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Role of energy storage in residential energy demand decarbonization: system-level techno-economic comparison of low-carbon heating and cooling solutions

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Abstract:

This paper explores various combinations of electric heat pumps (EHPs), hydrogen boilers (HBs), electric boilers (EBs), hydrogen absorption heat pumps (AHPs) and energy storage technologies (electric and thermal) to assess their potential for matching heating and cooling demand at low cost and with low carbon footprint. Thermodynamic and component-costing models of various heating and cooling technologies are integrated into a whole-energy system cost optimisation model to determine cost-effective configurations of heating and cooling systems that minimise the overall investment and operation cost for both the system and the end-user. Case studies presented in the paper focus on two archetypal systems that differ in terms of heating and cooling demand and availability profiles of solar and wind generation. The proposed approach quantifies how the cost-efficient portfolios of low-carbon heating and cooling solutions are driven by the characteristics of the system such as share of variable renewables or heating and cooling demand. Modelling results suggest that capacity choices for heating and cooling technologies will vary significantly depending on system properties. More specifically, air-to-air EHPs, with their cost and efficiency advantages over air-to-water EHPs, could make a significant contribution to low-carbon heat supply as well as cooling, although their contribution may be constrained by the compatibility with existing heating systems. They are found to be a useful supplementary source of space heating that is able to displace between 20 and 33 $\mathrm{GW_{th}}$ of capacity of other heating technologies compared to the case where they do not contribute to space heating.

Keywords:

Heat decarbonisation; Cooling; Heat pumps; Energy storage; Hydrogen.

1. Introduction

An increasing number of countries and regions worldwide have committed to net-zero carbon emission targets, including the United Kingdom (UK) [1] and the European Union (EU) [2], who aim to reach net-zero by 2050. Reaching this target will require widespread decarbonisation across all sectors of the economy [3], including the residential energy sector, which accounts for over one-third of global carbon emissions [4].

A large portion of carbon emissions from the residential sector can be attributed to heating, which is predominantly supplied by natural gas boilers in many countries. In the UK for example, gas boilers account for more than 85 % of domestic heat supply [5]. The main low-carbon alternatives are electrically-driven vapour-compression heat pumps, which have seen a large market growth in recent years [6]. Electric heat pumps (EHPs) do however depend on a decarbonised electricity supply to realise their emission reduction potential [7]. Alternatives are hydrogen boilers (HBs) [8] or hydrogen-fired absorption heat pumps (AHPs) [9], which require a supply of low-carbon hydrogen, or solar-thermal heating systems, which typically require a backup heating system.

In addition to space heating and hot water, provision of space cooling is becoming increasingly relevant. It already constitutes a significant share of energy demand in warmer climates, with the demand also increasing in moderate climate countries, such as in central Europe, as the average temperatures increase and extreme heat waves become more frequent [10]. Over the last decade, energy demand for space cooling increased more than twice as fast as the overall energy demand in buildings. Higher temperatures caused by climate

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change [11], coupled with increasing incomes and growing populations, are driving rapid growth in residential cooling, with the share of households with air conditioning increasing globally from 25% in 2010 to 35% in 2021 and estimated to increase further to 45% by 2030 [12]. As reported in [13], some 2 to 4 billion people could be exposed to heat stress due to lack of effective indoor cooling, giving rise to multiple risk factors for heat-related illnesses [14].

It is also recognised that access to effective cooling (and heating) does not need to come at the expense of the environment if it is pursued through clean technologies. Residential cooling can account for a large share of peak electricity demand in critical periods of the year [15], potentially causing outages or requiring costly upgrades to energy infrastructure. These could be mitigated by demand response strategies, integration of energy storage assets and other sector coupling based solutions. IEA's Net Zero Emissions by 2050 Scenario [16] sets three space cooling-related goals: (i) 20% of existing buildings and all new buildings net zero by 2030, (ii) cooling set-point moderated in the range of 24-25°C, and (iii) average efficiency of new cooling devices increased by at least 50% by 2030.

EHPs come in various types and with various heat-source and sink fluids [17]. Space cooling has been traditionally provided by conventional electrically driven air-conditioning units [18], which are mostly able to only pump heat in one direction (i.e., to be only used for cooling). However, air-conditioning units are fundamentally air-to-air (AA) EHPs, and recently, almost all new commercially available AA EHPs are designed to be reversible [19]. This means that they can be used to provide both space heating and cooling, depending on the given weather. Naturally, however, air-to-air heat pumps cannot provide hot water.

At the same time, space heating can also be provided by air-to-water (AW) EHPs, which use water as the heat sink fluid. In this case, the heat is transferred to air using radiators. The advantage of AW EHPs is that they can also provide domestic hot water (which is often required at a temperature close to that required by modern radiators) [20], but unlike AA EHPs, they cannot be used to provide space cooling directly (additional equipment like ducts would be required in that case).

Large-scale electrification of heating and cooling will significantly increase national electricity demands. Moreover, it will increase seasonal differences in load, as heating and cooling demands are primarily driven by the ambient temperature. Therefore, it is expected that, in cold countries, electricity load in winter will be significantly higher, especially during peak hours. Similarly, hot countries are expected to have high electricity loads in the summer. In the UK context, Quiggin and Buswell [21] predicted an increase in peak electricity demand of 55 GW as a result of heating electrification, while Hoseinpoori et al. [22] expect that the peak demand may increase by up to 170% by 2050. It has been shown that energy storage, both at household-level and whole-energy system level, alongside other means of flexibility can help reduce necessary investments in low-carbon power generation capacity and therefore deliver decarbonisation objectives at a lower cost [23].

At the household level, energy storage typically comes in the form of thermal energy storage via hot water tanks or other sensible heat options, or more advanced approaches via thermochemical storage, phase change materials, building thermal inertia or molecular storage, which offers potential for inter-seasonal storage with extremely low energy losses [24,25]. In the case of storage integration to EHP, such storage could be in the form of thermal energy (to achieve higher seasonal COP due to the night-day temperature lift fluctuations) or electric energy, enabling demand response capabilities and withdrawal of electricity during off peak periods. In both cases, the strategy is to decouple heat demand of the household and electricity demand of the heat pump, thus allowing households to shift their demand to off-peak hours to level the electricity demand profile [20]. At the whole-system level, a distinction is typically made between short-term and long-term energy storage. Short-term storage is valuable for quick load balancing and grid stability [26], while long-term storage can provide large quantities of dispatchable generation for multiple hours or even days. The conventional large-scale energy storage technology is pumped-hydro storage, but further development potential is limited. Instead, novel storage technologies such as compressed-air energy storage [27], hydrogen storage [28] or large-scale batteries [29] show promise for application in future decarbonised energy systems.

This paper aims to provide a quantitative framework for identifying cost-optimal portfolios of heating and cooling technologies, including electrically driven technologies (i.e., AW EHPs and reversible AA EHPs) and hydrogen-driven technologies (HBs and AHPs) that can provide heating and cooling. Cost-optimisation is carried out from the whole-system cost perspective, including investment and operation cost of energy production, storage and end-use technologies. Heating demand is hereby distinguished between space heating, space cooling and domestic hot water demand. One of the main novelties of this specific work is the fact that, for the first time, the two types of EHPs (AW and AA) are included in the energy system optimisation framework, allowing the investigation of energy-system implications, and discussing transition cost trade-offs between different technological options in the context of simultaneously decarbonising residential heating and cooling. Additionally, the impact of long-duration energy storage is also explored as a means to reduce the impact of heat electrification on the electricity system.

The methodology used to identify energy-system implications of different heating technologies and the description of the techno-economic models is provided in Section 2. Energy-system results are provided in Section 3 and Conclusions are provided in Section 4.

2. Method

This section presents the key features of the energy system model that is applied to identifying cost-efficient portfolios of low-carbon heating and cooling technologies. This is followed by the description of the techno-economic models of heating and cooling technologies that have been used in the energy system model. The section concludes with the summary of key assumptions and scenarios used in the analysis.

2.1. Energy system model with decarbonised heating and cooling

The model presented in this section represents an upgraded version of the energy system model presented in [30]. This model optimises the total investment and operation cost of a carbon-constrained energy system, including electricity and hydrogen production and storage technologies, as well as the key techno-economic features of end-use heating and cooling technologies. The objective of the model is to minimise the overall cost of delivering electricity, heat, and cooling to end-consumers. Some features of the model that are not central for this paper have been omitted from the formulation due to space constraints.

Key extensions to the energy system model, when compared to [30], include: a) explicit consideration of investment decisions into end-use technologies for cooling; b) adding AA EHP to the portfolio of end-use heating and cooling technologies that the model can invest in; and c) distinguishing between heat demand for space heating (SH) and for hot water (HW), as well as between heat outputs from various technology to supply these two heat demands.

2.1.1. Objective function

The model minimises the total system cost, which contains terms associated with: a) investment in electricity generation and storage and the associated operation cost (φ_{el}), b) investment in hydrogen production and storage with associated operation cost including, if relevant, hydrogen import cost (φ_{H_2}), and c) investment cost in end-use technologies for low-carbon heating and cooling ($\varphi_{\text{heat-cool}}$):

$$\min z = \varphi_{\text{el}} + \varphi_{\text{H}_2} + \varphi_{\text{heat-cool}} \tag{1}$$

Terms representing the electricity sector and hydrogen sector costs are formulated in the same way as in [30]. The electricity cost includes investment cost of generation assets and battery energy storage systems (BESS) as well as generators' operating cost, while the hydrogen sector cost includes the investment and operation costs of electrolysers, methane reformers and hydrogen storage, as well as the cost of hydrogen imports. This ensures that the cost of supplying electricity and hydrogen to low-carbon heating and cooling systems are not fixed input parameters into the calculation, but rather endogenously integrated into the cost-minimisation model by explicitly representing all investment and operation cost categories associated with electricity and hydrogen supply.

The investment cost of end-use heating and cooling technologies $\varphi_{\text{heat-cool}}$ includes the cost of investment into heating and cooling assets, which is the product of the capacity decision variable μ and per unit cost π for AW EHP, AA EHP, EB, HB, AHP and TES assets:

$$\varphi_{\text{heat-cool}} = \pi^{\text{AW}}\mu^{\text{AW}} + \pi^{\text{AA}}\mu^{\text{AA}} + \pi^{\text{EB}}\mu^{\text{EB}} + \pi^{\text{HB}}\mu^{\text{HB}} + \pi^{\text{AHP}}\mu^{\text{AHP}} + \pi^{\text{TES}}\mu^{\text{TES}} \tag{2}$$

Note that the operating cost of low-carbon heating and cooling technologies is implicitly considered through electricity and hydrogen balance equations.

2.1.2. Energy balance constraints

The balance constraint for power supply and demand stipulates that in each time interval t the total electricity supply, which consists of the total electricity generation (p^{gen}) plus net electrical storage output ($p_{\text{dch}}^{\text{bs}} - p_{\text{ch}}^{\text{bs}}$), needs to match total demand across various categories, which include electrified heating (p_t^{AW}, p_t^{AA} and p_t^{EB}) but also other non-heat segments such as baseline system demand, appliance and EV demand (d_k^{el}), and electricity demand for operating methane reformers and electrolysers, which is expressed as the product of their hydrogen output ξ and specific electricity consumption L^{el}:

$$\sum_{g=1}^{G} p_{g,t}^{\text{gen}} + \sum_{s=1}^{S}\left(p_{\text{dch},s,t}^{\text{bs}} - p_{\text{ch},s,t}^{\text{bs}}\right) = \sum_{k=1}^{K} d_{k,t}^{\text{el}} + p_t^{\text{AW}} + p_t^{\text{AA}} + p_t^{\text{EB}} + \sum_{r=1}^{R} L_r^{\text{el}}\xi_{r,t}^{\text{ref}} + \sum_{e=1}^{E} L_e^{\text{el}}\xi_{e,t}^{\text{elH2}} \tag{3}$$

Hydrogen balance constraint (4) ensures that the total hydrogen supply from electrolysers (ξ^{elH2}), reformers (ξ^{ref}) and imports (ξ^{imp}) matches the total demand for each t, including non-heat demand for hydrogen (Ξ^{ext}), demand from HBs and AHPs (ξ^{HB} and ξ^{AHP}), consumption of hydrogen power generators (ξ^{gen}) and net hydrogen storage operation ($\xi_{\text{ch}}^{\text{hs}} - \xi_{\text{dch}}^{\text{hs}}$):

$$\sum_{r=1}^{R} \xi_{r,t}^{\text{ref}} + \sum_{e=1}^{E} \xi_{e,t}^{\text{elH2}} + \sum_{i=1}^{I} \xi_{i,t}^{\text{imp}} = \sum_{u=1}^{U}\left(\xi_{\text{ch},u,t}^{\text{hs}} - \xi_{\text{dch},u,t}^{\text{hs}}\right) + \xi_t^{\text{HB}} + \xi_t^{\text{AHP}} + \xi_t^{\text{gen}} + \Xi_t^{\text{ext}} \tag{4}$$

2.1.3. Energy production and storage constraints

The model also includes standard constraints for conventional and variable renewable generation, which are omitted here to avoid repetition. These constraints include limits on allowed new capacity of generation technologies, unit commitment and output constraints, operating cost constraints including no-load cost, variable cost and start-up cost, annual output limits and dynamic constraints (ramping, start-up, reserve, response and inertia). This part of model formulation is described in more detail in [35]. In a similar way, standard constraints on hydrogen production and storage are implemented as presented in [36].

2.1.4. Constraints on end-use heating and cooling technologies

End-use heat balance is represented separately for space heating and hot water (given that some technologies, such as AA EHP, can only provide one of those). The space heating constraint (5) ensures that the net space heating output of all technologies, expressed as the product of either hydrogen or electricity consumption and the relevant COP or efficiency coefficient η, or in case of TES as net discharging, meets the SH demand X^{sh}:

$$p_t^{\mathrm{AW,sh}}\eta_t^{\mathrm{AW}} + p_t^{\mathrm{AA,sh}}\eta_t^{\mathrm{AA,sh}} + p_t^{\mathrm{EB,sh}} + \xi_t^{\mathrm{HB,sh}}\eta^{\mathrm{HB}} + \xi_t^{\mathrm{AHP,sh}}\eta_t^{\mathrm{AHP}} + h_{\mathrm{dch},t}^{\mathrm{TES,sh}} - h_{\mathrm{ch},t}^{\mathrm{TES,sh}} = X_t^{\mathrm{sh}} \tag{5}$$

Expression (6) does the same for hot water demand X^{hw}; note that this constraint does not include any contribution from AA EHP, as it was assumed that they cannot be used to supply hot water.

$$p_t^{\mathrm{AW,hw}}\eta_t^{\mathrm{AW}} + p_t^{\mathrm{EB,hw}} + \xi_t^{\mathrm{HB,hw}}\eta^{\mathrm{HB}} + \xi_t^{\mathrm{AHP,hw}}\eta_t^{\mathrm{AHP}} + h_{\mathrm{dch},t}^{\mathrm{TES,hw}} - h_{\mathrm{ch},t}^{\mathrm{TES,hw}} = X_t^{\mathrm{hw}} \tag{6}$$

Finally, cooling demand balance is very straightforward as it assumes only AA EHPs can meet residential cooling demand X^{cl} (note that cooling COP for AA EHPs, $\eta^{\mathrm{AA,cl}}$, may be different from heating COP $\eta^{\mathrm{AA,sh}}$):

$$p_t^{\mathrm{AA,cl}}\eta_t^{\mathrm{AA,cl}} = X_t^{\mathrm{cl}} \tag{7}$$

Upper bounds on heating and cooling technology outputs limit their total output (which is the sum of space heating, hot water and cooling outputs, as applicable to different technologies) to the level of their installed heating capacity μ, which is ensured through constraints (8)-(10). Note that all heat technology capacities μ are expressed as heat output rates, except AA EHPs, where the capacity is expressed in terms of cooling output. Also note that the COP values for AA EHPs are differentiated between space heating and cooling, while for all other technologies the same COP applied for all types of heat output.

$$\left(p_t^{\mathrm{AW,sh}} + p_t^{\mathrm{AW,hw}}\right)\eta_t^{\mathrm{AW}} \le \mu^{\mathrm{AW}}, \qquad \frac{p_t^{\mathrm{AA,sh}}\eta_t^{\mathrm{AA,sh}}}{W_{\mathrm{HC}}^{\mathrm{AA}}} + p_t^{\mathrm{AA,cl}}\eta_t^{\mathrm{AA,cl}} \le \mu^{\mathrm{AA}}, \qquad p_t^{\mathrm{EB,sh}} + p_t^{\mathrm{EB,hw}} \le \mu^{\mathrm{EB}} \tag{8}$$

$$\left(\xi_t^{\mathrm{HB,sh}} + \xi_t^{\mathrm{HB,hw}}\right)\eta^{\mathrm{HB}} \le \mu^{\mathrm{HB}}, \qquad \left(\xi_t^{\mathrm{AHP,sh}} + \xi_t^{\mathrm{AHP,hw}}\right)\eta_t^{\mathrm{AHP}} \le \mu^{\mathrm{AHP}} \tag{9}$$

$$h_{\mathrm{dch},t}^{\mathrm{TES,sh}} + h_{\mathrm{dch},t}^{\mathrm{TES,hw}} \le \mu^{\mathrm{TES}}, \qquad h_{\mathrm{ch},t}^{\mathrm{TES,sh}} + h_{\mathrm{ch},t}^{\mathrm{TES,hw}} \le \mu^{\mathrm{TES}} \tag{10}$$

Coefficient $W_{\mathrm{HC}}^{\mathrm{AA}}$ in (8) denotes the ratio between heating and cooling capacity for AA EHPs, which in this study was assumed to be equal to 1.2.

Given that AA EHPs can provide space heating through hot air rather than hot water, it was assumed that they cannot produce excess heat output to be stored in TES, but rather to only meet a proportion of instantaneous heat demand. This is ensured through constraint (11):

$$p_t^{\mathrm{AA,sh}}\eta_t^{\mathrm{AA,sh}} \le X_t^{\mathrm{sh}} \tag{11}$$

TES balance and energy limit constraints are implemented using expressions (12) and (13), where q^{TES} is the State-of-Charge (SOC) of TES, τ is its duration, $\eta_{\mathrm{ch}}^{\mathrm{TES}}$ and $\eta_{\mathrm{dch}}^{\mathrm{TES}}$ are charging and discharging efficiencies, respectively, $\alpha_{\mathrm{loss}}^{\mathrm{TES}}$ is the hourly loss rate, and Δ is the duration of the unit time interval:

$$q_t^{\mathrm{TES}} = q_{t-1}^{\mathrm{TES}}\left(1 - \alpha_{\mathrm{loss}}^{\mathrm{TES}}\Delta\right) + \Delta\left[\eta_{\mathrm{ch}}^{\mathrm{TES}}\left(h_{\mathrm{ch},t}^{\mathrm{TES,sh}} + h_{\mathrm{ch},t}^{\mathrm{TES,hw}}\right) - \frac{1}{\eta_{\mathrm{dch}}^{\mathrm{TES}}}\left(h_{\mathrm{dch},t}^{\mathrm{TES,sh}} + h_{\mathrm{dch},t}^{\mathrm{TES,hw}}\right)\right] \tag{12}$$

$$q_t^{\mathrm{TES}} \le \mu^{\mathrm{TES}}\tau^{\mathrm{TES}} \tag{13}$$

2.1.5. System-wide constraints

Total carbon emissions in the energy system result from the operation of thermal generators and methane reformers. An annual system-wide carbon emission target is implemented as in [30], while the system reliability constraints are also included in the model as in [35].

2.2. Techno-economic models of end-use heating and cooling technologies

In this work, detailed techno-economic models of AW EHPs, AW AHPs, EBs and HBs previously developed by the authors in Refs [17] and [30] are used to estimate the cost of heating and cooling technologies as a function of size and their performance as a function of the outside temperature. In addition to these, comprehensive data has been now collected to also properly model AA EHPs. The characteristics of these technologies are integrated within the energy system model so that key technology attributes are adequately represented, allowing for an informed comparison of heating and cooling options from an energy system perspective.

EHPs in households are mainly made of four components: a condenser, an expansion valve, an evaporator and an electricity-driven compressor. The process involves heat being absorbed from a certain heat source, transferred to a working fluid (often referred to as refrigerant) in the evaporator. This is followed by the compression of the vapour working fluid, the temperature and pressure of which are raised during this process until it is condensed. Heat is then transferred to a heat sink fluid, which is used to satisfy the heat demand. The working fluid is lastly passed through an expansion valve, a process which reduces its temperature and pressure, and the cycle is then repeated. AHPs, like EHPs, involve a condenser, an expansion valve and an evaporator. The only difference is that the electricity-driven compressor is replaced by an absorption cycle, meaning that the main source of energy in an AHP is heat.

For all technology models, steady-state operation of components and negligible heat and pressure losses in heat exchangers and pipes are assumed. Both performance and cost estimates are validated using data obtained from UK manufacturers in the case of EHPs, where for AHPs the performance was validated against relevant previous studies. A simplified thermodynamic model was used to estimate the performance of the HB, while an efficiency of 100% was assumed for the EB. Unlike in previous work [30], EHPs are now separated in AW EHPs, which can provide space heating and hot water (but not space cooling), and AA EHPs, which can provide space heating and space cooling (but not hot water). It should be mentioned that an AW EHP could also provide cooling assuming ductwork and other equipment is installed, but this option is not common in residential applications and is not considered in this study.

Heat pump performance is often measured by the coefficient of performance (COP), which is a measure of the ratio between heat output and energy input. For EHPs, energy input is in the form of electricity $\dot{W}_{\mathrm{in}}$, while for hydrogen-driven AHPs, it in the form of heat $\dot{Q}_{\mathrm{in}}$ coming from a hydrogen boiler. Similarly, boiler efficiency is the ratio of heat output to energy input, where the latter is in the form of electricity for EBs and hydrogen fuel $\dot{Q}_{\mathrm{fuel}}$ for HBs. Technology performance is described by Eqs. (14)-(17):

$$COP_{\mathrm{EHP}} = \frac{\dot{Q}_{\mathrm{EHP}}}{\dot{W}_{\mathrm{in}}} \tag{14}$$

$$COP_{\mathrm{AHP}} = \frac{\dot{Q}_{\mathrm{AHP}}}{\dot{Q}_{\mathrm{in}}} \tag{15}$$

$$\eta_{\mathrm{EB}} = \frac{\dot{Q}_{\mathrm{EB}}}{\dot{W}_{\mathrm{in}}} \tag{16}$$

$$\eta_{\mathrm{HB}} = \frac{\dot{Q}_{\mathrm{HB}}}{\dot{Q}_{\mathrm{fuel}}} \tag{17}$$

The specific price of heating and cooling technologies is shown as a function of heat output at nominal operating conditions in Figure 1. The prices for AW EHP, AHP, EB and HB are estimated using the validated component-costing models and manufacturer data as in Ref. [30]. For AA EHPs, data has been collected for more than 75 currently commercially available units and a best-fit line based on power regression is generated. Installation costs are not included in Figure 1, but are set to be equal to £2,200 for all investigated HPs and £1,400 for all investigated boilers. All prices include VAT (20%).

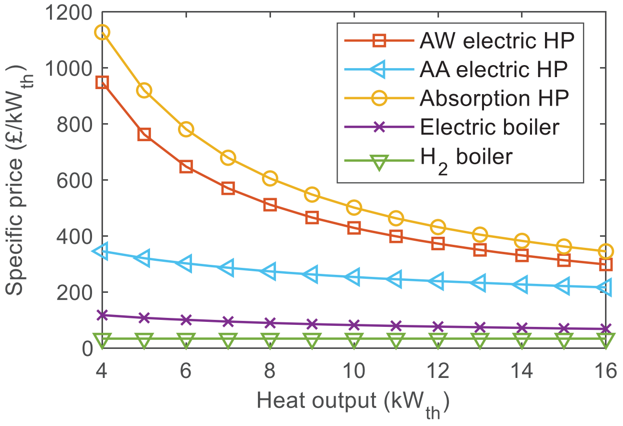
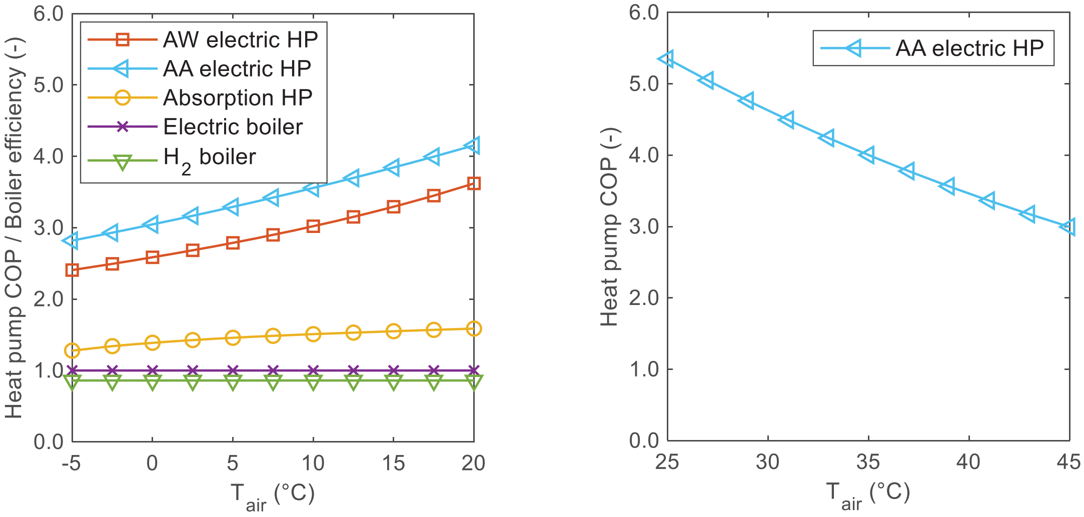


Figure 1. Specific price of heating and cooling technologies as a function of heat output at nominal operating conditions. Prices include VAT.

Heat pump COP is plotted as a function of outside air temperature for different HP types in Figure 2. For the AW EHP and AHP options, the hot-water delivery temperature is assumed to be equal to 55 °C, while the performance curves for heating and cooling of the AA EHP assume an indoor target air temperature of 21°C. The efficiencies of EB and HB are also shown for comparison purposes.

It is interesting to note the significantly lower cost and higher performance of AA EHPs when compared to AW EHPs. The cost difference is attributed to the need for additional components when installing AW EHPs, as well as the larger surface area required to transfer low-temperature heat to radiators and then to air. However, AA heat pumps have the disadvantage of requiring a separate system for hot water, while they may be often accompanied with noise and air-movement issues which may impact end-users and require careful consideration.



(a) (b)

Figure 2. Heat pump COP or boiler efficiency as a function of outside air temperature for (a) heating; and (b) cooling. For heating using AW electric HP or absorption HP, a hot-water delivery temperature of 55 °C is assumed. For heating and cooling using AA electric HP, an indoor target air temperature of 21 °C is assumed.

2.3. Key assumptions and system scenarios

This section discusses the key features of energy system scenarios used in the study and assumptions on the demand for end-use heating and cooling.

2.3.1. Archetypal energy systems

One of the main objectives of the paper is to study the impact of system characteristics on cost-efficient portfolios of low-carbon heating and cooling technologies. To that end, two archetypal energy systems are assumed in the study, North and South, similarly to the approach in [30]. Size of both systems has been chosen to approximately correspond to the size of the UK electricity system, with an annual demand of 400 TWh_{el}. The two archetypal systems have the following key distinctive features:

1. North system represents a simplified version of the UK energy system, characterised by cooler climate conditions, which has a much higher residential heating demand (142 TWh_{th} for SH and 43 TWh_{th} for HW) than the South system (30 TWh_{th} for SH and 21 TWh_{th} for HW), which is broadly modelled to resemble a southern European country. Peak heat demand was also much higher in the North than in the South, as illustrated in the heat Load Duration Curves (LDCs) for the two systems in Figure 3. At the same time the energy demand for cooling energy was assumed to be about 10 times higher in the South (203 TWh_{th}) than in the North (19 TWh_{th}). LDCs for cooling demand are also shown in Figure 3.
2. Availability profiles for renewable generation are assumed to be different between the two systems, with the wind utilisation factor in the North significantly higher than in the South (58% vs. 35%), and the solar PV utilisation factor in the North much lower than in the South (11% vs. 24%). As a result, the nominal Levelised Cost of Electricity (LCOE) of wind and PV in the North was £43/MWh_{el} and £56/MWh_{el}, respectively, while in the South the same LCOEs were £39/MWh_{el} and £25/MWh_{el}.

In each case study the model cost-optimised the supply of low-carbon heating and cooling to 15.7 million residential customers by investing in end-use technologies including AW EHPs, AA EHPs, AHPs, EBs, HBs and TES. Any electricity or hydrogen demand for residential heating was subject to optimisation by the model, depending on investment choices for end-use technologies. Additionally, it was also assumed the system

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needs to supply a hydrogen demand of 97.5 TWh annually to meet the hydrogen requirements outside the residential heating sector, such as in the industrial and transport sectors.

In all studies both systems are cost-optimised with the objective to achieve net zero carbon emissions. The model can meet this target by investing in a range of production technologies (both zero-carbon and positive-carbon) as well as in carbon offsets in the form of electricity generation using Bioenergy with Carbon Capture and Storage (BECCS). In all cases the energy system is modelled in hourly resolution as a single node system, i.e., ignoring the transmission, interconnection or distribution networks.

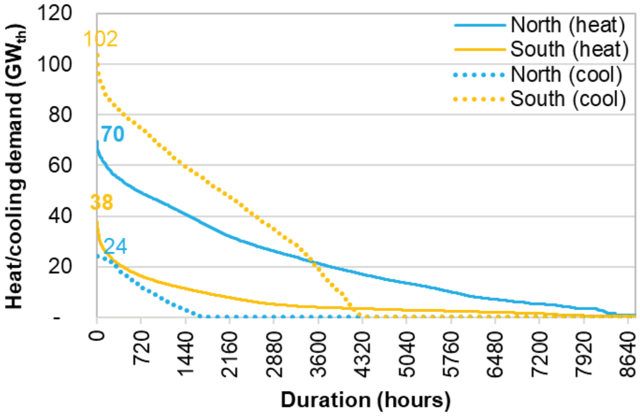

Figure 3. Load duration curves (LDCs) for hourly heat and cooling demand in North and South systems.

The assumed price of natural gas for power generation and H_2 production was £21.8/MWh, while hydrogen import was also assumed to be available (in addition to production) at the price of £100/MWh. District heat networks or industrial heat demand were not included in the scope of this analysis.

2.3.2. Space heating and hot water demand modelling

Household-level heating and cooling technologies are optimised for a typical UK household, which was identified by applying a k-means clustering method to the Cambridge Housing Model [31] data set, which contains detailed information on the UK building stock. The data set only provides annual values for space heating and domestic hot water demand, however, hourly demand values are required as model inputs. For space heating, the methodology of Watson et al. [32] is used to disaggregate the demand. The daily space heating demand is determined from a correlation with the daily mean ambient temperature. It is then distributed to the individual hours using the daily profile for the coldest range presented by Watson et al. [32], as it was deemed to be the most representative of pure space heating demand. For domestic hot water, the daily hot water flowrate profile of Herrando et al. [33] is applied. The flowrate is then converted into an energy demand by assuming a hot water delivery temperature of 55 °C and a monthly-varying cold water mains temperature according to [34].

UK-representative space heating and hot water demand profiles were used in the North archetypal system, as well as representative cooling demand profiles for the UK. In the South system, all heating demand was scaled down according to temperature fluctuations that are representative for Greece, while at the same time cooling demand was scaled upward in the same way. Daily average values for COP for various heating and cooling technologies for the North and South annual temperature profiles (obtained based on Figure 2) are shown in Figure 4. As expected, due to generally lower temperatures, the North system is characterised by higher COP values for cooling but lower COPs for heating. There is also a noticeable COP advantage when using AA EHPs to provide space heating rather than AW EHPs, although as discussed elsewhere in the paper using AA EHPs for space heating may not be practical, especially in colder climates.

The assumed costs of low-carbon heat options were based on the analysis presented in the previous section and on typical asset sizes, as follows (note that these figures include both the component costs from Figure 1 and the relevant installation cost):

- AA EHP: £578/kW$_{th}$
- AW EHP: £300/kW$_{th}$
- AHP: £638/kW$_{th}$
- EB: £139/kW$_{th}$
- HB: £98/kW$_{th}$
- TES: £75/kWh$_{th}$

In addition to the upfront investment cost, it was also assumed that all assets require an annual maintenance cost in the amount of £35/kW$_{th}$/yr for all HP and boiler technologies, and £20/kW$_{th}$/yr for TES. Asset lifetime

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was assumed to be 20 years for AA EHPs, AW EHPs and AHPs and 15 years for EBs, HBs and TES. A 5% interest rate has been assumed for all heating technologies to convert overnight cost into annualised values required by the model. The assumed duration of TES (the ratio between energy capacity and heat charge and discharge rate) was 3 hours.

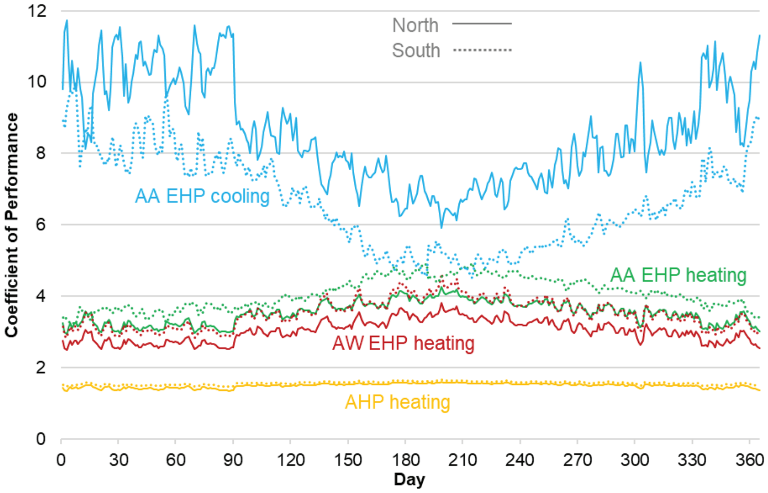

Figure 4. Values of Coefficient of Performance for various heating and cooling technologies in North and South systems.

2.3.3. Case studies

Main case studies run for both the North and South archetypal energy systems with a net-zero caron target include:

- Unlimited: no limits to provision of space heating (SH) from AA EHPs
- No SH from AA EHPs: no SH allowed from AA EHPs
- AA SH 30%: share of AA EHPs in SH limited to 30%
- AA SH 20%: share of AA EHPs in SH limited to 20%
- AA SH 10%: share of AA EHPs in SH limited to 10%

The main purpose of these studies is to explore the potential contribution of various heating technologies, and in particular AA EHPs, to space heating under different assumptions and constraints. The reason for this is that although AA EHPs could potentially offer a competitive alternative to AW EHPs with high COP values for heating, there are several practical barriers for their widespread deployment in countries such as the UK. These include space constraints, multiple room installations, difficult integration with existing heating systems and radiators etc. For that reason, AA EHPs are often seen as a possible top-up source of space heating rather than a bulk source of heat, and the range of case studies listed above is an attempt to explore how various levels of contribution of AA EHPs to space heating affect the overall portfolio of end-use heating technologies.

In addition to the case studies above, another set of modelling runs was carried out to study the impact of peakiness of heat demand, where the heat profiles used in this study were replaced with peakier heat demand profiles used in [30], in order to assess the impact of the shape of the heat profile on the cost-efficient portfolio of heating technologies. For illustration, heating profiles used in the main case studies had a peak per household of around 4.5 kW_{th}, which is lower than the peak of 7 kW_{th} that was used in the previous study. Case studies with higher peak heat demand were only carried out for the two extreme cases, i.e., “Unlimited” and “No SH from AA EHPs”.

The final set of studies assumed that the system also had an option to invest in very low-cost long-duration energy storage (LDES). The aim of these studies was to test whether installing LDES in the electricity system could help with managing the seasonality of heating and cooling demand. The LDES case studies were also run only for the “Unlimited” and “No SH from AA EHPs” scenarios. The cost of LDES in these studies was assumed at the level of 100% (£6.5/kWh) and 50% (£3.2/kWh) of the cheapest LDES option identified in [37], which was a 120-hour underground Compressed Air Energy Storage (CAES).

3. Results

This section discusses the results of various case studies aimed at establishing cost-efficient portfolios of low-carbon heating and cooling technologies across different system conditions and scenarios. More specifically, the case studies presented here focus on the following aspects:

- Impact of system geography, reflected in the volumes of heating and cooling demand and in the availability profiles of wind and solar PV generation;
- Impact of availability of AA EHPs for space heating;
- Impact of availability of low-cost long-duration electricity storage (LDES);
- Impact of heat demand profile, i.e., the level of peak demand for space heating.

Key modelling results presented in this section focus on the cost-optimal capacity mix of low-carbon heating and cooling technologies and the annual volumes of supplied heat and cooling from different technologies.

3.1. Cost-efficient portfolios of end-use heating and cooling technologies in baseline scenarios

Results for the cost-optimal compositions of heating and cooling portfolios across the main case studies for the North and South systems are shown in Figure 5. Not surprisingly, a significant volume of AA EHP capacity is added across all case studies as it represents the only option to supply cooling demand. This capacity is at least 24 GW$_{th}$ in the North and 104 GW$_{th}$ in the South system. In the "Unlimited" scenarios in the North the model adds even more AA EHPs than the minimum required for cooling, around 43 GW$_{th}$, as it represents a more cost-efficient option than installing AW EHPs. Such high capacity is sufficient to cover almost the entire space heat demand in the "Unlimited" scenarios for the North and South systems. Given that AA EHPs cannot provide hot water, a relatively small volume of AW EHPs and TES (as well as some HBs in the North) is installed to ensure that hot water demand is met.

In the other extreme, where AA EHPs are not used to provide any space heating, the heat demand is met through a mix of AW EHPs (49 GW$_{th}$ in the North, 13 GW$_{th}$ in the South), EBs (3 GW$_{th}$ and 15 GW$_{th}$), HBs (10 GW$_{th}$ and 5 GW$_{th}$) and TES (8 GW$_{th}$ and 6 GW$_{th}$). Due to their higher investment cost, AW EHPs are installed to operate as baseload heat source, meeting most of the heat requirements, while boilers and TES are used as peak heat sources. AHPs are not chosen as part of the cost-optimal portfolio in any case studies due to their high assumed investment cost.

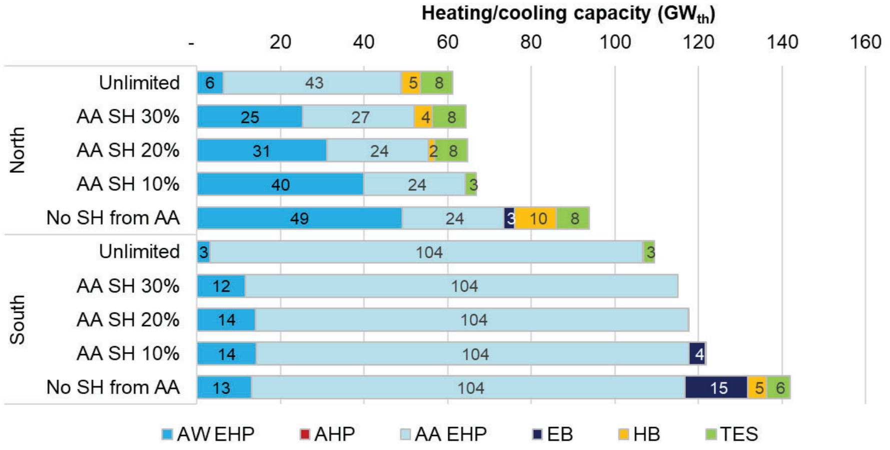

Figure 5. Cost-optimal capacities of low-carbon heating and cooling technologies for various scenarios in North and South systems.

In case studies where AA EHPs were allowed to contribute between 10% and 30% of the annual space heating demand, the model installed a significantly higher capacity of AW EHPs than in the "Unlimited" scenarios, but lower than in the opposite extreme without contribution of AA EHPs to SH, as it was now possible to use AA EHPs as a peaking technology instead of boilers or TES. In the North system, reducing the target contribution of AA EHPs to heat supply also reduced their capacity to 24 GW$_{th}$, the minimum needed to meet cooling load.

Finally, it needs to be noted that the case studies with low-cost LDES available for investment in the electricity system did not yield any change in system investment decisions including the investment in end-use heating and cooling technologies. In other words, even at a low cost the model did not decide to invest in LDES, resulting in the same investment decisions as in the case studies without LDES.

3.2. Share of various technologies in heating and cooling supply in baseline scenarios

Figure 6 shows the split of annual supply of space heating (SH), hot water (HW) and cooling between different technologies. Supply of cooling is very straightforward as it was assumed that only one technology (AA EHPs) can meet cooling demand.

In both North and South systems most of the HW demand is supplied using AW EHPs, which is the most efficient technology for converting electricity into heat for HW supply (note that AA EHPs were not assumed to be able to supply HW). In scenarios with no SH from AA EHPs there is some supply of HW from EBs and HBs, although their share in HW supply is well below 10%.

The mix of SH supply on the other hand varies significantly across different scenarios. In the "Unlimited" scenarios the contribution to of AA EHPs to space heating is between 93% (South) and 96% (North), while the remainder is supplied by AW EHPs. As the share of AA EHPs in SH supply is gradually constrained to 30%, 20%, 10% and 0% of total SH demand, the share of AW EHPs expectedly increases to make up for the shortfall, as does the installed AW EHP capacity (see Figure 5). When the share of AA EHPs in SH supply drops to zero, some of the SH is also supplied from boiler technologies (mostly from EBs), at the level of 2% in the North and 17% in the South. Higher share of EBs in heat supply in the South can be explained by the availability of low-cost electricity from solar PV in the South, allowing for inexpensive supply of electricity to EBs.

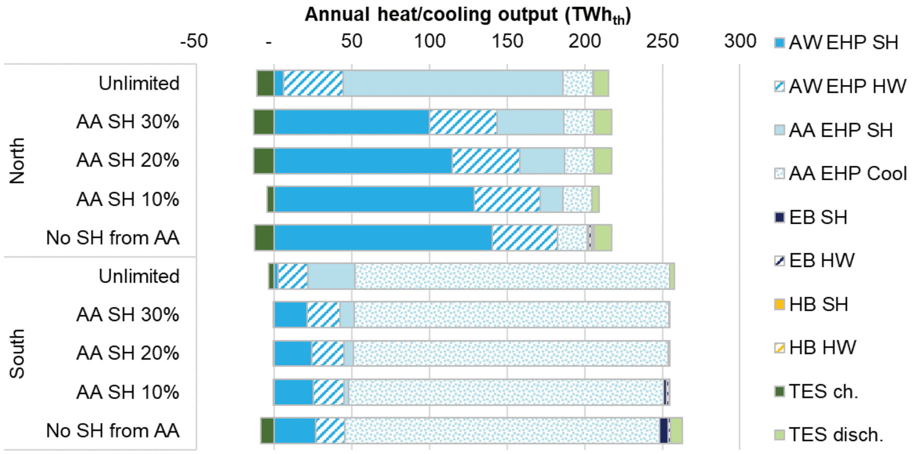

Figure 6. Annual output of low-carbon heating and cooling technologies for various scenarios in North and South systems.

In all North scenarios and the 0% scenario in the South there is also a visible contribution of TES to total SH and HW supply, at the level of up to 6% of total heat in the North and 14% in the South. Note, however, that due to cycle losses associated with charging and discharging TES, it effectively represents a net heat demand.

3.3. Impact of heat demand profiles

Sensitivity studies with higher peak heat demand resulted in cost-optimal portfolios of end-use technologies shown in Figure 7. Higher peak heat demand did not affect the technology portfolio in the "Unlimited" scenario in the South, while in the North the capacity of AA EHPs increases by 9 GW$_{th}$ as it is used to contribute to meeting the higher peaks in heating demand.

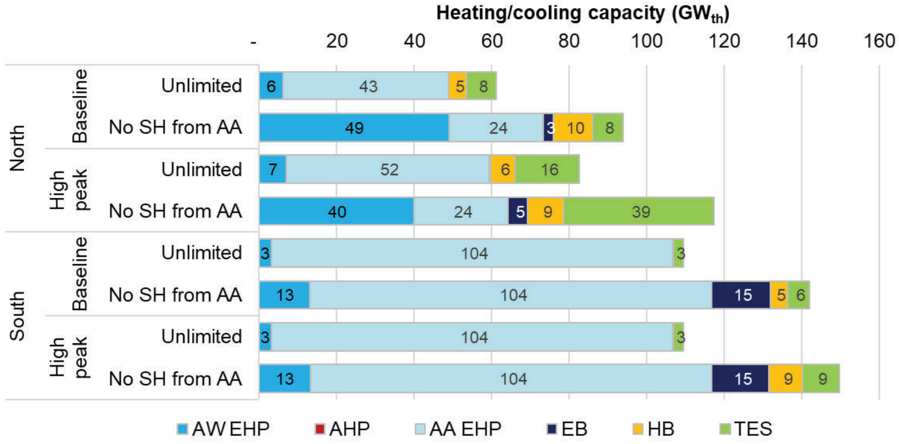

Figure 7. Cost-optimal capacities of low-carbon heating and cooling technologies for various peak heat demand scenarios in North and South systems.

In the scenarios with the AA EHP share in SH supply constrained to 0% there are more notable differences in the cost-optimal technology portfolios. In the South system, where the SH demand is several times lower than in the North, the main change is that the higher peak requires a slightly higher capacity of HBs (9 vs. 5 GW_{th}) and TES (9 vs. 6 GW_{th}) than in the baseline studies, while the capacities of other technologies remain the same.

In the North system, however, the SH peak demand is much higher and therefore the composition of end-use heating technologies changes to a much greater extent. Peakier demand makes AW EHPs slightly less economically attractive due to their cost structure (high investment cost but relatively low operation cost), so their capacity reduces from 49 to 40 GW_{th}. At the same time, higher peaks make technologies such as boilers (with lower investment cost but higher operating cost) more attractive, so their total capacity increases from 13 to 14 GW. Nevertheless, the greatest change is observed in the capacity of TES, which increases from 8 to 39 GW_{th}. This indicates that TES is the preferred end-use option to meet high peak demand through discharging heat, while being recharged during off-peak periods using the heat produced by AW EHPs.

4. Conclusion

This paper formulated an approach for making cost-optimal selection of low-carbon heating and cooling technologies from the system perspective, looking at two archetypal systems, North and South, with different heating and cooling demand characteristics as well as different availability profiles for variable renewables. The modelling included various boiler technologies, thermal energy storage and heat pumps, including a distinction between two types of EHPs (Air-to-Water and Air-to-Air), into the energy system optimisation framework.

Case studies presented in the paper show that a cost-optimal portfolio of end-use heating and cooling options will greatly depend on the characteristics of the system where they are deployed, both in terms of typical heating and cooling demand patterns, but also with respect to the availability of low-cost variable renewable generation. The results suggest that AA EHPs, with their cost and efficiency advantages over AW EHPs, could make a significant contribution to the future low-carbon heat supply in addition to cooling, although their share of heat supply may be constrained by several factors such as compatibility with incumbent heating systems or the need for multiple unit installations. Nevertheless, they could be used as an efficient top-up source of space heating in addition to AW EHPs, displacing some of the need for electric or hydrogen boilers, as well as thermal energy storage.

Note that the presented approach considers the aggregate heating/cooling sector, and therefore does not suggest an appropriate mix of technologies for an individual household. Given the variety of heat requirements across different customers and the diversity of heat demand, different households would install different portfolios of technologies depending on their specific circumstances, including their individual heat demand patterns, willingness to adopt new low-carbon technologies, and the household income profile. Future work in this area will focus on the effects of diversity and extreme weather on capacity requirements for low-carbon heating and cooling technologies, where higher peaks during extreme weather conditions may require more peaking capacity.

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List of acronyms

AA EHP	Air-to-air electric heat pump	HB	Hydrogen boiler
AW EHP	Air-to-water electric heat pump	HP	Heat pump
AHP	Absorption heat pump	HW	Hot water
BECCS	Bioenergy with carbon capture and storage	IEA	International Energy Agency
BESS	Battery energy storage system	LCOE	Levelised Cost of electricity
CAES	Compressed air energy storage	LDC	Load duration curve
COP	Coefficient of performance	LDES	Long-duration energy storage
EB	Electric boiler	SH	Space heating
EHP	Electric heat pump	SOC	State of charge
EU	European Union	TES	Thermal energy storage
EV	Electric vehicle	UK	United Kingdom
HB	Hydrogen boiler		

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