this is currently not commercially available and thought to have an upper CCS efficiency of 90 % [18]. The end goal for hydrogen production is Hydrogen Electrolysis from water and electricity, which can become low-carbon when using a high percentage of renewable electricity [4].

Utilisation of TES needs to be considered alongside many low-carbon heating technologies to resolve the mismatch 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 [19]. 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.

This paper seeks to address 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. The 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. Fig. 1 shows the complexity of 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 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. Hydrogen heating technologies also consider use with the range of production methods as this alters the economic and environmental case for the hydrogen boilers and fuel cells. 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.

### 1.2. Low-carbon heating literature review

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, often from spatiotemporal differences [2,16,20]. 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 [22,23]. However, consumers are very much aware of their lack of knowledge around low-carbon heating systems [21]. 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 [4,5,24–28]. Table 1 shows the studies that have been reviewed for this paper 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 [14,29]. 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 [36]. Other papers 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 [33]. 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.

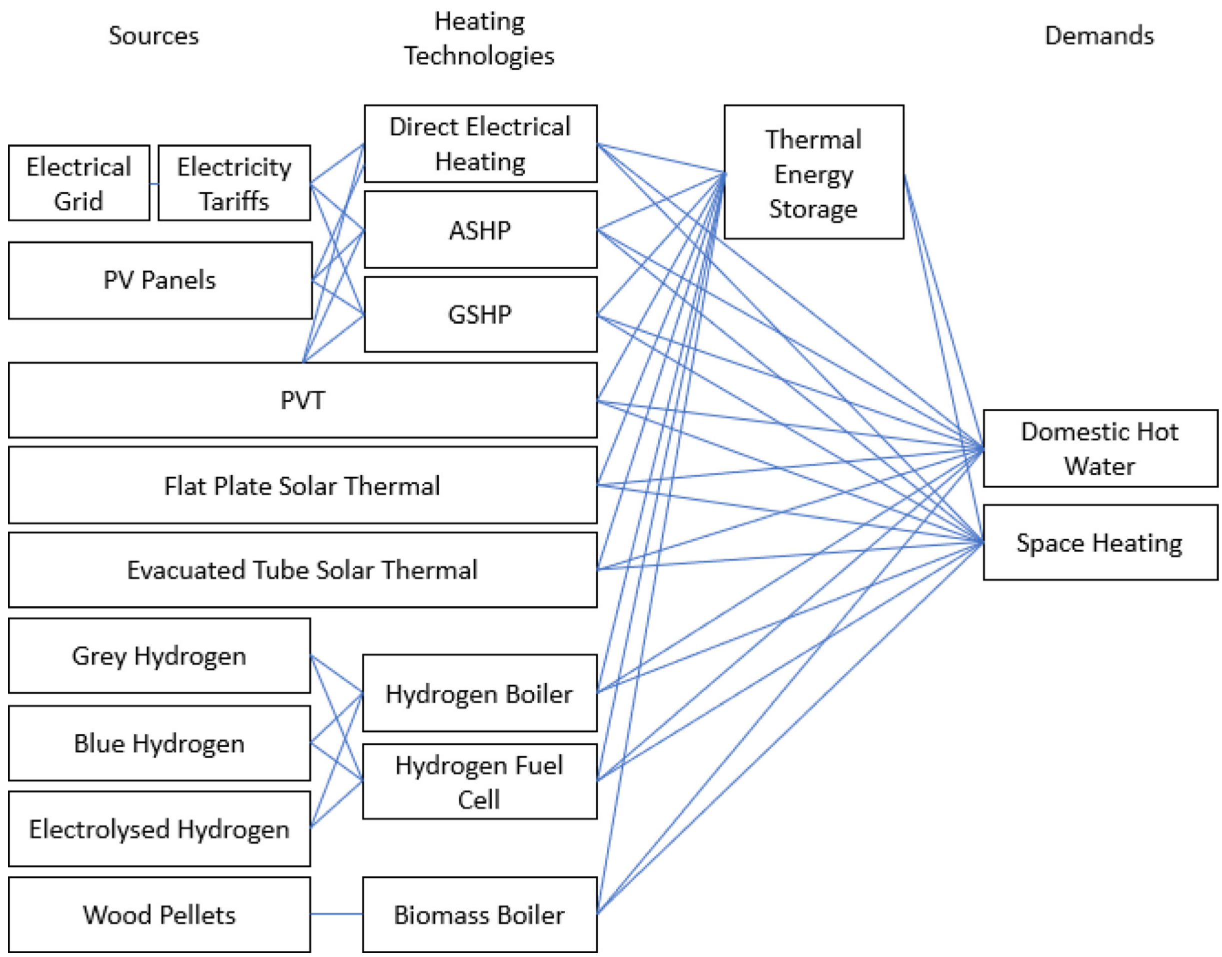


**Fig. 1.** Fuel sources, heating technologies, and demands considered in the comprehensive framework. Air Source Heat Pumps (ASHP), Ground Source Heat Pump (GSHP), Photovoltaic (PV).

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 [6] and from the detail analysis focused on GSHP by Jenkins et al. [41]. 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 [31]. Yet there are no studies 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 [14].

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 [13,32].

Reviewing the 15 studies in Table 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 [34]. 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 [35].

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. There is also a lack of studies demonstrating how spatiotemporal and dwelling changes together alter the position of the optimum heating systems.

### *1.3. Objectives of this study*

From the literature reviewed there are no frameworks existing which offer a comprehensive model to analyses low-carbon heating systems for consumers across the range and combinations of technologies including electrical heating, hydrogen heating, solar technologies, biomass, and the use of thermal storage, for comparing with fossil fuel solutions. There is also little consideration of how spatiotemporal and dwelling variations affect the optimum heating technology selection. To address these, objectives of this study are:

**Table 1**
Heating analysis studies for consumers reviewed in the literature. Air Source Heat Pump (ASHP), Capital Expenditure (CapEx), Combined Heat and Power (CHP), Direct Electrical Heating (DEH), Ground Source Heat Pump (GSHP), Hydrogen (H2), Operational Expenditure (OpEx), Photovoltaic (PV), Photovoltaic/Thermal (PVT), Solar Thermal (ST), Thermal Energy Storage (TES), Time of Use (ToU).

| | Modelling | | | | Economics and Environment | | | Technologies | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Study Reference | Tailorable/ Cases | Num of Locations | Modelling/weather resolution | Analysis duration | Emissions | OpEx | CapEx | Fossil fuel baseline | Electrified heating | | | | H2 heating | | Solar resource | | | Biomass | TES options |
| | | | | | | | | | DEH | ASHP | GSHP | ToU/Multiple tariffs | H2 boiler | Fuel cell/CHP | PVT | ST | PV | | |
| [13] | 3 | 8 | 1 h | Avg day/month | | | | | | | | | | | | ✓ | | | ✓ |
| [30] | 3 | 3 | 1 h | 1 year | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | | | | | ✓ | | |
| [31] | 3 | 1 | 15 min | 1 year | | ✓ | ✓ | | | ✓ | | ✓ | | | | | ✓ | | ✓ |
| [32] | 1 | 8 | 1 h | 1 year | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | ✓ | | | |
| [33] | 14 | 1 | 10 min | Season | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | | ✓ |
| [34] | 1 | 1 | 1 h | Season | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | | |
| [35] | 4 | 1 | 1 h | Avg day/month | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | ✓ | | ✓ |
| [36] | Yes | 1 | 1 h | 1 year | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | | | | | | | ✓ |
| [6] | 1 | 1 | 1 year | 1 year | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | |
| [37] | 1 | 1 | 1 h | 1 year | | ✓ | ✓ | | | | | | | | | ✓ | | | ✓ |
| [14] | 1 | 1 | 1 h | 1 year | ✓ | ✓ | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ |
| [38] | 1 | 1 | 30 min | Avg day/month | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | | ✓ | | |
| [39] | 1 | 1 | 1 year | 1 year | ✓ | ✓ | ✓ | ✓ | | ✓ | | | ✓ | ✓ | | | | | |
| [40] | 3 | 1 | 1 h | 1 year | ✓ | | | ✓ | ✓ | | | | | ✓ | | | | | |
| [29] | 2 | 1 | 1 h | 1 year | ✓ | ✓ | | ✓ | | ✓ | | | | | | | | | |
| [41] | 1 | 1 | 1 h | 1 year | ✓ | ✓ | | ✓ | | | ✓ | | | | | | | | |
| [42] | 1 | 1 | 1 min | 1 year | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | | | | | | |
| [43] | 5 | 3 | 1 h | 1 year | ✓ | ✓ | | ✓ | | ✓ | | | | | | | | | ✓ |
| [44] | 3 | 1 | 5 min | Avg day/season | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | | | |

- Assess the full range of prime heater technologies costs and carbon emission when combined and optimised with: different fuel sources; ancillary solar technologies and their optimal sizing; TES sizing; and a modern array of tariffs.
- Determine how spatiotemporal alongside dwelling variations alter the effectiveness of different low-carbon heating systems, to create a full landscape of low-carbon heating technologies.

The developed comprehensive and versatile framework can be used by end consumers, local network operators and policy makers to determine optimum technologies and how other technologies may need to be incentivised or improved to make them competitive. The compound effect of dwelling and spatiotemporal changes on the selection of the cost optimum low-carbon heating system can then be examined to develop consumer-tailored solutions.

## 2. Analysis methodology

A mathematical 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. Analysis is completed from the end-users' perspective so does not consider infrastructure upgrade costs of electrical or gas networks. 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. The framework is based on the logic flow diagram as shown in Fig. 2.

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 [7,45].

### 2.1. Spatiotemporal heating demand methodology

Space heating demand is calculated using formula, data and assumptions in the Standard Assessment Procedure (SAP) and Building Research Establishment Domestic Energy Model and equations are shown in Table 2 [46,47]. 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 [48], and an average SAP overshading of 0.77, a frame factor of 0.7 and a transmission factor of 0.76 are used [47]. The dwelling heat capacity $C_d$, is based on using a typical dwelling specific heat capacity of 250 kJ/m$^2$K [46].

The ambient and solar irradiance data uses the closest 0.5° longitude and latitude reanalysis weather dataset from renewable ninja from the year 2019 [50]. For ASHP and GSHP the dwelling is kept at the desired indoor temperature all of the time, as per manufacturer's and installer's recommendations [25]; for all other heating technologies it is kept at the desired temperature from 07:00–22:00 and a maximum of 2 °C cooler outside of those times.

DHW 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 [47]. An hourly run off profile across the day, from Energy Saving Trust [51], is used to create an hourly DHW ratio of the daily DHW volume. A monthly DHW factor is also applied from Building Research Establishment Domestic Energy Model [47]. Monthly values are used for the temperature of the cold-water entering the DHW system depending on the location of the dwelling [51]. A temperature of 51 °C is used for the hot

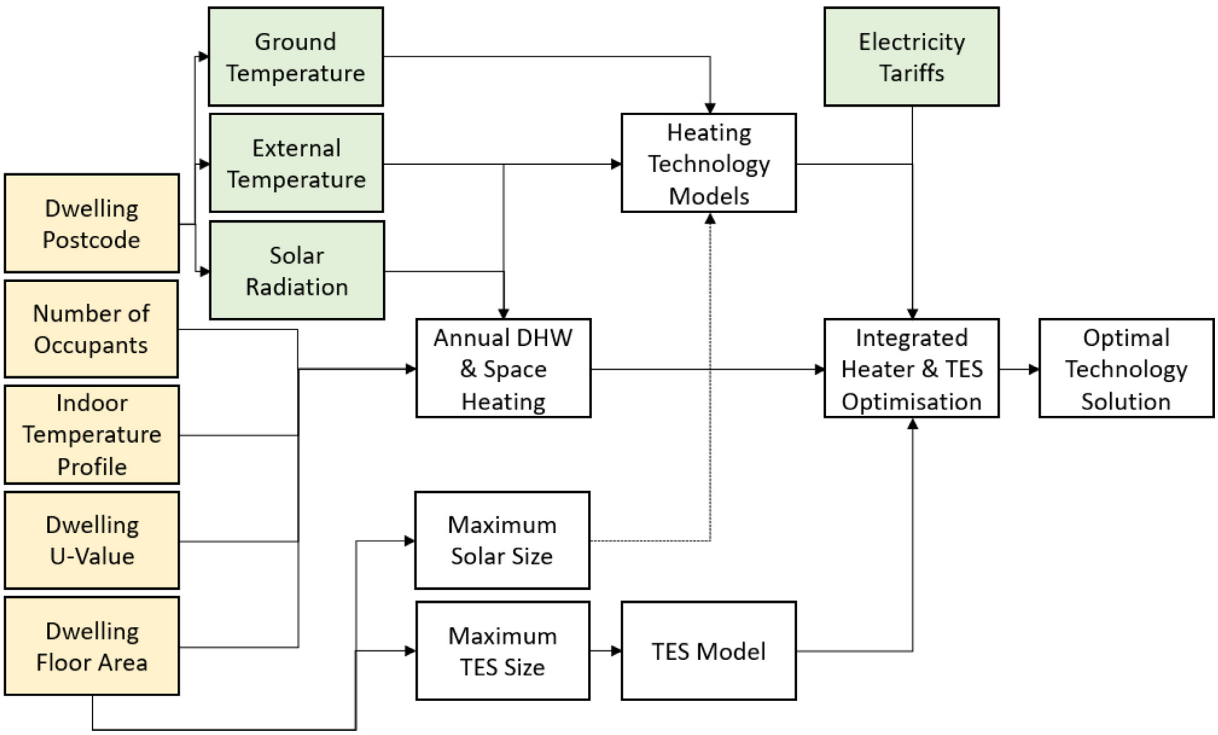


**Fig. 2.** Logic flow diagram for the Thermal Energy Storage (TES) integrated domestic heating mathematical model. Yellow boxes are inputs, green are datasets and white are model calculations with references to equations used shown in brackets. Domestic Hot Water (DHW). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
Space heating demand model formulas.

| Source | Formula | Equation Number |
|---|---|---|
| [47] | $f^i_{\varphi\delta} = cos(\pi/180 \times (\varphi - \delta_m))$ | (1) |
| | $f_{pitch} = sin(\pi/180 \times 90/2)$ | (2) |
| | $A_n = 26.3 \times f_{pitch}{}^3 - 38.5 \times f_{pitch}{}^2 + 14.8 \times f_{pitch}$ | (3) |
| | $B_n = -16.5 \times f_{pitch}{}^3 + 27.3 \times f_{pitch}{}^2 - 11.9 \times f_{pitch}$ | (4) |
| | $C_n = -1.06 \times f_{pitch}{}^3 - 0.0872 \times f_{pitch}{}^2 - 0.191 \times f_{pitch} + 1$ | (5) |
| | $A_s = -0.66 \times f_{pitch}{}^3 - 0.106 \times f_{pitch}{}^2 + 2.93 \times f_{pitch}$ | (6) |
| | $B_s = 3.63 \times f_{pitch}{}^3 - 0.374 \times f_{pitch}{}^2 - 7.4 \times f_{pitch}$ | (7) |
| | $C_s = -2.71 \times f_{pitch}{}^3 - 0.991 \times f_{pitch}{}^2 + 4.59 \times f_{pitch} + 1$ | (8) |
| | $R^i_{h-p,n} = A_n \times f^i_{\varphi\delta} + B_n \times f^i_{\varphi\delta} + C_n$ | (9) |
| | $R^i_{h-p,s} = A_s \times f^i_{\varphi\delta} + B_s \times f^i_{\varphi\delta} + C_s$ | (10) |
| | $I^i_{i,n} = I^i_{h,n} \times R^i_{h-p,n}$ | (11) |
| | $I^i_{i,s} = I^i_{h,s} \times R^i_{h-p,s}$ | (12) |
| | $G^i_{s,n} = (I_{i,n} \times (A_d \times 0.15)/2 \times 0.77 \times 0.7 \times 0.76 \times 0.9)/1000$ | (13) |
| | $G^i_{s,s} = (I_{i,s} \times (A_d \times 0.15)/2 \times 0.77 \times 0.7 \times 0.76 \times 0.9)/1000$ | (14) |
| [46] | $G_m = (N \times 60)/1000$ | (15) |
| [49] | $Q^i_{hl} = A_d \times U_d \times \left(T^i_{in} - T^i_{out}\right)/1000$ | (16) |
| [46] | $C_d = (250 \times A_d)/3600$ | (17) |
| | $T^i_{in} = T^{i-1}_{in} + \left(Q^i_{hl} + G^i_{s,n} + G^i_{s,s} + G_m\right)/C_d$ | (18) |
| | $Q^i_{sh} = \begin{cases} \left(T^i_d - T^i_{in}\right) \times C_d; IfT^i_d > T^i_{in} \\ 0; IfT^i_d \leq T^i_{in} \end{cases}$ | (19) |

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 [52]. Using this combination of information and the equations in Table 3, the DHW demand is calculated based on the specific heat formula.

The annual tailored heating demand is calculated for both the continuous heat pump temperature profile and the on/off profile for other technologies.

### 2.2. Heating technologies and thermal energy storage methodologies

Heat pumps are sized based on the heating demands calculated. COP is determined for ASHP dependent on the outside temperature, 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. Thermal power is limited to a minimum

**Table 3**
Domestic hot water demand model formulas.

| Source | Formula | Equation Number |
|---|---|---|
| [47] | $V_s = (0.45 \times N + 0.65) \times 28.8$ | (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) |
| [53] | $Q^i_{dhw} = (V_t \times 4.18 \times (T_{hw} - T_{cw,m})/3600) \times R_{dhw,m} \times R^i_{dhw,h}$ | (25) |

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 [54,55]. The upper limit is found to be sufficient for most homes when operating at continuous temperature, 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 often used with 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 [56,57]. 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 DHW demands.

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. Their maximum 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, it is assumed to be a south facing pitch, a minimum size of 2 $m^2$ is used, and optimisation is in 2 $m^2$ increments [46]. 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 2 $m^2$:

1. No solar technologies.
2. PV panels alone.
3. Flat plate solar thermal collectors alone.
4. Evacuated tube solar thermal collectors alone.
5. Flat plate solar thermal collectors alongside PV panels.
6. Evacuated tube solar thermal collectors alongside PV panels.
7. PVT collectors alone.

TES sizes are simulated from a minimum size of 0.1 $m^3$, up to the user set maximum size, in increments of 0.1 $m^3$, 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 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/$m^2$K which is a calculated from hot water tank data [36,59]. TES energy storage capacity is calculated based on a minimum useful temperature of 40 °C. Initially simulations start with charge at 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 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.

Electricity generated from solar is calculated. For PV a fixed electrical efficiency of 19.28 % is used, as efficiency changes are relatively small for cooler climates, which require more heating demands [59]. 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 this 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 capacity, with any overflow energy being lost.

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 DHW, 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-generates 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 10*L* of hot water 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 and TES charging has been completed, it is assumed half of it is used in the dwelling for other purposes, thus reducing the electricity bill by the energy and tariff rate at the time. The other half is taken as sold to the grid at the feed in tariff rate. Both options are taken as a reduction to the OpEx of heating, allowing very low to negative heating OpEx from simulations with PV or PVT.

For the other heating technologies, as their fuel costs are not dependant on the time of use, and efficiency differences with changing ambient conditions are negligible in comparison to heat pumps and solar thermal technologies, the analysis is simplified to aid computational time. Instead, the annual heating demand from the temperature profile which reduces 2 °C at night is used, then this can be multiplied by the technology efficiency and fuel costs. Natural gas, hydrogen and biomass boilers all use an efficiency of 90 %.

Hydrogen fuel cell efficiency is based on a proton exchange membrane fuel cell which is typically used in domestic applications, with a thermal efficiency at 39 % and an electrical efficiency at 55 % [61]. As with surplus PV generation, fuel cell generated electricity uses the assumption that half reduces the electricity at the import tariff rate, and the other half is exported at the feed in tariff rate. Due to lower power output, fuel cell operation is continuous, as per heat pumps, and therefore uses the demand from the continuous temperature profile. Tables 4-6.

**Table 4**
Heat pump model formulas.

| Source | Formula | Equation Number |
|---|---|---|
| [56] | $COP_{ASHP} = 6.81 - 0.121 \times \left(T_{hw} - T^i_{out}\right) + 0.00063 \times \left(T_{hw} - T^i_{out}\right)^2$ | (26) |
| [56] | $COP_{GSHP} = 8.77 - 0.150 \times (T_{hw} - T_g) + 0.000734 \times (T_{hw} - T_g)^2$ | (27) |
| [58] | $T_g = 15 - (\varphi - 50) \times (4/9)$ | (28) |

**Table 5**
Thermal energy storage model formulas.

| Source | Formula | Equation Number |
|---|---|---|
| [53] | $Q^i_{tes} = V_{tes} \times 1000 \times 4.18 \times (T_{hw} - 40)/3600$ | (29) |
| [60] | $Q^i_{tes,up} = \left(T^i_{tes,up} - T^i_{in}\right) \times U_{tes} \times \left(\pi \times 2r \times \left(h^i_{t,c} \times h_{tes}\right) + \pi \times r^2_{tes}\right)/1000$ | (30) |
| [60] | $Q^i_{tes,lower} = \left(T^i_{tes,low} - T^i_{in}\right) \times U_{tes} \times \left(\pi \times 2r \times \left(\left(1 - h^i_{t,c}\right) \times h_{tes}\right) + \pi \times r^2_{tes}\right)/1000$ | (31) |
| [46] | $T^i_{in} = T^{i-1}_{in} + \left(Q^i_{tes,up} + Q^i_{tes,lower}\right)/C_d$ | (32) |

**Table 6**
Solar technology model formulas.

| Source | Formula | Equation Number |
|---|---|---|
| [19] | $T^i_{st} = \left(T^i_{tes,up} + T^i_{tes,low}\right)/2$ | (33) |
| [14] | $\eta^i_{pv} = 14.7 \times \left(1 - 0.0045 \times \left(T^i_{st} - 25\right)\right)$ | (34) |
| [46] | $E^i_{pv} = A_{pv} \times \eta^i_{pv} \times I^i_{i,roof} \times 0.8$ | (35) |
| [19,46] | $Q^i_{st,fp} = A_{st} \times \left(0.78 \times I^i_{i,roof} - 0.0035\left(T^i_{st} - T^i_a\right) - 0.000038\left(T^i_{st} - T^i_a\right)^2\right) \times 0.8$ | (36) |
| [19,46] | $Q^i_{st,et} = A_{st} \times \left(0.625 \times I^i_{i,roof} - 0.0009\left(T^i_{st} - T^i_a\right) - 0.00002\left(T^i_{st} - T^i_a\right)^2\right) \times 0.8$ | (37) |
| [14,46] | $Q^i_{st,pvt} = A_{st} \times \left(0.726 \times I^i_{i,roof} - 0.003325\left(T^i_{st} - T^i_a\right) - 0.0000176\left(T^i_{st} - T^i_a\right)^2\right) \times 0.8$ | (38) |

### 2.3. 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 7 shows the values or formula used in the framework.

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 8. The electricity tariffs are based on a UK west midlands location using 2020 pre-energy crisis data.

All other technologies have constant fuel costs which are shown alongside the emissions for each fuel source in Table 9. Hydrogen 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) [18,39].

### 2.4. Comparison metrics

The lifetime cost of the heating system is used as the comparison metric, to allow the consideration of the contribution of CapEx

**Table 7**
Technologies capital expenditure formulas.

| Source | Formula | Equation Number |
|---|---|---|
| [62] | $TESCapex = 2068.3 \times V_{tes}{}^{0.553}$ | (39) |
| [59] | $DEHCapex = 100$ | (40) |
| [56] | $ASHPCapex = \left(200 + 4750/P_{hp,th}{}^{1.25}\right) \times P_{hp,th} + 1500$ | (41) |
| [56] | $GSHPCapex = \left(200 + 4750/P_{hp,th}{}^{1.25}\right) \times P_{hp,th} + 800 \times P_{hp,th}$ | (42) |
| [38,59] | $SolarPVCapex = A_{pv} \times 50 + 3400$ | (43) |
| [38,59] | $FlatPlateCapex = A_{st} \times 244 + 2090$ | (44) |
| [38,59] | $EvacuatedTubeCapex = A_{st} \times 299 + 2090$ | (45) |
| [38] | $PVTCapex = A_{st} \times 319 + 3370$ | (46) |
| [18,59] | $GasBoilerCapex = \begin{cases} 15000 + Q_{sh,epc}/25; IfQ_{sh,epc} \le 25000 \\ 2500; IfQ_{sh,epc} > 25000 \end{cases}$ | (47) |
| [18] | $HydrogenBoilerCapex = \begin{cases} 2000 + Q_{sh,epc}/25; IfQ_{sh,epc} \le 25000 \\ 3000; IfQ_{sh,epc} > 25000 \end{cases}$ | (48) |
| [59,63] | $BiomassBoilerCapex = \begin{cases} 9000 + Q_{sh,epc}/4; IfQ_{sh,epc} \le 40000 \\ 19000; IfQ_{sh,epc} > 40000 \end{cases}$ | (49) |
| [61] | $HydrogenFuelCellCapex = 12000$ | (50) |

**Table 8**
Electricity tariffs used in the framework.

| Tariff [64,65] | Peak Cost p/kWh | Peak Times Hour | Off-Peak Cost p/kWh | Off-Peak Times Hour | PV feed in tariff p/kWh | Standing charge p/day |
|---|---|---|---|---|---|---|
| Flat Rate | 13.35 | 0–23 | N/A | N/A | 5.5 | 20.06 |
| Traditional night off-peak | 15.33 | 7–22 | 8.91 | 23–06 | 5.5 | 20.06 |
| EV off-peak | 13.45 | 5–23 | 5.0 | 0–4 | 3.0 | 25.0 |
| Variable Time of Use | Variable, day ahead tariff. Average cost 9.3p/kWh, min −10.4p/kWh, max 35p/kWh. Off-peak considered as anything less than 9.0p/kWh. | | | | 5.5 | 21.0 |

**Table 9**
Fuel costs used in the framework.

| | Fuel Cost p/kWh | Emissions $gCO_2e/kWh$ |
|---|---|---|
| Grid Electricity [12] | Table 8 | 212 |
| Natural gas [12,64] | 2.1 (with a day rate of 17.85p/day) | 183 |
| Biomass [63,12] | 4.11 | 90 |
| Grey Hydrogen [18,39,17] | 4.9 | 382 |
| Blue Hydrogen [18,39,17] | 9.3 | 60 |
| Electrolysed Hydrogen [18,39,17] | 15.2 | $1.87 \times gridemissions$ |

and OpEx of heating technologies. Net Present Cost (NPC) methodology is used calculated over 20 years, which is considered as the lifetime of all technologies, other than fuel cells which have a life of 10 years, requiring twice the CapEx frequency compared to other technologies [61]. 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 is recorded and if any new system combination results in a lower NPC for that prime heater it replaces the current minimum. This ensures the lowest possible NPC option for each prime heater is captured.

$$NPC = \sum_{t=0}^{n} \frac{OpEx}{(1+r_d)^t} + CapEx \quad (51)$$

*2.5. Inputs to determine economic against environmental aspects of heating technologies*

To assess the economic performance of the different heating technologies and TES against their environmental impacts, analysis is completed for different UK dwellings. All cases use inputs of two occupants, 0.5 $m^3$ maximum TES size, and the average European thermostat set point of 20 °C [21].

The initial study uses average UK dwelling thermal efficiency with a U-value of 1.85 $W/m^2K$ and floor area of 87 $m^2$ in a central England location of Coventry, CV4 7AL [13,66–68]. Using these average dwelling inputs, the framework simulates an annual gas boiler heating demand of 12920kWh. This validates the framework as the heating demand falls in 50th percentile gas heating demand range of 12000-14000kWh, from UK smart gas meter data as shown in Fig. 3. A very low demand dwelling is then calculated using the same average thermal efficiency and a reduced house size to meet the lower 10th percentile heating demand at 5100kWh.

The emission calculations for both the average and very low demand dwellings are based on the current UK grid emissions at 212$gCO_2e/kWh$ [12]. Simulations are also complete for the average dwelling using 2035 targeted grid emissions of 37.3$gCO_2e/kWh$, which are calculated by scaling down current emissions using the carbon budget emissions reduction target [69].

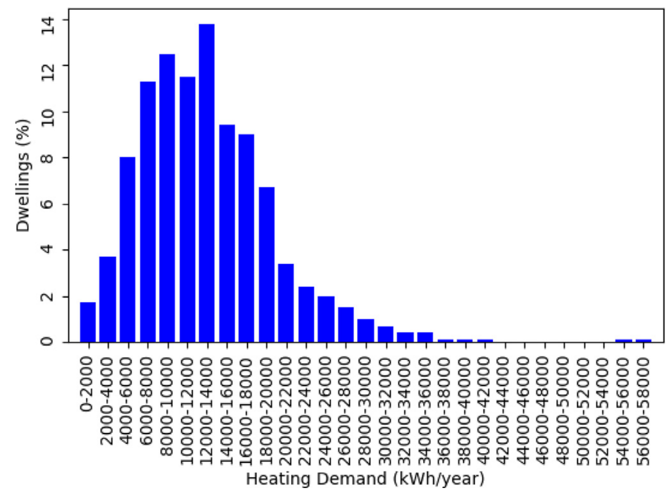


**Fig. 3.** UK dwelling annual heating demands from gas meter data [70].

*2.6. Inputs for spatiotemporal variation evaluation*

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. Five dwelling properties are used in the spatiotemporal 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 Fig. 3 data at the Coventry location.

## 3. Results and discussion of technology simulations

*3.1. Comparison of low-carbon heating systems*

Simulations complete in the developed framework compare heating technology combinations, sizes, and tariffs for the average UK dwelling in central England location of Coventry and optimise parameters based on the lowest NPC solutions. The systems with their optimum tariffs, TES sizes, and solar technology sizes are shown with their OpEx and CapEx in Fig. 4 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 variable time of use tariff, as this was very competitive on average cost across the day (pre-energy crisis). The continuous operation of heat pumps complements the use of time of use, 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 cost rate across the day become more favourable as the dwelling demand reduces with larger TES sizes, conversely in high demand dwellings and smaller TES sizes,

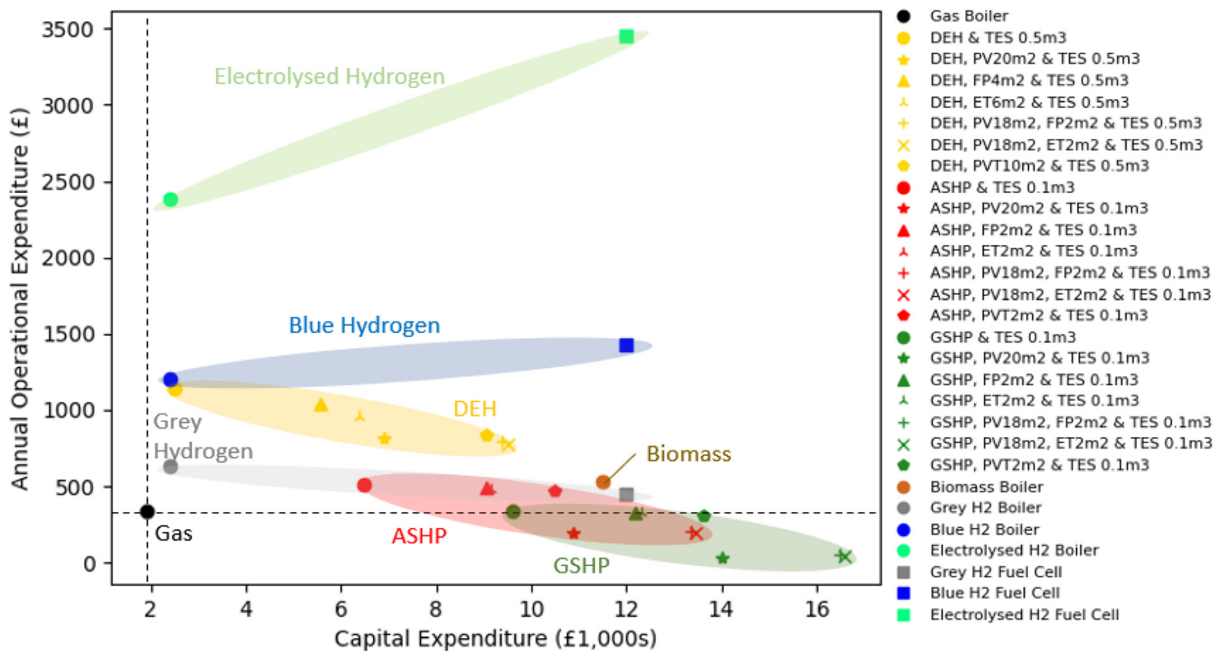


**Fig. 4.** OpEx against CapEx for heating technologies with optimised tariffs, Thermal Energy Storage (TES) sizes and solar technology sizes, in an average UK dwelling. Air Source Heat Pump (ASHP), Direct Electrical Heater (DEH), Evacuated Tube solar thermal (ET), Flat Plate solar thermal (FP), Ground Source Heat Pump (GSHP), Hydrogen (H2), Photovoltaic (PV), Photovoltaic/Thermal (PVT).

the lowest average cost of electricity across the day becomes more beneficial.

Although TES capacity was allowed to be selected up to 0.5 $m^3$, this maximum available size was only selected as the optimum for DEH, where it is preferred over the 20-years for all secondary technology options. For all heat pump configurations, the minimum TES size is selected of 0.1 $m^3$. 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 [36]. 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. When alongside heat pumps, the minimum solar thermal/PVT sizing is selected as heat pump OpEx is already relatively low and further reductions from solar thermal are therefore only small, 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.

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

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 Fig. 5 a-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 hydrogen, 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

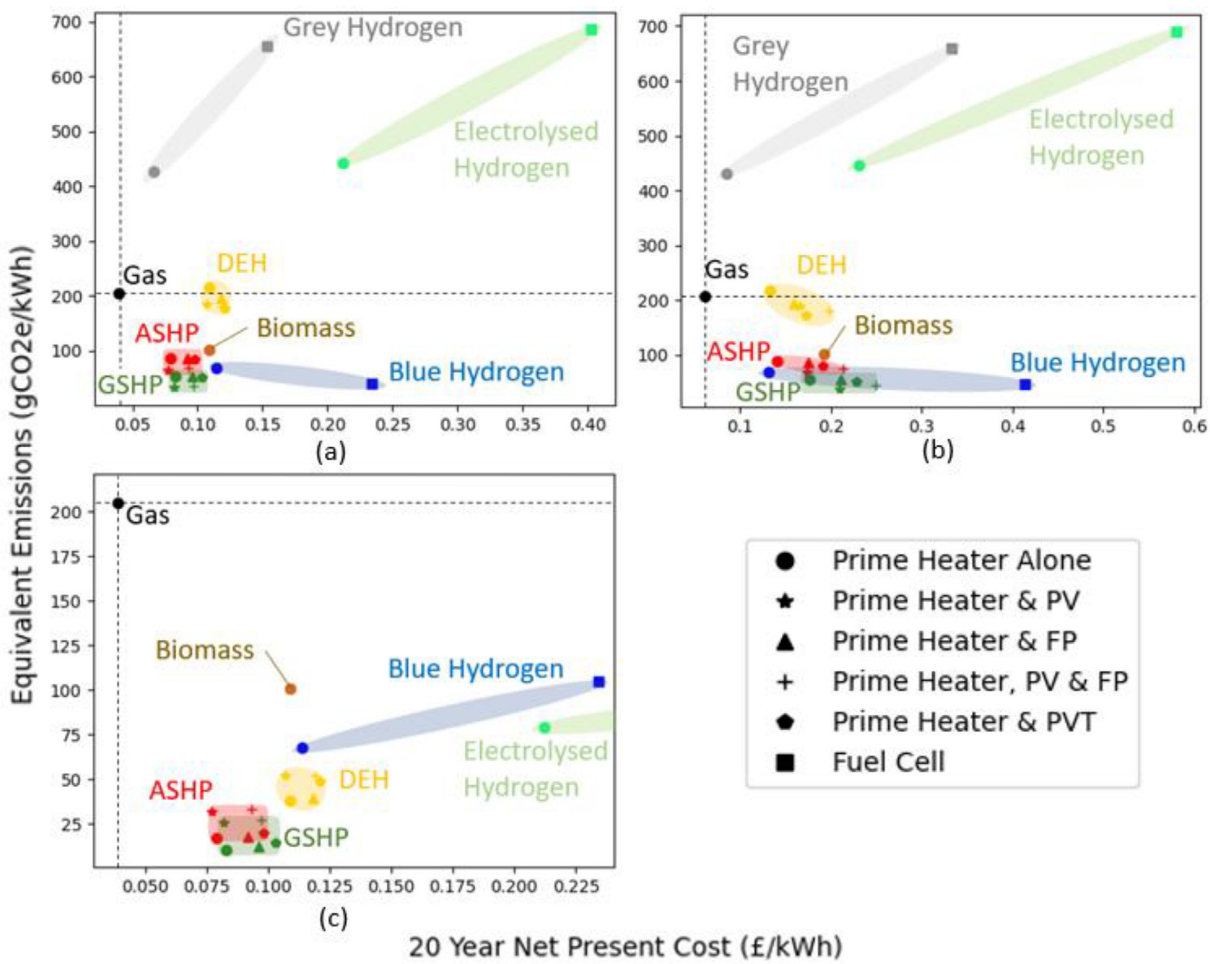


**Fig. 5.** Emissions and life-time costs for heating technologies with optimised tariffs, TES sizes, and solar technology sizes. For (a) the average demand UK dwelling in Coventry, (b) the 10th percentile very low demand UK dwelling in Coventry, and (c) the average demand UK dwelling in Coventry with 2035 target grid emissions. Air Source Heat Pump (ASHP), Direct Electrical Heater (DEH), Flat Plate solar thermal (FP), Ground Source Heat Pump (GSHP), Photovoltaic (PV), Photovoltaic/Thermal (PVT).

Hydrogen and Electrolysed Hydrogen fuel cells are also not shown in (c) to aid image clarity.

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 prime 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 used to reduce the dwellings non-heating electrical demands (assumed 50 % of the surplus generated electricity) 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.

Across the range of hydrogen production methods, other than Grey Hydrogen boilers, the NPC for hydrogen boilers and fuel cells are the highest compared to other technologies due to the higher OpEx. Fuel cells are then significantly higher 20-year cost due to the shorter lifetime of the fuel cell at only 10 years coupled with the high CapEx. Although Grey Hydrogen 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 CCS. Adding efficient an ideal CCS allows the theoretical Blue Hydrogen 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 Hydrogen 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 Hydrogen compared to electrified heating.

Fig. 5(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 Hydrogen boilers and closely followed by DEH, when excluding Grey Hydrogen 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 doesn't decrease linearly to size.

To demonstrate how potential future reduced grid emissions may affect the emissions of heating technologies Fig. 5(c) 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 Hydrogen. In this scenario heat pumps are now more noticeably the lowest emitting technologies with DEH slightly higher but now lower than Biomass and Blue Hydrogen. 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 Hydrogen are also decreased to be on par with Blue Hydrogen; as also found by Ueckerdt et al. electricity generation needs to have high amounts of renewable energy for Electrolysed Hydrogen emissions to be competitive [4].

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 Fig. 6 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.

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 Fig. 4 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. Fig. 5 shows the emissions reduction potential of technologies, as the electricity grid may become decarbonised. Where solar technologies can have a positive impact with

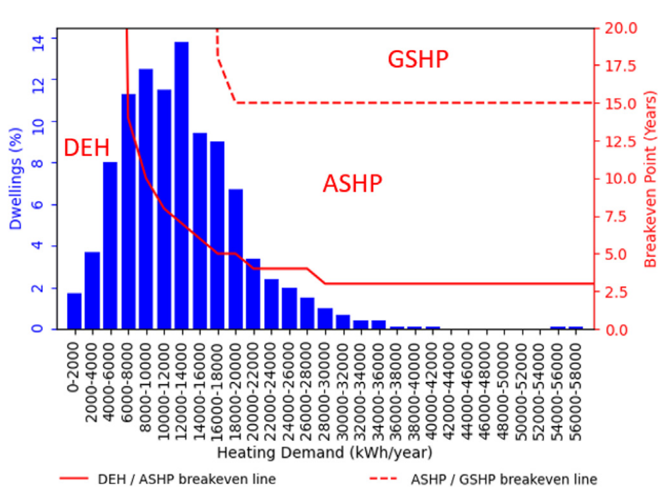


**Fig. 6.** Optimal cost heating technology breakeven durations against dwelling heating demands, compared to the percent of UK dwellings at the different ranges of heating demands. Air Source Heat Pump (ASHP), Direct Electrical Heater (DEH), Ground Source Heat Pump (GSHP).

the current grid state of play but reduce their effectiveness with lower grid emissions. Although Blue Hydrogen, when commercially available, can reduce emissions straight away, Electrolysed Hydrogen is only effective as the grid becomes significantly decarbonised.

### 3.2. Effect of spatiotemporal variations on the optimum low-carbon 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 Hydrogen due to inability to reduce emissions) at each 0.5x0.5° longitude and latitude across the UK. Fig. 7 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 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 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 cold Winter temperatures increase heat demands and reduce ASHP efficiency.

As dwelling heating demand increases for the large and very large 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 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 shows more varied results, as DEH becomes more prominent, but then in the warmest locations Blue Hydrogen 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.

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 H2 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 H2 then ASHP. However, as the electrical grid emissions reduce ASHP and DEH emissions become lower than Blue H2 emissions.

Optimum technologies shown in Fig. 7 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 ground source heat pumps where cost variations can be substantial percentage of the NPC. Higher CapEx of heat pumps

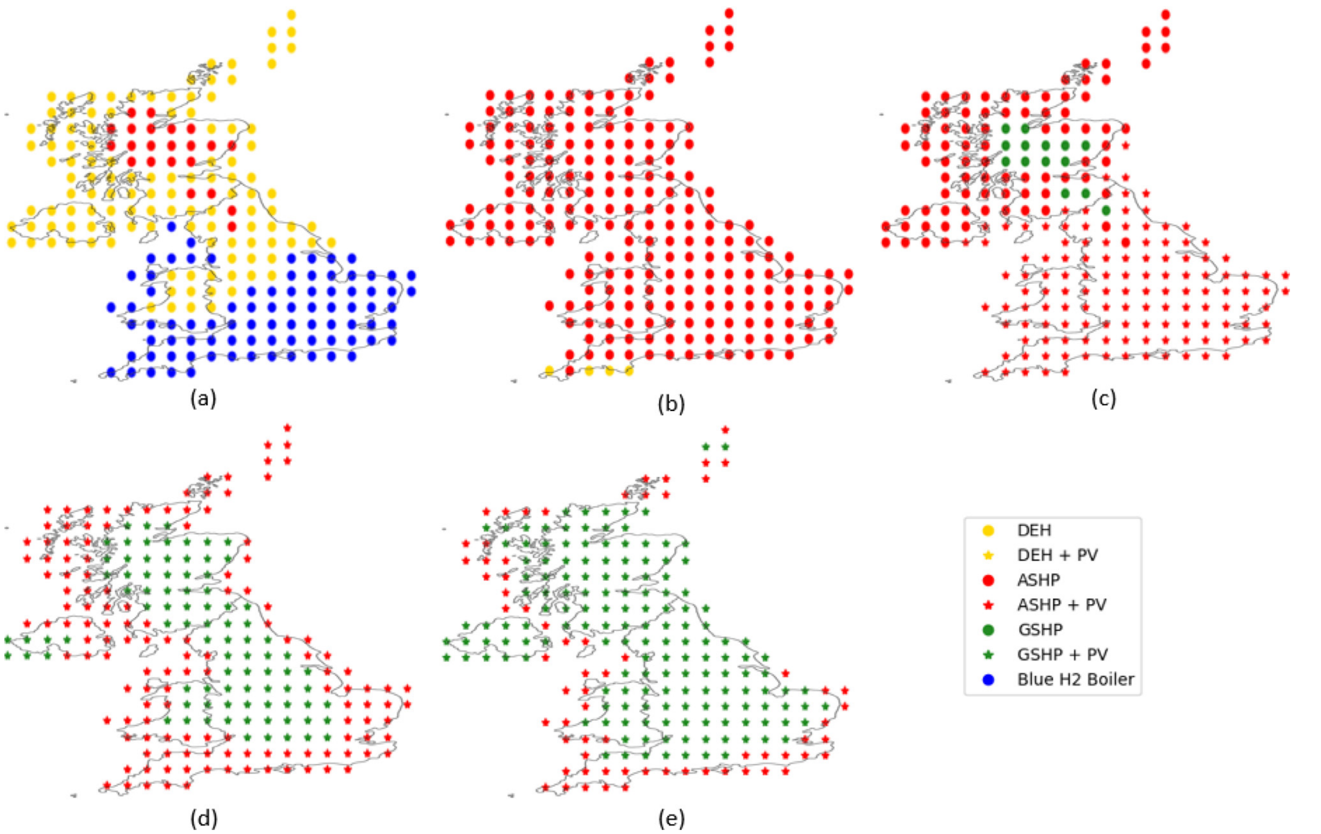


**Fig. 7.** Optimal cost heating technology maps for different size dwellings, where the size is based on percentile heating demands when in central England, Coventry, location (a) very small lower 10th percentile dwelling, (b) small lower 25th percentile dwelling, (c) 50th percentile dwelling, (d) large upper 75th percentile dwelling, and (e) very large upper 90th percentile dwelling. Heating degree days at Coventry is 3717, and the lowest and highest locations in GB are 2699 and 5079 respectively. Air Source Heat Pump (ASHP), Direct Electrical Heater (DEH), Ground Source Heat Pump (GSHP), Hydrogen (H2), Photovoltaic (PV), Photovoltaic/Thermal (PVT).

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 and the dwellings heating demand.

## 4. Conclusion of low-carbon heating technologies

This paper presents a novel versatile framework 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 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 Hydrogen can produce low emissions but requires nearly complete grid decarbonisation to be competitive with Blue Hydrogen on emissions. All low-carbon heating technologies struggle against the economic competitiveness of current fossil fuel boilers which have low OpEx and CapEx. Future work could therefore 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. Another area for development is the analysis of the sensitivity of the results on the tariff costs, which is particularly pertinent given the energy crisis causing higher energy costs. 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 Hydrogen 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 reduce, and DEH becomes 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 [5], 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.

## Data availability

Data will be made available on request.

## Declaration of Competing Interest

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

## Acknowledgements

The authors wish to thank the School of Engineering at the University of Warwick who funded this research. Wei He acknowledges the financial support from the Royal Academy of Engineering (RF\201819\18\89).

## References

[1] Visual Capitalist, "Race to Net Zero: Carbon Neutral Goals by Country." https://www.visualcapitalist.com/race-to-net-zero-carbon-neutral-goals-by-country/ (accessed Sep. 28, 2021).
[2] International Energy Agency, "Energy Technology Perspectives 2020." Accessed: Nov. 26, 2020. [Online]. Available: https://www.iea.org/reports/energy-technology-perspectives-2020.
[3] M. Fajardy and D. M. Reiner, "An overview of the electrification of residential and commercial heating and cooling and prospects for decarbonisation," *CWPE*, Accessed: Oct. 06, 2021. [Online]. Available: https://www.econ.cam.ac.uk/research-files/repec/cam/pdf/cwpe20120.pdf.
[4] F. Ueckerdt, C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, G. Luderer, Potential and risks of hydrogen-based e-fuels in climate change mitigation, Nat. Clim. Chang. 11 (5) (2021) 384–393, https://doi.org/10.1038/s41558-021-01032-7.
[5] J. Love et al., The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial, Appl. Energy 204 (Oct. 2017) 332–342, https://doi.org/10.1016/j.apenergy.2017.07.026.
[6] J. Barnes, S.M. Bhagavathy, The economics of heat pumps and the (un)intended consequences of government policy, Energy Policy 138 (2020), https://doi.org/10.1016/j.enpol.2019.111198.
[7] European Commision, "Energy Performance Certificates | Energy." https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-performance-certificates_en (accessed Oct. 14, 2021).
[8] Energy Information Administration, "Electric Sales, Revenue, and Average Price." https://www.eia.gov/electricity/sales_revenue_price/(accessed Nov. 12, 2021).
[9] Energy Information Administration, "Natural Gas Average Residential Price." https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_m.htm (accessed Nov. 12, 2021).
[10] J. Palmer, N. Terry, O. Sutton, G. Bennett, and A. Stephenson, "Cost-Optimal Domestic Electrification (CODE) Final Report," 2021. Accessed: Oct. 05, 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1018772/code-research-study.pdf.
[11] S.J. Darby, Smart electric storage heating and potential for residential demand response, Energy Effic. 11 (1) (2018) 67–77, https://doi.org/10.1007/s12053-017-9550-3.
[12] Department for Buisness Energy & Industrial Strategy, "Greenhouse gas reporting: conversion factors 2021." Accessed: Aug. 17, 2021. [Online]. Available: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021.
[13] Z. Ma, H. Bao, A.P. Roskilly, Feasibility study of seasonal solar thermal energy storage in domestic dwellings in the UK, Sol. Energy 162 (2018) 489–499, https://doi.org/10.1016/j.solener.2018.01.013.
[14] K. Wang, M. Herrando, A.M. Pantaleo, C.N. Markides, Technoeconomic assessments of hybrid photovoltaic-thermal vs. conventional solar-energy systems: Case studies in heat and power provision to sports centres, Appl. Energy 254 (2019), https://doi.org/10.1016/J.APENERGY.2019.113657.
[15] Prime Minister's Office 10 Downing Street, "PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs." https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs (accessed Nov. 27, 2020).
[16] Committe on Climate Change, "Net Zero The UK's contribution to stopping global warming," 2019. [Online]. Available: https://d423d1558e1d71897434.b-cdn.net/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf.
[17] A. Goater and J. Squires, "Carbon Footprint of Heat Generation." Accessed: May 25, 2021. [Online]. Available: https://post.parliament.uk/research-briefings/post-pn-0523/.
[18] J. Speirs, P. Balcombe, E. Johnson, J. Martin, N. Brandon, A. Hawkes, A greener gas grid: What are the options, Energy Policy 118 (2018) 291–297, https://doi.org/10.1016/j.enpol.2018.03.069.
[19] W. Streicher, "Solar Thermal Technologies for Domestic Hot Water Preparation and Space Heating," in *Renewable Heating and Cooling: Technologies and Applications*, Elsevier Inc., 2016, pp. 9–39.
[20] The Royal Society, "Low-carbon heating and cooling: overcoming one of world's most important net zero challenges." Accessed: May 27, 2021. [Online]. Available: https://royalsociety.org/-/media/policy/projects/climate-change-science-solutions/climate-science-solutions-heating-cooling.pdf.
[21] B.K. Sovacool et al., Decarbonizing household heating: Reviewing demographics, geography and low-carbon practices and preferences in five European countries, Renew. Sustain. Energy Rev. 139 (2021), https://doi.org/10.1016/J.RSER.2020.110703.
[22] ofgem, "Insights into consumer attitudes to decarbonisation and future energy solutions.".
[23] D. Caiger-Smith and A. Anaam, "Public awareness of and attitudes to low-carbon heating technologies," 2020, 10.7488/era/724.
[24] S. Heinen, P. Mancarella, C. O'Dwyer, M. O'Malley, Heat electrification: The latest research in Europe, IEEE Power Energy Mag. 16 (4) (2018) 69–78, https://doi.org/10.1109/MPE.2018.2822867.
[25] S.D. Watson, K.J. Lomas, R.A. Buswell, How will heat pumps alter national half-hourly heat demands? Empirical modelling based on GB field trials, Energy Build. 238 (2021), https://doi.org/10.1016/j.enbuild.2021.110777.
[26] A. Anderson, B. Stephen, R. Telford, and S. McArthur, "A Probabilistic Model for Characterising Heat Pump Electrical Demand versus Temperature," in *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, Oct. 2020, pp. 1030–1034, 10.1109/ISGT-Europe47291.2020.9248942.
[27] S. Samsatli, N.J. Samsatli, The role of renewable hydrogen and inter-seasonal storage in decarbonising heat – Comprehensive optimisation of future renewable energy value chains, Appl. Energy 233–234 (2019) 854–893, https://doi.org/10.1016/j.apenergy.2018.09.159.
[28] C. Quarton, The role of hydrogen value chains in decarbonised energy systems, University of Bath, 2021.
[29] D. Jenkins, R. Tucker, M. Ahadzi, R. Rawlings, The performance of air-source heat pumps in current and future offices, Energy Build. 40 (10) (2008) 1901–1910, https://doi.org/10.1016/J.ENBUILD.2008.04.015.
[30] F. Padovani, N. Sommerfeldt, F. Longobardi, J.M. Pearce, Decarbonizing rural residential buildings in cold climates: A techno-economic analysis of heating electrification, Energy Build. 250 (2021), https://doi.org/10.1016/J.ENBUILD.2021.111284.
[31] A. Pena-Bello, P. Schuetz, M. Berger, J. Worlitschek, M.K. Patel, D. Parra, Decarbonizing heat with PV-coupled heat pumps supported by electricity and heat storage: Impacts and trade-offs for prosumers and the grid, Energy Convers. Manag. 240 (2021), https://doi.org/10.1016/J.ENCONMAN.2021.114220.
[32] C. Treichel, C.A. Cruickshank, Economic analysis of heat pump water heaters coupled with air-based solar thermal collectors in Canada and the United States, J. Build. Eng. 35 (2021), https://doi.org/10.1016/J.JOBE.2020.102034.
[33] P. Vatougiou, D. P. Jenkins, and P. Mccallum, "Techno-economic Feasibility of Replacing Oil Boilers with Air-To-Water-Heat-Pumps Coupled with Thermal Energy Storage," Accessed: Jun. 23, 2021. [Online]. Available: http://www.ibpsa.org/proceedings/BSO2020/BSOV2020_Vatougiou.pdf.

[34] O. Eguiarte, P. de Agustín-Camacho, A. Garrido-Marijuán, A. Romero-Amorrortu, Domestic space heating dynamic costs under different technologies and energy tariffs: Case study in Spain, Energy Reports 6 (2020) 220–225, https://doi.org/10.1016/j.egyr.2020.11.112.
[35] H. Harb, J. Reinhardt, R. Streblow, D. Müller, MIP approach for designing heating systems in residential buildings and neighbourhoods, J. Build. Perform. Simul. 9 (3) (2015) 316–330, https://doi.org/10.1080/19401493.2015.1051113.
[36] R. Renaldi, A. Kiprakis, D. Friedrich, An optimisation framework for thermal energy storage integration in a residential heat pump heating system, Appl. Energy 186 (2017) 520–529, https://doi.org/10.1016/j.apenergy.2016.02.067.
[37] M. Nájera-Trejo, I.R. Martin-Domínguez, J.A. Escobedo-Bretado, Economic Feasibility of Flat Plate vs Evacuated Tube Solar Collectors in a Combisystem, Energy Procedia 91 (2016) 477–485, https://doi.org/10.1016/J.EGYPRO.2016.06.181.
[38] M. Herrando, C.N. Markides, Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations, Appl. Energy 161 (2016) 512–532, https://doi.org/10.1016/J.APENERGY.2015.09.025.
[39] C. Baldino, S. Searle, Y. Zhou, and A. Christensen, "Hydrogen for heating? Decarbonization options for households in the United Kingdom in 2050," 2020. Accessed: Sep. 01, 2021. [Online]. Available: https://theicct.org/sites/default/files/publications/Hydrogen-heating-UK-dec2020.pdf.
[40] J. Cockroft, N. Kelly, A comparative assessment of future heat and power sources for the UK domestic sector, Energy Convers. Manag. 47 (15–16) (2006) 2349–2360, https://doi.org/10.1016/J.ENCONMAN.2005.11.021.
[41] D.P. Jenkins, R. Tucker, R. Rawlings, Modelling the carbon-saving performance of domestic ground-source heat pumps, Energy Build. 41 (6) (2009) 587–595, https://doi.org/10.1016/J.ENBUILD.2008.12.002.
[42] N.J. Kelly, J. Cockroft, Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data, Energy Build. 43 (1) (2011) 239–245, https://doi.org/10.1016/J.ENBUILD.2010.09.018.
[43] L. Cabrol, P. Rowley, Towards low carbon homes – A simulation analysis of building-integrated air-source heat pump systems, Energy Build. 48 (May 2012) 127–136, https://doi.org/10.1016/J.ENBUILD.2012.01.019.
[44] A. Vijay and A. Hawkes, "The Techno-Economics of Small-Scale Residential Heating in Low Carbon Futures," *Energies 2017, Vol. 10, Page 1915*, vol. 10, no. 11, p. 1915, Nov. 2017, 10.3390/EN10111915.
[45] Energy Star, "About ENERGY STAR." https://www.energystar.gov/about (accessed Oct. 14, 2021).
[46] BRE, "The Governments Standard Assessment Procedure for Energy Rating of Dwellings," 2014. Accessed: Jan. 28, 2021. [Online]. Available: https://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf.
[47] J. Henderson and J. Hart, "BREDEM 2012 A technical description of the BRE Domestic Energy Model," 2013. Accessed: Jan. 12, 2021. [Online]. Available: https://www.bre.co.uk/filelibrary/bredem/BREDEM-2012-specification.pdf.
[48] Environmental Protection Agency, "ENERGY STAR ® for Windows, Doors, and Skylights Version 6.0 Criteria Revision Review of Cost Effectiveness Analysis." Accessed: Jan. 13, 2021. [Online]. Available: https://www.energystar.gov/sites/default/files/ESWDS-ReviewOfCost_EffectivenessAnalysis.pdf.
[49] The Engineering ToolBox, "Overall Heat Transfer Coefficient." https://www.engineeringtoolbox.com/overall-heat-transfer-coefficient-d_434.html (accessed Sep. 03, 2021).
[50] S. Pfenninger and I. Staffell, "Renewables.ninja." https://www.renewables.ninja/(accessed Jan. 12, 2021).
[51] Energy Saving Trust, "Measurement of Domestic Hot Water Consumption in Dwellings." Accessed: Jan. 12, 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48188/3147-measure-domestic-hot-water-consump.pdf.
[52] P.M. Armstrong, Enhancing the energy storage capability of electric domestic hot water tanks, University of Oxford, 2015.
[53] The Engineering ToolBox, "Energy Transfer Equation." https://www.engineeringtoolbox.com/energy-transfer-equation-d_1051.html (accessed Sep. 03, 2021).
[54] Mitsubishi Electric, "Ecodan Air Source Heat Pumps." https://library.mitsubishielectric.co.uk/pdf/book/Ecodan_PUHZ_Databook_FTC4#page-6-7 (accessed Apr. 23, 2021).
[55] Kensa, "Shoebox Ground Source Heat Pump." https://www.kensaheatpumps.com/shoebox-ground-source-heat-pump/(accessed Aug. 11, 2021).
[56] I. Staffell, D. Brett, N. Brandon, and A. Hawkes, "A review of domestic heat pumps," *Energy and Environmental Science*, vol. 5, no. 11. The Royal Society of Chemistry, pp. 9291–9306, Nov. 18, 2012, 10.1039/c2ee22653g.
[57] Department for Buisness Energy & Industrial Strategy, "RHI monthly deployment data: April 2021." Accessed: Sep. 07, 2021. [Online]. Available: https://www.gov.uk/government/statistics/rhi-monthly-deployment-data-april-2021.
[58] Y. Wang, W. He, Temporospatial techno-economic analysis of heat pumps for decarbonising heating in Great Britain, Energy Build. 250 (Nov. 2021), https://doi.org/10.1016/J.ENBUILD.2021.111198.
[59] A. V. Olympios, M. Mersch, P. Sapin, A. M. Pantaleo, and C. N. Markides, "Library of price and performance data of domestic and commercial technologies for low-carbon energy systems," Apr. 2021. 10.5281/ZENODO.4692649.
[60] D. Steen, M. Stadler, G. Cardoso, M. Groissböck, N. DeForest, C. Marnay, Modeling of thermal storage systems in MILP distributed energy resource models, Appl. Energy 137 (Jan. 2015) 782–792, https://doi.org/10.1016/J.APENERGY.2014.07.036.
[61] P. E. Dodds *et al.*, "Hydrogen and fuel cell technologies for heating: A review," *International Journal of Hydrogen Energy*, vol. 40, no. 5. Elsevier Ltd, pp. 2065–2083, Feb. 09, 2015, 10.1016/j.ijhydene.2014.11.059.
[62] Department for Buisness Energy & Industrial Strategy, "Thermal Energy Storage (TES) technologies report," 2016. Accessed: Aug. 16, 2021. [Online]. Available: https://www.gov.uk/government/publications/evidence-gathering-thermal-energy-storage.
[63] GreenMatch, "How Much Does A Biomass Boiler Cost? (2021)." https://www.greenmatch.co.uk/blog/2015/02/how-much-does-a-biomass-boiler-cost (accessed Aug. 16, 2021).
[64] Octopus Energy, "All our tariffs." https://octopus.energy/tariffs/(accessed Apr. 28, 2022).
[65] Energy-Stats, "Octopus Agile – Energy Stats UK." https://www.energy-stats.uk/octopus-agile/(accessed Jun. 01, 2022).
[66] C. Smith, "Energy Performance of Buildings Certificates Statistical Release." Accessed: Nov. 27, 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/904844/EPB_Cert_Statistics_Release_-_Q2_2020.pdf.
[67] Department for Buisness Energy & Industrial Strategy, "Annual Fuel Poverty Statistics in England, 2020 (2018 data)." Accessed: Nov. 27, 2020. [Online]. Available: https://www.gov.uk/government/statistics/annual-fuel-poverty-statistics-report-2020.
[68] Department for Buisness Energy & Industrial Strategy, "Annual domestic energy bills." Accessed: Jan. 13, 2021. [Online]. Available: https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics.
[69] Department for Buisness Energy & Industrial Strategy, "Carbon Budgets." https://www.gov.uk/guidance/carbon-budgets#setting-of-the-sixth-carbon-budget-2033-2037 (accessed Mar. 15, 2022).
[70] H. Foster *et al.*, "EFUS: household energy consumption and affordability," 2021.