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System-level techno-economic comparison of residential low-carbon heating and cooling solutions

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ABSTRACT

This paper studies portfolios of electricity- and hydrogen-driven heat pumps, electricity- and hydrogen-driven boilers and thermal energy storage technologies from an energy system perspective. Thermodynamic and component-costing models of heating and cooling technologies are integrated into a whole-energy system cost optimisation model to determine configurations of heating and cooling systems that minimise the overall system cost. Case studies focus on two archetypal systems (North and South) that differ in terms of heating and cooling demand and availability profiles of solar and wind generation. Modelling results suggest that optimal capacities for heating and cooling technologies vary significantly depending on system properties. Between 83 % and 100 % of low-carbon heat is supplied by electric heat pump technologies, with the rest contributed by electric or hydrogen boilers, supplemented by heat storage. Air-to-air electric heat pumps emerge as a significant contributor to both heating and cooling, although their contribution may be constrained by the compatibility with existing heating systems and the inability to provide hot water. Nevertheless, they are found to be a useful supplementary source of space heating that can displace between 20 and 33 GW_{th} of other heating technologies compared to the case where they do not contribute to space heating.

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], both of which aim to reach net zero emissions by 2050. Reaching this target is necessary to achieve international environmental sustainability goals for human systems and ecosystems worldwide [3], and will require widespread decarbonisation across all sectors of the economy [4]. This includes the residential energy sector, which accounts for over one-third of global carbon emissions [5].

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 [6]. The main low-carbon alternative to gas boilers are vapour-compression air-to-water electric heat pumps (AW EHPs), which use water as the heat sink fluid and have seen a large market growth in the last decade [7]. The average coefficient of performance (COP) of AW EHPs, which is the ratio of thermal output to electricity input, varies between about 2 and 5 depending on the design and operating conditions [8]. It has recently been shown that they are able to perform well even at low temperatures [9]. This represents superior thermodynamic performance compared to boilers, which have a heat-to-fuel efficiency lower than 1. However, in 2023, heat pump sales in Europe fell by around 5 % compared to 2022, demonstrating that AW EHPs still face a number of challenges [10]. AW EHPs depend on a decarbonised electricity supply to maximise their emission reduction potential [11], and their uptake is sensitive to the

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ratio between the electricity and natural gas price [12].

Electric boilers (EBs), in contrast to traditional gas boilers, operate using electricity for resistive heating, positioning them as a low-carbon technology similar to AW EHPs. Although their performance is notably inferior to EHPs, with a COP of approximately 1, EBs presently have substantially lower upfront costs. Consequently, they have been suggested either as the primary heating technology or as a supplementary option in various scenarios, providing heat to a hot-water cylinder to enhance flexibility instead of opting for an electric heat pump [13,14].

Other low-carbon options include hydrogen boilers (HBs) [15] or hydrogen-fired absorption heat pumps (AHPs) [16], which require a supply of low-carbon hydrogen. Absorption heat pumps were shown to reduce the fuel consumption by more than 20 % compared to boilers [17], while technologies driven by hydrogen could potentially have positive environmental impacts [18]. Most studies looking at heating decarbonisation pathways based on electricity and hydrogen have suggested that electrified heating in most cases represents a more cost-effective option than hydrogen [19]. However, hydrogen is receiving growing attention. Exploring hydrogen as a pathway for decarbonising heating requires comparing different production methods due to their impact on decarbonisation cost, energy requirements, and hydrogen carbon intensity [20]. Hydrogen production is often categorised by colour codes: green hydrogen is produced via electrolysis using renewable energy, while blue hydrogen is derived from methane reforming with carbon capture and storage (CCS) [21]. Other types include grey hydrogen (from methane reforming without CCS), black and brown hydrogen (from fossil fuels), pink hydrogen (via nuclear energy), and white hydrogen (naturally occurring). Each method has distinct technical and economic characteristics, and the future potential of hydrogen will rely on further technological advancements and cost reductions [22]. Recent progress includes improved and more mature hydrogen storage and more efficient and less expensive electrolysers and fuel cells [23].

In addition to heating, provision of cost-effective and low-carbon space cooling is becoming increasingly relevant globally. Cooling 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 [24]. 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 change [25], 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 [26]. As reported in the work of Mastrucci et al. [27], 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 [28].

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 [29], potentially causing outages or requiring costly upgrades to energy infrastructure. These could be mitigated by demand-side response strategies, integration of energy storage assets and other sector coupling based solutions. IEA's Net Zero Emissions by 2050 Scenario [30] 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.

Electric heat pumps have a variety of configurations, working fluids and component types, as well as various heat source and sink fluids [31,32]. Space cooling has been traditionally provided by conventional electrically driven air-conditioning units [33], 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 electric heat pumps (AA EHPs) and as of recent, almost all new commercially available AA EHPs are designed to be reversible [34]. This means that they can be used to provide both space heating and cooling, depending on the weather. However, air-to-air heat pumps cannot provide hot water. At the same time, space heating can also be provided by AW EHPs. 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) [35], 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-scale electricity demand. Also, it will accentuate seasonal variations in demand, as heating and cooling requirements are driven by the ambient temperature. It is therefore expected that in colder countries the electricity load in winter will be significantly higher, especially during peak hours. Similarly, hot countries are expected to experience high electricity demand in the summer. In the UK context, Quiggin and Buswell [36] predicted an increase in peak electricity demand of 55 GW as a result of heating electrification; Hoseinpoori et al. [37] project that the peak demand may increase by up to 84 GW (170 %) by 2050, while Peacock et al. [38] estimate a peak increase of up to 40 GW. In addition, White et al. [39] predict an increase in peak electrical power demand in the residential sector of Texas in the USA by as much as 36 %, while Thomaβen et al. [11] estimate a 20–90 % increase in peak electricity demand in the EU. It has been shown that energy storage, both at household-level and whole-energy system level, as well as other means of flexibility can help reduce necessary investments in low-carbon power generation capacity and therefore deliver decarbonisation objectives at a lower cost [40].

At the household level, energy storage can be implemented in the form of thermal energy storage such as hot water tanks or other sensible heat options, or through more advanced approaches such as thermochemical storage, phase change materials, building thermal inertia or molecular storage, all of which offer potential for inter-seasonal storage with extremely low energy losses [41,42]. In the case of integrating energy storage with electric heat pumps, this could take the form of thermal energy storage (to achieve higher seasonal COP due to the diurnal temperature fluctuations) or electric energy storage, enabling demand response capabilities and withdrawal of electricity during off peak periods. In both cases, the utilisation of storage effectively achieves decoupling of household's heat demand from the electricity demand of the heat pump, thus allowing households to shift their electricity demand to off-peak hours and level their demand profile [35]. 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 [43], while long-term storage can provide large quantities of dispatchable generation for multiple hours or even days. The main conventional large-scale energy storage technology is pumped-hydro storage; however, its further development potential is limited. Instead, novel storage technologies such as compressed-air energy storage [44], hydrogen storage [45] or large-scale batteries [46] show promise for application in future decarbonised energy systems.

Previous work on optimal configuration of low-carbon heating systems mostly optimised the heating systems from the customer's perspective, not necessarily accounting for the characteristics of the wider energy system and how it could be co-optimised with the deployment and utilisation of low-carbon heating and cooling technologies in buildings. Kotzur et al. [47] optimised the supply of energy at the level of 200 archetypal buildings in Germany and concluded that a combination of photovoltaic and heat pumps would offer the best performance in the 2050 horizon. A Mixed-Integer Linear Programming (MILP) model to optimise HP design (including TES and auxiliary heaters) for a single-family house in Germany has been developed in Ref. [48], suggesting 45 % lower investment cost compared to a standard solution to meet the space heating and hot water demand profiles [49]. Dongellini et al. [50] have also found that hybrid heating systems based on HPs and back-up heaters can deliver energy and cost savings with smaller-sized HPs. Detailed MILP-based approaches have also been developed for optimising the component design of household-level HP systems [51,52].

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. Unlike the previous bottom-up approaches, the cost-optimisation in this paper is carried out from the whole-system cost perspective, including investment and operation cost of energy production, storage and end-use technologies at the system level concurrently with the cost of investing in and operating low-carbon heating and cooling technologies. This analysis represents an extension of the authors' previous work on system-driven design of low-carbon heating systems [53], while previous versions of this model were used to provide evidence to the UK government in support of heating decarbonisation [54]. Since then, many technologies have evolved in terms of performance and cost, and previous work did not address decarbonisation of cooling. Hence, this work represents a significant improvement in the state of the art.

Heating and cooling demand are here considered separately for space heating, space cooling and domestic hot water. Detailed thermodynamic and component-costing models of the considered heating and cooling technologies are used to inform the energy system model. One of the main novelties of the approach presented in this work is that for the first time, two different 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 another option to potentially improve the efficiency of integrating heat into the electricity system.

The methodology used to identify efficient system-driven portfolios of low-carbon heating and cooling technologies is elaborated in Section 2, along with the description of techno-economic models of individual technologies. Case study results for two archetypal energy systems are provided in Section 3 while the conclusions of the analysis 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 extended version of the energy system model presented by Aunedi et al. [53]. This mixed-integer linear programming (MILP) 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 determine the optimal mix of technologies and how to operate the system to minimise the total system cost associated with delivering electricity, heating, and cooling to end-consumers. It aims to meet the whole-system demand for heating and cooling over the course of one year while adhering to environmental and energy security constraints.

Key extensions to the energy system model compared to the approach presented in Ref. [53] 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 segments of heat demand.

The main inputs and outputs of the system optimisation model are illustrated in Fig. 1, which also includes the information received from the techno-economic models of low-carbon heating and cooling technologies described in Section 2.2. The optimisation model presented in this section has been implemented using the FICO Xpress Optimisation tool [55], and the optimisation was carried out using the Newton-barrier algorithm. The model execution time for the case studies presented in the paper varied between 42 and 98 min when run on a x64-based workstation PC with 512 GB RAM and 28 logical processors.

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 ($\varphi_{\mathrm{H_2}}$), and c) investment cost in end-use technologies for low-carbon heating and cooling ($\varphi_{\mathrm{heat-cool}}$):

$$\min z = \varphi_{\mathrm{el}} + \varphi_{\mathrm{H_2}} + \varphi_{\mathrm{heat-cool}} \tag{1}$$

Terms representing the electricity sector and hydrogen sector costs are formulated in the same way as in Ref. [53]. 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 approach allows for an exploration of the potential of both green and blue hydrogen, the main pathways for hydrogen-based heat decarbonisation. 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 $\varphi_{\mathrm{heat-cool}}$ 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:

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

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 ($p^{\mathrm{bs}}_{\mathrm{dch}} - p^{\mathrm{bs}}_{\mathrm{ch}}$), needs to match total demand across various categories. These categories include electrified heating (p^{AW}_t, p^{AA}_t and p^{EB}_t), other non-heat segments such as baseline system demand, appliance and EV demand (d^{el}_k), as well as any electricity demand required for operating methane reformers and electrolysers, which is expressed as the product of their hydrogen output ξ and specific electricity consumption L^{el}:

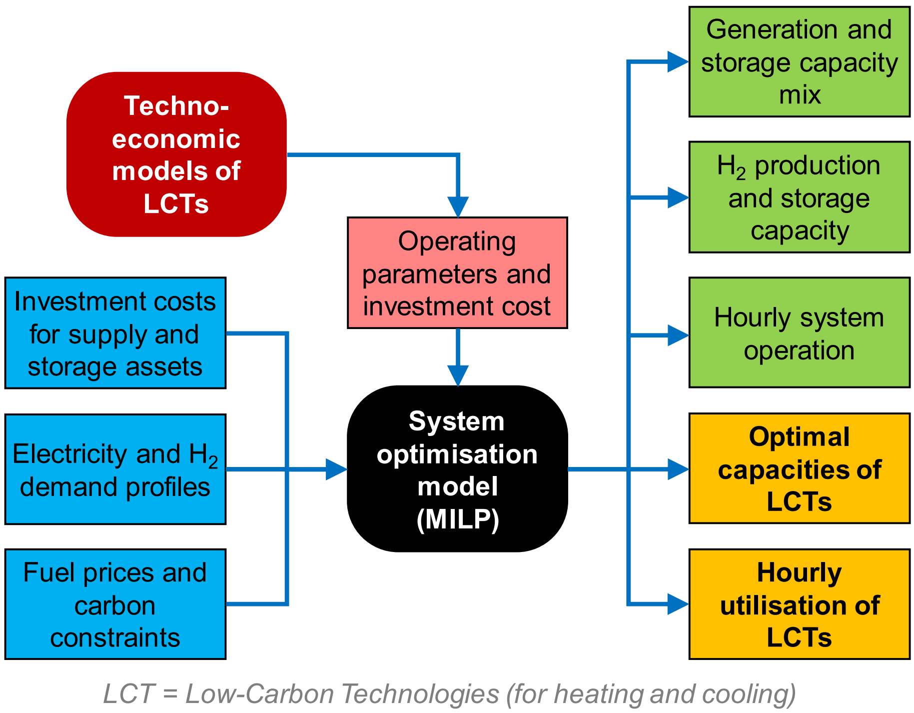

Fig. 1. Flowchart of the main inputs and outputs from the thermo-economic technology models and system optimisation model.

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

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 output ($\xi_{\mathrm{ch}}^{\mathrm{hs}} - \xi_{\mathrm{dch}}^{\mathrm{hs}}$):

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

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 Ref. [56]. In a similar way, standard constraints on hydrogen production and storage are implemented as presented in Ref. [57].

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.

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

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

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

Coefficient W_{HC}^{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):

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

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, η_{ch}^{TES} and η_{dch}^{TES} are charging and discharging efficiencies, respectively, α_{loss}^{TES} is the hourly loss rate, and Δ is the duration of the unit time interval:

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

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

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 Ref. [53], while the system reliability constraints are also included in the model as in Ref. [56].

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. [31,53] 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 typically consist of four main 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 finally 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 [53], EHPs are now distinguished between 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). Note that an AW EHP could also provide cooling provided that ductwork and other equipment is installed, but this option is not common in residential applications and is therefore not considered in this study.

Heat pump performance is normally quantified through its coefficient of performance (COP), which represents the ratio between heat output and energy input. For EHPs, energy input is in the form of electricity $\dot{W}_{in}$, while for hydrogen-driven AHPs, it in the form of heat $\dot{Q}_{in}$ 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 $\dot{Q}_{fuel}$ for HBs. Technology performance is described by Eqs. (14)–(17):

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

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

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

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

The specific (unit) price of heating and cooling technologies is shown as a function of heat output at nominal operating conditions in Fig. 2. The prices for AW EHP, AHP, EB and HB are estimated using the validated component-costing models and manufacturer data as in Ref. [53]. For AA EHPs, data has been collected for more than 75 currently commercially available units and a best-fit line generated based on power regression. Installation costs are not included in Fig. 2, but are set to be equal to £2200 for all investigated HPs and £1400 for all investigated boilers. All prices include VAT (20 %).

The heat pump COP is plotted as a function of outside air temperature for different HP types in Fig. 3. For the AW EHP and AHP options, the hot-water delivery temperature is assumed to be fixed 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 COP 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 EHPs 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

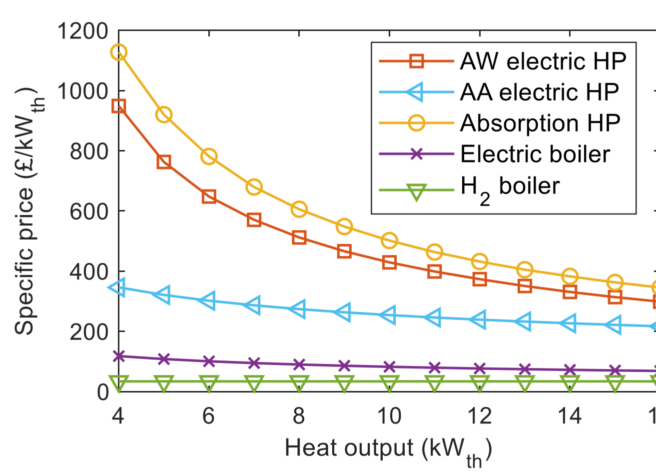

Fig. 2. Specific price of heating and cooling technologies as a function of heat output at nominal operating conditions. Prices include VAT.

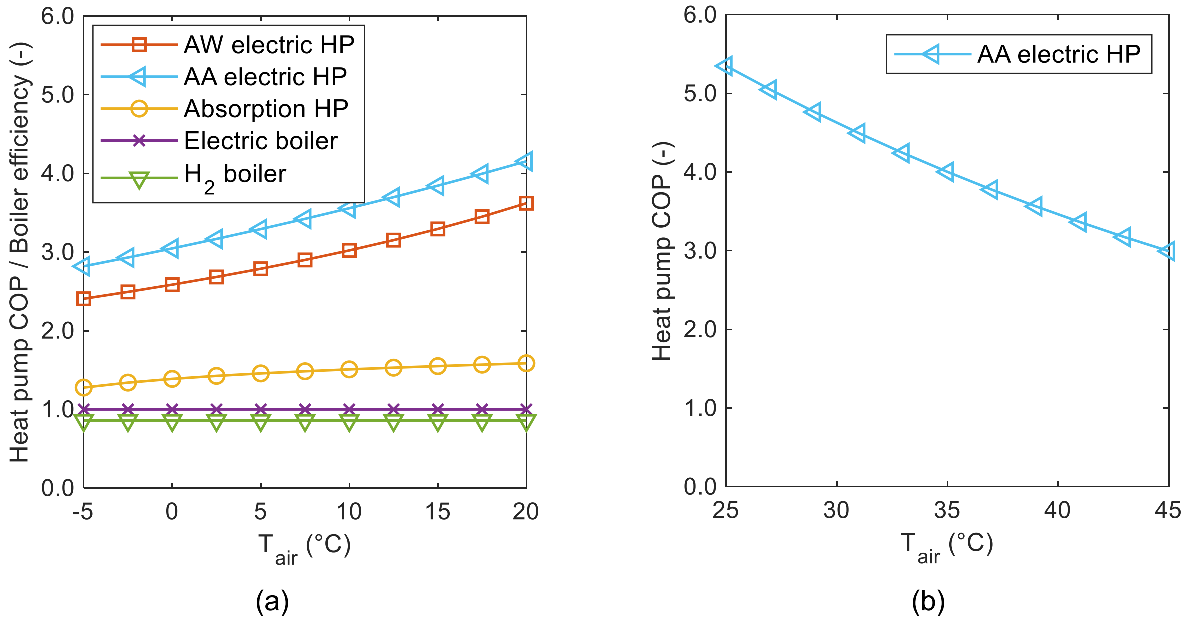

Fig. 3. Heat pump COP or boiler efficiency as a function of outside air temperature for (a) heating; and (b) cooling. For heating using AW electric HP or absorption HP, a hot-water delivery temperature of 55 °C is assumed. For heating and cooling using AA electric HP, an indoor target air temperature of 21 °C is assumed.

end-users and require careful consideration.

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. As in any study of this nature, the input data assumptions are subject to significant uncertainties, in particular with respect to projecting future technology costs, as these are affected by a variety of economic, demographic, and technological factors. Most assumptions are taken from reputable sources wherever available, while some of the assumptions and the related uncertainties were explored through sensitivity analysis.

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 Ref. [53]. The size of both systems has been chosen to approximately correspond to the size of the UK electricity system, with an annual demand of around 400 TWh_{el}. Nevertheless, the exact numbers varied, which means that the results are intended as useful indicators rather than definitive benchmarks for the UK. 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 Fig. 4. At the same time, the cooling demand 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 Fig. 4.
2. Availability profiles for renewable generation are also 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

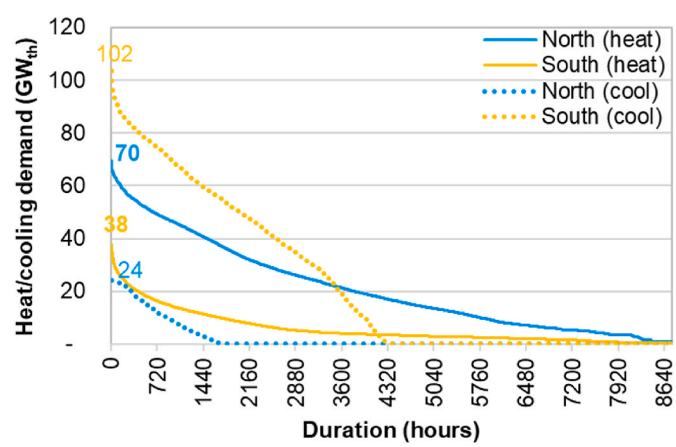

Fig. 4. Load duration curves (LDCs) for hourly heat and cooling demand in North and South systems.

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 two 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 that included 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 optimised investment choices for end-use technologies. Additionally, it was also assumed the system needs to supply a hydrogen demand of 97.5 TWh annually to meet the hydrogen requirements outside of the residential heating sector, such as in the industrial and transport sectors.

In all studies both energy systems were cost-optimised with the objective to achieve net zero carbon emissions. The model could meet this target by investing in a range of electricity 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.

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.

This analysis focused on the primary technologies for decarbonising UK heating and cooling: heat pumps and hydrogen [1]. Other options, such as solar thermal or biomass systems, were not considered but will be explored in future work. District heat networks and industrial heat demand were not included in the scope of this study. The potential for district heating in the UK is location-dependent, and a thorough examination would require spatially detailed energy system methods, which is beyond the scope of this work.

2.3.2. Space heating and hot water demand modelling

Household-level heating and cooling technologies are optimised based on demand estimated for a typical UK household identified by applying *k*-means clustering to the Cambridge Housing Model dataset for the UK building stock [58]. This dataset only provides annual totals for space heating and domestic hot water demand; however, the system model requires hourly demand values to be provided as input. For space heating, the methodology of Watson et al. [59] is used to disaggregate the demand. Daily space heating demand is determined based on the correlation of demand 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. [59], 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. [60] is applied. The flowrate is then converted into an energy demand by assuming a hot water delivery temperature of 55 °C and a monthly variation in cold water mains temperature according to Ref. [61].

Space heating and hot water demand profiles representative for the UK were used for the North archetypal system, as well as UK-representative cooling demand profiles. In the South system, all heating demand was scaled down according to temperature fluctuations representative for Greece, while the cooling demand was scaled upwards 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 Fig. 3) are shown in Fig. 5. 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.

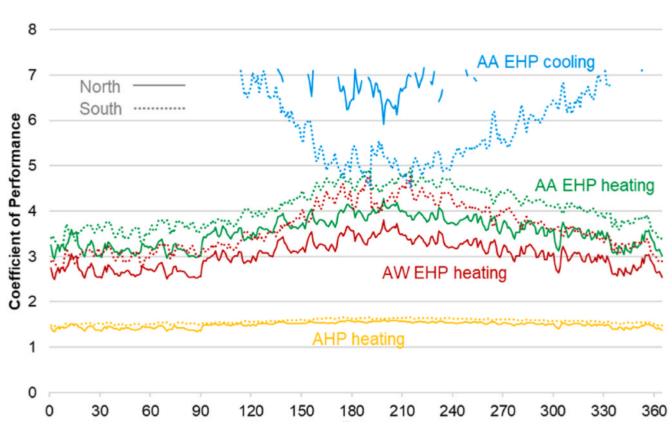

Fig. 5. Values of Coefficient of Performance for various heating and cooling technologies in North and South systems. COP for cooling is only plotted for days when there is demand for cooling.

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 only include the component costs from Fig. 2 but not the relevant installation cost, which was added separately).

- AW EHP: £578/kW_{th}
- AA 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 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 h.

2.3.3. Case studies

The main case studies carried out for both North and South archetypal energy systems with a net-zero carbon target include.

- Unlimited: no limits to provision of 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, and difficult integration with existing heating systems and radiators. 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 explores 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 Ref. [53], 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 demand 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 the cheapest LDES option identified in Ref. [62], which was a 120-h underground Compressed Air Energy Storage (CAES) with the unit energy cost of £6.5/kWh.

3. Results

This section discusses the results of various case studies aimed at identifying cost-efficient portfolios of low-carbon heating and cooling technologies across different system conditions and scenarios. The case studies 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 the remainder of 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-optimal generation and storage portfolios

To illustrate the key characteristics of North and South electricity systems, Fig. 6a shows the generation capacity mix for the two systems for the Unlimited scenario, while Fig. 6b shows the annual electricity outputs for various technologies.

Due to the differences in the availability of renewable generation resources, the North system is dominated by offshore and onshore wind generation, while in the South the dominant generation technology is solar PV. In addition to variable renewables, both systems also include some conventional gas and nuclear power, ensuring a sufficient level of firm generation and system inertia, as well as BECCS capacity, which ensures net-zero carbon emissions from the power system.

Both systems also include a significant volume of grid-scale energy storage, which in the main scenarios consists of Li-ion battery storage (note that LDES was only made available for investment in the sensitivity studies presented later in this section). Battery storage is installed by the model in order to enable the system to cope with variations in renewable electricity output. The volume of battery storage was 58 GW_{el} in the North and 100 GW_{el} in the South, as the PV generation in the South was subject to higher output variability than the wind in the North.

Fig. 6b shows that although both systems are dominated by variable renewable output (onshore and offshore wind in the North, and a mix of onshore wind and solar PV in the South), they also include a significant volume of nuclear and gas generation output. Carbon emissions from gas generation are offset by BECCS operation in order to achieve net-zero carbon emissions annually. One can also observe that for both systems the net annual output of grid-scale energy storage is shown as a negative value, given that energy storage represents a net electricity demand due to its roundtrip losses.

3.2. 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 Fig. 7. Unsurprisingly, 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 for supplying SH 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 meet the hot water demand.

In the other extreme, where AA EHPs are not allowed 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 but also higher efficiency, AW EHPs are operated as baseload heat source, meeting most of the heat requirements, while boilers and TES are used as peak heat sources.

Interestingly, in none of the case studies were AHPs chosen as part of the cost-optimal portfolio. This can be attributed to their relatively high upfront investment cost. Despite the potential operating cost savings they offer compared to hydrogen boilers, these savings are not substantial enough to offset the higher upfront investment required for AHPs. It is also worth noting that the performance of AHPs is less affected by outside temperature fluctuations compared to AW and AA EHPs. This means that in scenarios where hydrogen becomes more affordable than indicated in this study or if the region under consideration experiences significantly colder temperatures [63], AHPs could potentially play a more significant role in the energy system.

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.

The role of hydrogen-based heating in both South and North systems is relatively low, but still significant. In this work, hydrogen for HBs is produced from electrolysis using renewable sources, i.e., it is produced as green hydrogen. It is important to note that potential technological

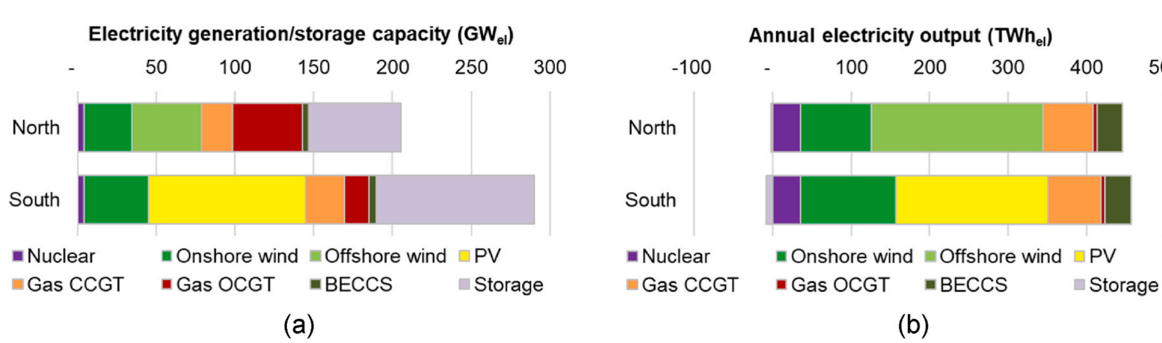

Fig. 6. Cost-optimal capacities of electricity generation and storage technologies (a) and annual electricity output (b) for Unlimited scenario in North and South systems.

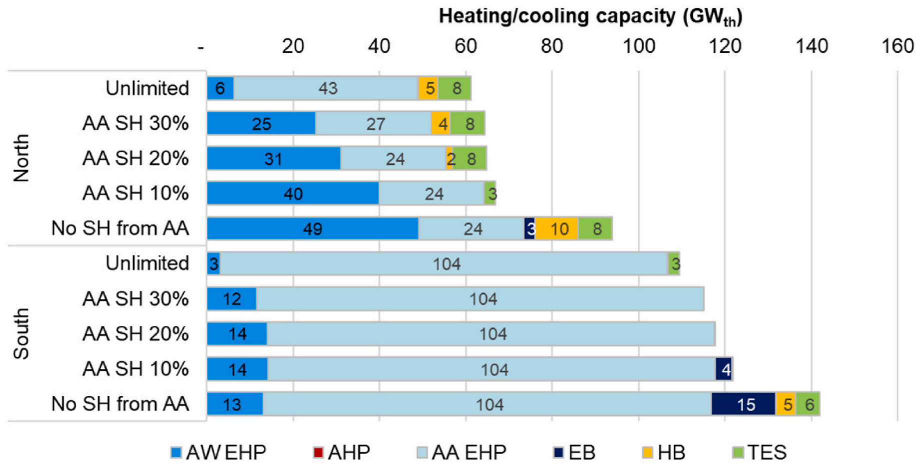

Fig. 7. Cost-optimal capacities of low-carbon heating and cooling technologies for various scenarios in North and South systems.

advancements and cost reductions in technologies like CCS could lead to different cost-optimal hydrogen pathways in the future.

3.3. Heating and cooling supply in baseline scenarios

Fig. 8 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 (as noted before, AA EHPs were not assumed 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 compensate this, as does the installed AW EHP capacity (see Fig. 7). 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, providing low-cost electricity to EBs.

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 an additional net heat demand.

3.4. Impact of heat demand profiles

Sensitivity studies carried out with higher peak heat demand assumptions resulted in different cost-optimal portfolios of end-use technologies, as shown in Fig. 9. Higher peak heat demand did not affect the technology portfolio in the "Unlimited" scenario in the South (where the AA EHP capacity is primarily driven by cooling requirements), 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.

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 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

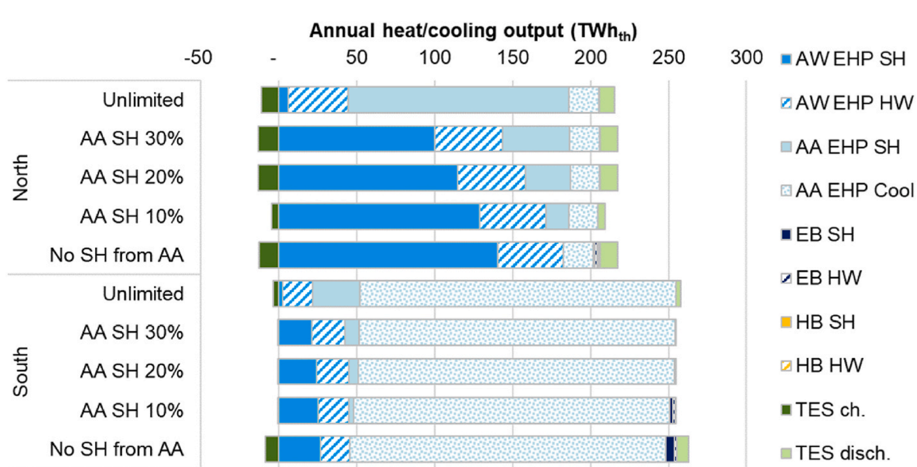

Fig. 8. Annual output of low-carbon heating and cooling technologies for various scenarios in North and South systems.

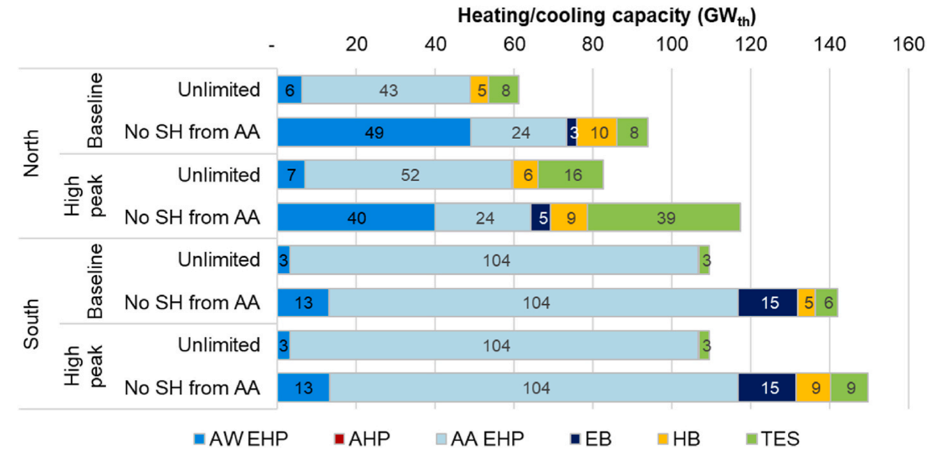

Fig. 9. Cost-optimal capacities of low-carbon heating and cooling technologies for various peak heat demand scenarios in North and South systems.

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.

When comparing the results obtained in this sensitivity analysis with the previous results published by the authors in Ref. [53] (where the same peak demand values were used), one can observe that the obtained results are similar, especially in the case with high peak and no SH contribution from AA EHPs. This provides a level of validation of the approach presented in this paper, allowing for the differences across the two approaches as elaborated in the Introduction section.

3.5. Impact of availability of LDES

Sensitivity studies with LDES being available for investment found that this option only had a marginal impact on the portfolio of end-use heating and cooling technologies, as these seemed to be primarily driven by the shape and volume of heating and cooling demand. Nevertheless, LDES did significantly affect the generation and storage mix, as it helped the system to more efficiently deal with the seasonality and longer-term fluctuations in wind and solar PV output.

The composition of grid-scale energy storage portfolio for the North and South systems is shown in Fig. 10 for the Unlimited scenario, comparing the cases with and without LDES available for investment. Fig. 10a shows the breakdown of power capacity of grid-scale storage (in GW), while Fig. 10b quantifies the energy capacity (in TWh). The results obtained for the LDES variant of the "No SH from AA EHPs" scenario were very similar to the Unlimited scenario and are therefore not shown in Fig. 10.

Fig. 10a suggests that if LDES is available at a sufficiently low cost, it may represent a viable investment opportunity in systems with high volumes of variable renewables and high, temperature-driven variability of electricity demand. In the North, 28 GW of LDES is added, reducing the volume of Li-ion battery storage by 3 GW, while in the South 43 GW of LDES is installed, displacing 15 GW of battery storage. It is also interesting to note from Fig. 10a that without LDES the cost-efficient mix of storage technologies includes both 2-h and 6-h Li-ion batteries in the South, while in the North only 2-h duration batteries are installed. This can be explained by the relatively regular variability of solar PV output (which is the dominant source in the South) with peak production at midday and zero output in the night.

The prominence of LDES is even more visible in Fig. 10b, which shows the total energy available in grid-scale storage technologies. Given that LDES has a much longer duration than battery technologies, its capacity to store energy is more than an order of magnitude greater than the energy that can be stored in Li-ion batteries. In the South the cost-optimal energy volume of LDES exceeds 5 TWh, which represents more than 1 % of total annual electricity demand in the system.

Depending on the type of LDES, it may offer additional benefits compared to batteries, such as the simultaneous storage of electricity and heat, a feature found in many thermo-mechanical energy storage options. For instance, stored thermal energy could be utilised to provide district heating; a factor not explored in this study. Hence, future research should adopt a broader multi-vector perspective on the advantages and potential applications of LDES.

4. Conclusion

In this work, a technology-to system modelling framework for

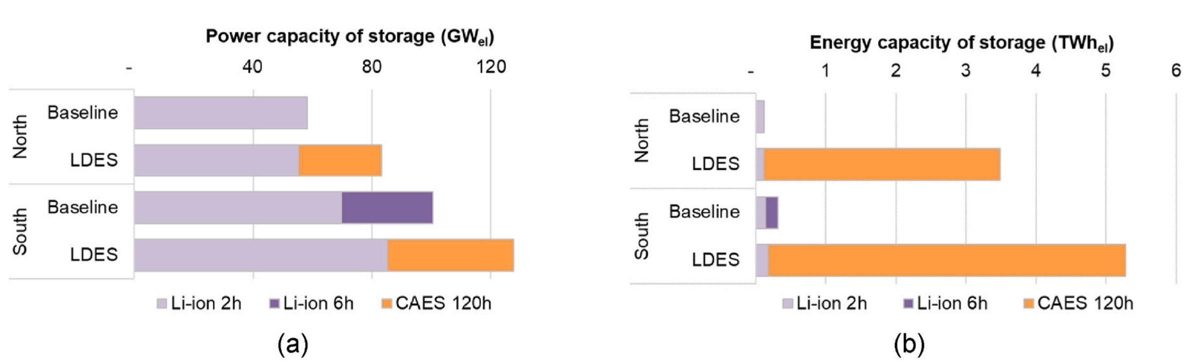

Fig. 10. Cost-optimal capacities of grid-scale energy storage technologies in terms of power (a) and energy (b) for various LDES availability scenarios in Unlimited scenario for North and South systems.

making cost-optimal choices for the capacities of low-carbon heating and cooling technologies from the energy system perspective was developed. The study focuses on two archetypal energy systems, North and South, with different heating and cooling demand characteristics as well as different availability profiles for variable renewables, resembling UK's and southern European conditions, respectively. Specifically, the North system has notably higher residential heating demand (142 TWh_{th} for space heating compared to 30 TWh_{th} in the South), while the South experiences significantly higher cooling demand (203 TWh_{th} compared to 19 TWh_{th} in the North). Differences in renewable generation availability were also considered, with the North having a higher wind utilisation factor (58 %) and lower solar PV utilisation factor (11 %), while the opposite was the case in the South (35 % and 24 %, respectively).

The whole-energy system model included various technologies (electricity- and hydrogen-driven boilers, thermal energy storage, electricity- and hydrogen-driven heat pumps), including a distinction between two types of electric heat pumps (air-to-water and air-to-air). The case studies presented in the paper show that a cost-optimal portfolio of end-use heating and cooling options will vary depending 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 air-to-air electric heat pumps, with their assumed cost and efficiency advantages over air-to-water electric heat pumps, 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 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 air-to-water electric heat pumps, displacing some of the need for electric or hydrogen boilers, as well as thermal energy storage.

Across the main case studies, a significant volume of air-to-air electric heat pumps is installed to meet cooling demand, with a minimum capacity of 24 GW_{th} in the North and 104 GW_{th} in the South system. Such high capacity is sufficient to cover almost the entire space heat demand, with a small capacity of air-to-water heat pumps and thermal energy storage used mainly for the hot water demand. In scenarios where air-to-air electric heat pumps are not included in the available technology options for providing space heating, a mix of air-to-water electric heat pumps (49 GW_{th} in the North, 13 GW_{th} in the South), electric boilers (3 GW_{th} and 15 GW_{th}), hydrogen boilers (10 GW_{th} and 5 GW_{th}) and thermal energy storage (8 GW_{th} and 6 GW_{th}) is used to meet heat demand. Sensitivity studies with higher peak heat demand resulted in much higher cost-optimal capacity of thermal energy storage, which is in agreement with the authors' earlier work [53].

Despite potential operational cost savings compared to hydrogen boilers, hydrogen-driven absorption heat pumps were not included in the cost-optimal portfolio due to their higher initial investment cost compared to hydrogen boilers, suggesting further cost reductions are necessary to make this technology a viable investment option. The availability of relatively low-cost long-duration energy storage was not found to significantly influence the cost-efficient choices for capacities of end-use heating and cooling technologies, however it did affect investment decisions in the wider energy system, changing the mix of generation and storage technologies and allowing the system to better cope with variability of renewable output.

These results are valuable for energy policy because market and regulatory frameworks should support cost-optimal technology choices. By providing subsidies for technologies that are optimal at the system level – such as air-to-air and air-to-electric heat pumps, thermal energy storage, and, to a lesser extent, electric and hydrogen boilers – policymakers can encourage end-users to make choices that are cost-effective both for themselves but also from a wider whole-energy system perspective. In order to achieve national and international carbon neutrality objectives, these policies should be accompanied by proper implementation plans to ensure timely infrastructure upgrades.

The method proposed in this paper relied on a number of simplifying assumptions, which will be addressed in future research in this area. 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 individual heat demand patterns, willingness to adopt new low-carbon technologies, and the household income profile.

In this paper a constant heat supply temperature was assumed due to a number of complexities involved with modelling the wider energy system, while also assuming the same supply temperatures (and therefore COP) for SH and DHW. Future work in this area will refine these assumptions. Also, further research will focus on the effects of diversity and extreme weather on capacity requirements for low-carbon heating and cooling technologies, where higher peaks in extreme weather conditions may require more peaking capacity. Finally, more work will be required to study other regions where the relative magnitudes of investment and operating cost for end-use heating and cooling technologies might be different from the UK-based assumptions adopted in this paper. This can involve conducting multiple correlation analyses to understand the strength of relationships between the dependent variables of the proposed model and varying assumptions specific to different locations.

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		

CRediT authorship contribution statement

Marko Aunedi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Andreas V. Olympios:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation, Conceptualization. **Antonio M. Pantaleo:** Writing – original draft, Supervision, Investigation, Formal analysis. **Matthias Mersch:** Writing – original draft, Validation, Investigation, Data curation. **Christos N. Markides:** Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marko Aunedi reports financial support was provided by Engineering and Physical Sciences Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] Department for Business. Energy and industrial Strategy (BEIS). Net Zero Strategy: Build Back Greener; 2021. https://www.gov.uk/government/publications/net-zero-strategy.
[2] European Commission. A European green deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en; 2019.
[3] Intergovernmental Panel on Climate Change. Climate change 2023: synthesis report. IPCC_AR6_SYR_FullVolume.pdf 2023.
[4] Climate change committee, sixth carbon budget. https://www.theccc.org.uk/publication/sixth-carbon-budget; 2020.
[5] International Energy Agency. Global status report for buildings and construction. https://www.worldgbc.org/news-media/2019-global-status-report-buildings-and-construction; 2019.
[6] Climate Change Committee. Heat in UK buildings today. https://www.theccc.org.uk/wp-content/uploads/2017/01/Annex-2-Heat-in-UK-Buildings-Today-Committee-on-Climate-Change-October-2016.pdf; 2016.
[7] Rosenow J, Gibb D, Nowak T, Lowes R. Heating up the global heat pump market. Nat Energy 2022;7:901–4. https://doi.org/10.1038/s41560-022-01104-8.
[8] Olympios AV, Sapin P, Mersch M, Maghrabi AM, Markides CN. A review of domestic heat pumps. Next Energy 2024;5:100163. https://doi.org/10.1016/j.nxener.2024.100163.
[9] Gibb D, Rosenow J, Lowes R, Hewitt NJ. Coming in from the cold: heat pump efficiency at low temperatures. Joule 2023;7:1939. https://doi.org/10.1016/j.joule.2023.08.005. 142.
[10] European Heat Pump Association. Heat pump sales fall by 5% while EU delays action, European Heat Pump Association. https://www.ehpa.org/news-and-resources/news/heat-pump-sales-fall-by-5-while-eu-delays-action; 2024.
[11] Thomaßen G, Kavvadias K, Jiménez Navarro JP. The decarbonisation of the EU heating sector through electrification: a parametric analysis. Energy Pol 2021;148:111929. https://doi.org/10.1016/j.enpol.2020.111929.
[12] Olympios AV, Hoseinpoori P, Markides CN. Toward optimal designs of domestic air-to-water heat pumps for a net-zero carbon energy system in the UK. Cell Rep Sustain 2024;1:100021. https://doi.org/10.1016/j.crsus.2024.100021.
[13] Dai Y, Hao J, Wang X, Chen L, Chen Q, Du X. A comprehensive model and its optimal dispatch of an integrated electrical-thermal system with multiple heat sources. Energy 2022;261(A):125205. https://doi.org/10.1016/j.energy.2022.125205.
[14] Ciabattoni L, Comodi G, Ferracuti F, Foresi G. A methodology to enable electric boiler as a storage for residential energy management. 2020 (ICCE) 2020:4–6. https://doi.org/10.1109/ICCE46568.2020.9043007. Las Vegas, Nevada, USA.
[15] Sunny N, Mac Dowell N, Shah N. What is needed to deliver carbon-neutral heat using hydrogen and CCS? Energy Environ Sci 2020;13:4204–24. https://doi.org/10.1039/D0EE02016H.
[16] Critoph R, Metcalf S. UK Summary report on IEA heat pump technology collaboration programme (TCP) Annex 43: thermally driven heat pumps. https://www.gov.uk/government/publications/fuel-driven-heat-pumps; 2019.
[17] Famiglietti J, Toppi T, Pistocchini L, Scoccia R, Motta M. A comparative environmental life cycle assessment between a condensing boiler and a gas driven absorption heat pump. Sci Total Environ 2021;762:144392. https://doi.org/10.1016/j.scitotenv.2020.144392.
[18] Famiglietti J, Toppi T, Bonalumi D, Motta M. Heat pumps for space heating and domestic hot water production in residential buildings, an environmental comparison in a present and future scenario. Energy Convers Manag 2023;276:116527. https://doi.org/10.1016/j.enconman.2022.116527.
[19] Rosenow J. A meta-review of 54 studies on hydrogen heating. Cell Rep Sustain 2024;1(1):100010. https://doi.org/10.1016/j.crsus.2023.100010.
[20] Kourougianni F, Arsalis A, Olympios AV, Yiasoumas G, Konstantinou C, Papanastasiou P, Georghiou GE. A comprehensive review of green hydrogen energy systems. Renew Energy 2024;231:120911. https://doi.org/10.1016/j.renene.2024.120911.
[21] Incer-Valverde J, Korayem A, Tsatsaronis G, Morosuk T. "Colors" of hydrogen: definitions and carbon intensity. Energy Convers Manag 2023;291:117294. https://doi.org/10.1016/j.enconman.2023.117294.
[22] Ajanovic A, Sayer M, Haas R. The economics and the environmental benignity of different colors of hydrogen. Int J Hydro 2022;47(57):24136–54. https://doi.org/10.1016/j.ijhydene.2022.02.094.
[23] Sebastian S, Wijewardane S, Srinivasan S. Recent advances in hydrogen production, storage, and fuel cell technologies with an emphasis on inventions, innovations, and commercialization. Solar Compass 2023;8:100065. https://doi.org/10.1016/j.solcom.2023.100065.
[24] Attia S, Levinson R, Ndongo E, Holzer P, Kazanci OB, Homaei S, Zhang C, Olesen BW, Qi D, Hamdy M, Heiselberg P. Resilient cooling of buildings to protect against heat waves and power outages: key concepts and definition. Energy Build 2021;239:110869. https://doi.org/10.1016/j.enbuild.2021.110869.
[25] Intergovernmental Panel on Climate Change. Climate change 2021 – the physical science basis. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf; 2021.
[26] International Energy Agency. Space cooling – analysis. https://www.iea.org/reports/space-cooling; 2022.
[27] Mastrucci A, Byers E, Pachauri S, Rao ND. Improving the SDG energy poverty targets: residential cooling needs in the Global South. Energy Build 2019;186:405–15. https://doi.org/10.1016/j.enbuild.2019.01.015.
[28] Ebi KL, Capon A, Berry P, Broderick C, de Dear R, Havenith G, Honda Y, Kovats RS, Ma W, Malik A, Morris NB. Hot weather and heat extremes: health risks. Lancet 2021;398(10301):698–708. https://doi.org/10.1016/S0140-6736(21)01208-3.
[29] Waite M, Cohen E, Torbey H, Piccirilli M, Tian Y, Modi V. Global trends in urban electricity demands for cooling and heating. Energy 2017;127:786–802. https://doi.org/10.1016/j.energy.2017.03.095.
[30] International Energy Agency. Net zero by 2050: a roadmap for the global energy sector. https://www.iea.org/reports/net-zero-by-2050; 2021.
[31] Olympios AV, Song J, Ziolkowski A, Shanmugam S, Markides CN. Data-driven compressor performance maps and cost correlations for small-scale heat-pumping applications. Energy 2024;291:130171. https://doi.org/10.1016/j.energy.2023.130171.
[32] Olympios AV, Aunedi M, Mersch M, Krishnaswamy A, Stollery C, Pantaleo AM, Sapin P, Strbac G, Markides CN. Delivering net-zero carbon heat: technoeconomic and whole-system comparisons of domestic electricity- and hydrogen-driven technologies in the UK. Energy Convers Manag 2022;262:115649. https://doi.org/10.1016/j.enconman.2022.115649.
[33] Goetzler W, Guernsey M, Young J, Fuhrman J, Abdelaziz O. The future of air conditioning for buildings. US Department of Energy, Navigant Consulting. Oak Ridge National Laboratory; 2016. https://www.energy.gov/sites/prod/files/2016/07/f33/The%20Future%20of%20AC%20Report%20-%20Full%20Report_0.pdf.
[34] International energy agency, heat pumps. https://www.iea.org/reports/heat-pumps; 2022.
[35] Olympios AV, Sapin P, Freeman J, Olkis C, Markides CN. Operational optimisation of an air-source heat pump system with thermal energy storage for domestic applications. Energy Convers Manag 2022;273:116426. https://doi.org/10.1016/j.enconman.2022.116426.
[36] Quiggin D, Buswell R. The implications of heat electrification on national electrical supply-demand balance under published 2050 energy scenarios. Energy 2016;98:253–70.
[37] Hoseinpoori P, Olympios AV, Markides CN, Woods J. A whole-system approach for quantifying the value of smart electrification for decarbonising heating in buildings. Energy Convers Manag 2022;268:115952. https://doi.org/10.1016/j.enconman.2022.115952.
[38] Peacock M, Fragaki A, Matuszewski BJ. The impact of heat electrification on the seasonal and interannual electricity demand of Great Britain. Appl Energy 2023;337:120885. https://doi.org/10.1016/j.apenergy.2023.120885.
[39] White PR, Rhodes JD, Wilson EJH, Webber ME. Quantifying the impact of residential space heating electrification on the Texas electric grid. Appl Energy 2021;298:117113. https://doi.org/10.1016/j.apenergy.2021.117113.
[40] Strbac G, Pudjianto D, Aunedi M, Djapic P, et al. Role and value of flexibility in facilitating cost-effective energy system decarbonisation. Prog Energy 2020;2.
[41] Wang Z, Roffey A, Losantos R, Lennartson A, Jevric M, Petersen AU, Quant M, Dreos A, Wen X, Sampedro D, Börjesson K. Macroscopic heat release in a molecular solar thermal energy storage system. Energy Environ Sci 2019;12(1):187–93. https://doi.org/10.1039/C8EE01011K.
[42] Shangguan Z, Sun W, Zhang ZY, Fang D, Wang Z, Wu S, Deng C, Huang X, He Y, Wang R, Li T. A rechargeable molecular solar thermal system below 0° C. Chem Sci 2022;13(23):6950–8. https://doi.org/10.1039/D2SC01873J.
[43] Aunedi M, Strbac G. System benefits of residential heat storage for electrified heating sector in the United Kingdom. In: ISGT-europe: 2022 IEEE PES innovative Smart grid technologies Conference Europe; 2022. Oct 10-12, Novi Sad, Serbia.
[44] Mersch M, Sapin P, Olympios AV, Ding Y, Mac Dowell N, Markides CN. Thermo-economic optimisation of grid-scale compressed-air energy storage systems with solid and liquid thermal storage. In: 17th Conference on sustainable development of energy, water and environment systems; 2022 Nov 6-10, Paphos, Cyprus; 2022.
[45] Kharel S, Shabani B. Hydrogen as a long-term large-scale energy storage solution to support renewables. Energies 2018;11(10):2825. https://doi.org/10.3390/en11102825.
[46] Zhu Z, Jiang T, Ali M, Meng Y, Jin Y, Cui Y, Chen W. Rechargeable batteries for grid scale energy storage. Chem Rev 2022;122(22):16610–751. https://doi.org/10.1021/acs.chemrev.2c00289.
[47] Kotzur L, Markewitz P, Robinius M, Cardoso G, Stenzel P, Heleno M, Stolten D. Bottom-up energy supply optimization of a national building stock. Energy Build 2020;209:109667.
[48] Krützfeldt H, Vering C, Mehrfeld P, Müller D. MILP design optimization of heat pump systems in German residential buildings. Energy Build 2021;249:111204.
[49] Fischer D, Wolf T, Scherer J, Wille-Haussmann B. A stochastic bottom-up model for space heating and domestic hot water load profiles for German households. Energy Build 2016;124:120–8.

[50] Dongellini M, Naldi C, Morini GL. Influence of sizing strategy and control rules on the energy saving potential of heat pump hybrid systems in a residential building. Energy Convers Manag 2021;235:114022.
[51] Vering C, Wüllhorst F, Mehrfeld P, Müller D. Towards an integrated design of heat pump systems: application of process intensification using two-stage optimization. Energy Convers Manag 2021;250:114888.
[52] Vering C, Maier L, Breuer K, Krützfeldt H, Streblow R, Müller D. Evaluating heat pump system design methods towards a sustainable heat supply in residential buildings. Appl Energy 2022;308:118204.
[53] Aunedi M, Olympios AV, Pantaleo AM, Markides CN, Strbac G. System-driven design and integration of low-carbon domestic heating technologies. Renew Sustain Energy Rev 2023;187:113695.
[54] Strbac G, Pudjianto D, Sansom R, Djapic P, Ameli H, Shah N, Hawkes A. Analysis of alternative UK heat decarbonisation pathways. https://www.theccc.org.uk/publication/analysis-of-alternative-uk-heat-decarbonisation-pathways; 2018.
[55] FICO xpress optimization. https://www.fico.com/en/products/fico-xpress-optimization. [Accessed 29 May 2024].
[56] Pudjianto D, Aunedi M, Djapic P, Strbac G. Whole-systems assessment of the value of energy storage in low-carbon electricity systems. IEEE Trans Smart Grid 2014;5:1098–109. https://doi.org/10.1109/TSG.2013.2282039.
[57] Fu P, Pudjianto D, Zhang X, Strbac G. Integration of hydrogen into multi-energy systems optimisation. Energies 2020;13:1606. https://doi.org/10.3390/en13071606.
[58] Department for Business, Energy & Industrial Strategy (BEIS). Cambridge housing model and user guide. https://www.gov.uk/government/publications/cambridge-housing-model-and-user-guide; 2015.
[59] Watson SD, Lomas KJ, Buswell RA. Decarbonising domestic heating: what is the peak GB demand? Energy Pol 2019;126:533–44. https://doi.org/10.1016/j.enpol.2018.11.001.
[60] Herrando M, Markides CN, Hellgardt K. A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: system performance. Appl Energy 2014;122:288–309. https://doi.org/10.1016/j.apenergy.2014.01.061.
[61] Davies G, Maidment G, Paurine A, Rutter P, Evans T, Tozer R. Large scale cooling systems using mains water. Refrigerat Sci Technol 2016:1076–83. https://doi.org/10.18462/iir.gl.2016.1183.
[62] Olympios AV, McTigue JD, Farres-Antunez P, Tafone A, Romagnoli A, Li Y, Ding Y, Steinmann WD, Wang L, Chen H, Markides CN. Progress and prospects of thermo-mechanical energy storage—a critical review. Prog Energy 2021;3(2):022001. https://doi.org/10.1088/2516-1083/abdbba.
[63] Scoccia R, Toppi T, Aprile M, Motta M. Absorption and compression heat pump systems for space heating and DHW in European buildings: energy, environmental and economic analysis. J Build Eng 2018;16:94–105. https://doi.org/10.1016/j.jobe.2017.12.006.