Development of Efficient, Flexible and Affordable Heat Pumps for Supporting Heat and Power Decarbonisation in the UK and Beyond: Review and Perspectives

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Abstract

Half of the global final energy consumption is related to heat, which accounts for 40% of global energy-related carbon emissions. Particularly in the UK, nearly 24 million end-users rely on gas boilers to provide heat, leading to 37% of the country's carbon emissions. Quick and successful heat decarbonisation is critical if ambitious climate goals need to be met by the mid-21st century. Heat pumps have been recognised as a key solution to reduce carbon emissions. This would instead draw carbon-reduced electricity from the electrical grid to produce heat more efficiently. Reciprocatively, the potential flexibility offered by the growing adoption of heat pumps on a (gigawatt) scale could also potentially support the deep decarbonisation of power and reduce the costs involved in the power system balancing and upgrades. By reviewing the technical development and barriers to creating high-efficiency and high-flexibility heat pumps, this study discusses how heat pumps could support the decarbonisation of heat and power with a focus on the UK system and market, which is also useful to countries in which heating is currently relying on fossil fuels. The major hurdle that mitigates the use of heat pumps - the high cost involved - and the methods to improve the economics of the technology are also discussed. If these techno-economic challenges can be overcome, electrification of heat using heat pumps could provide a route towards decarbonising heat and power and give the two communities and industries a collaborative way of tackling climate change at the root.

Keywords: Energy efficiency, Energy flexibility, Power Decarbonisation, Heat Decarbonisation, Heat pump

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1. Introduction

1.1. Background

Currently, residential and commercial buildings account for 36% of global final energy use (mainly for heating and cooling) [1]. In particular, heating accounts for over 36% of total emissions in Europe [2], over 29% in the US [3] and 30-50% in China [4]. Therefore, heat decarbonisation is a crucial step toward meeting global goals for substantially reducing greenhouse gases emissions. In the context, the UK has legislated the country's greenhouse gas emissions to reach net zero by 2050 [5]. Although the UK has made great strides towards decarbonising its power generation over the past decade (33% electricity generated from renewable sources and over 50% generated from low-carbon sources in 2018) [6], a net-zero system requires drastic changes across all energy sectors to reduce carbon emissions. Currently, heating accounts for more than 40% of the final energy consumed by nearly 24 million homes, businesses, and industrial customers across the UK, the majority of which rely on gas boilers [7]. This extremely high adoption of gas-based heating led to about 40% of total emissions in the UK [8].

Decarbonising heat is challenging. Technically, due to extremely large energy consumption, temporal variations, and fast dynamic response, heat demand exhibits very high volatility over multiple timescales (seasonal, weekly, and daily). For example, in the UK, on a daily basis, the total amount of heating energy generated from gas could be approximately four times the amount of electrical energy used in winter [9]. The peak local gas demand between 5am and 8am (mainly for space and water heating) at over +100 GW is

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10X the peak electrical demand [9]. Electrification of heat using heat pumps has been recognised as one key solution to tackle the challenge of decarbonising heat in the UK [10] and worldwide [11, 12], but the progress to date has been slow in many regions. One major reason that negatively affects the replacement of fossil fuels by heat pumps is their high economic costs, particularly capital costs. For domestic heating systems, the capital cost of a heat pump is £450-1500/kW_{th} depending the system type [13], in comparison to about £70/kW_{th} and £90/kW_{th} for a gas or oil boiler [14], respectively. Additionally, even meeting only part of the domestic heating demand in countries that currently rely on fossil fuels for heating through electrification would likely require substantial investment to upgrade the power infrastructure, such as installing low-carbon generators and expanding the current power transmission and distribution networks. Therefore, any improvements in electrified heating that might be used to tackle these challenges and mitigate infrastructure investments and upgrades must merit attention.

1.2. Why heat pumps can support decarbonisation of heat and power

Heat pumps can offer much higher electrical efficiency for generating heat compared to electrical heaters whose theoretical maximum efficiency of energy conversion from electricity to heat is capped to be 100%. The coefficient of performance (COP), which is the ratio of the useful thermal energy generated to the work required, is often used to evaluate the energy efficiency of heat pump and air conditioning systems. Usually, the COP of air source heat pumps (ASHP) and ground source heat pumps (GSHP) is 2-4 (i.e. 200-400%) and 3-5 (i.e. 300-500%), respectively [15], offering much more efficient electrified heating solutions than typical electrical heaters.

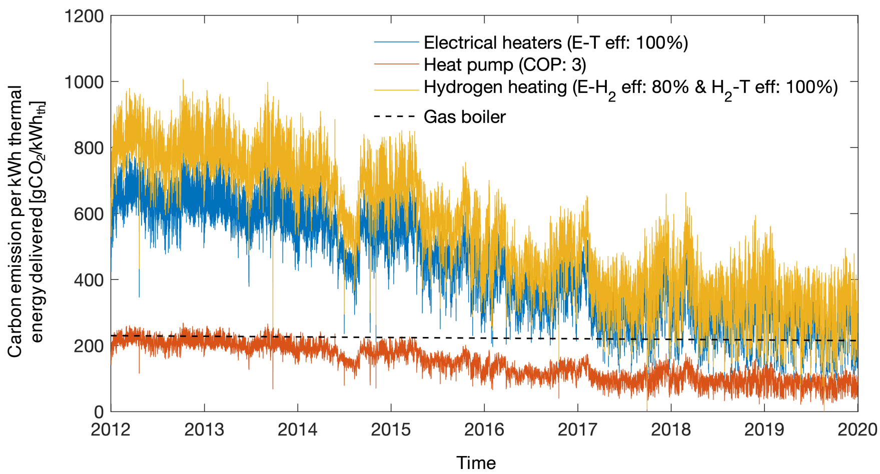

Figure 1: Estimated carbon emissions of ideal electrical heaters (the conversion efficiency from electricity to heat is assumed to be 100%), heat pump (COP=3), hydrogen heating (the electrical efficiency of electrolysis is assumed to be 80%, and the conversion efficiency from hydrogen to heat is assumed to be 100%) and gas boilers using historical data from the UK power system.

With the increasingly reduced carbon intensity of electricity, in many regions, heat pumps already have a much lower carbon footprint than gas boilers. In fact, most of the CO_2 emissions related to heat pumps stem from the consumption of the power that is produced [16]. For comparison, Figure 1 plots the trending carbon emissions of electrical heater, heat pump, and hydrogen heating in the UK (see Appendix A.1). It indicates that the carbon emissions per kWh thermal energy produced by the three heating technologies have fallen significantly since 2012 due to the carbon intensity of the grid falling, and heat pumps have the lowest carbon emissions. The estimated carbon emissions per kWh of thermal energy produced are only about one third of those produced by gas boilers [17]. Furthermore, with the increasing use of low-carbon power sources and the development of negative-carbon technologies (such as carbon capture and sequestration technologies), the instant carbon intensity of electricity may fall to zero or even below. As a result, the carbon emissions of electricity-based heating solutions could potentially also fall to zero or negative.

Heat pumps can offer flexibility to decouple heat provision from electricity consumption, resulting in a temporally shiftable electrical load on the grid. The flexibility of heat pumps could also be leveraged to underpin the power decarbonisation. A study focused on domestic heating in Austria indicated that at least 50% of domestic heating peak loads can be shifted to off-peak periods during the day for building standards after 1980 during the heating season without compromising thermal comfort [18]. This flexible power capacity could be substantial [19], and will likely expand rapidly over the next few decades. Taking the UK as an example, the current peak gas demand for heating is more than 100 GW in the median week, and about 200 GW in the maximum week [20]. If 50% of this heating demand was replaced by heat pumps with a COP of 3 on average, an additional 16-35 GW of electrical loads from heat pumps could be added to the grid. On the one hand, although heating loads are user- and region-dependent, the electricity consumption for heating likely will be highly synchronised due to the dependence of heat demand on weather conditions (e.g. ambient temperature). This may lead to substantial investment to upgrade infrastructure and thereby cause huge problems for the system operator to balance the transmission and distribution networks. On the other hand, the flexibility of such substantial power capacity offered by heat pumps on the demand side could fundamentally ease the challenge of balancing and maintaining the power system with a high penetration of variable renewable energy sources. Therefore, leveraging these electrical demands could facilitate the power decarbonisation and mitigate the scale of investiment required, if heat pumps could be optimally coordinated temporally and spatially.

1.3. The organisation in this study

Reviewing and discussing both challenges and opportunities for using heat pumps for heat and power decarbonisation, therefore, this study reviews and analyses two prospective technological improvements and their barriers in heat pump technology: 1) boosting electrical efficiency so that carbon emissions can be reduced by decreasing the use of electricity (in Section 2); and 2) catalysing electrical flexibility so that heat pump systems can use temporally shifted electricity from low-carbon and low-cost periods (in Section 3). To pave a pathway towards massive roll-out of high-efficiency and high-flexibility heat pumps, approaches are also discussed to improve the economics of the technology involved and potential areas for collaborative research and innovation by engaging various stakeholders (in Section 4). Section 5 discusses other factors that may affect the uptake of heat pumps in the transition to a deeply decarbonised future. Finally, Section 6 concludes the findings in this study and recommends potential future R&D directions.

The searching engines used in this study includes *Google Scholar*, *Web of Science*, and *Google Search* with several combinations of keywords relevant to heat pumps, air source heat pump, ground source heat pump, water source heat pump, waste heat, electrical flexibility, efficiency, decarbonisation, electrical market, electrical services, and economic cost. In addition to the above, reverse tracking is used for citations and references in several relevant papers from the search. Publications include research articles, public reports, whitepapers, websites, and open database are screened and reviewed for wider a literature and information searching.

2. The development of high-efficiency heat pumps

Energy efficiencies of heat pumps are determined by many factors. This section starts with theoretical analysis of an ideal thermodynamic cycle of the vapour compression heat pump for finding key parameters that affect the performance of heat pumps. Then, practical factors including heat sources, heat distribution, and compressors are reviewed and discussed.

2.1. The ideal thermodynamic cycle of a vapour compression heat pump

A heat pump is a heat cycle in which the working fluid (also called the refrigerant) transfers heat from a low-temperature heat source to a high-temperature sink using electricity. As shown in Figure 2a, a vapour compression heat pump system consists of a compressor, a condenser, an expansion valve, and an evaporator. The working fluid is pressurised and circulated through the system by the compressor. Then, the pressurised vapor at an enhanced temperature is cooled in the condenser until it fully condenses into a saturated liquid. The condensed refrigerant then passes through the expansion device before flowing to another heat exchanger, namely the evaporator, in which the working fluid absorbs heat from the low-temperature heat source (e.g. outdoor air in ASHPs or the ground in GSHPs) and boils to become gaseous. The refrigerant then returns to the compressor and the cycle is repeated.

Figure 2b shows the pressure-enthalpy (p-h) diagram of an ideal heat pump system. According to the labelled states in Figure 2a, 1-2 represents the compression with the associated work W_c; 2-3 represents the isobaric phase-changing condensation with the heat released to an external heat sink, Q_{out}; 3-4 represents

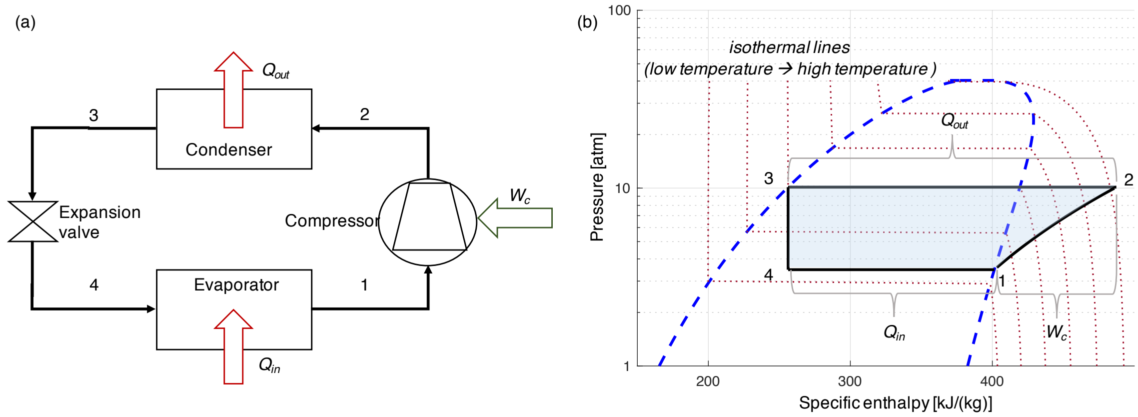

Figure 2: Illustrated diagrams of heat pump. (a): an illustrated diagram of the heat engine cycle of a heat pump. (b): an illustrated pressure-enthalpy diagram of a heat pump.

the isoenthalpy throttling process; and 4-1 represents the isobaric phase-changing from liquid to gas with the heat absorbed from an external source, Q_{in}.

The COP is a key metric to quantify the system efficiency of heat pumps, which is

$$COP = \frac{Q_{out}}{W_c} = \frac{Q_{in} + W_c}{W_c} = 1 + \frac{Q_{in}}{W} \tag{1}$$

where Q_{out} is the heat released to the heat sink (e.g. water tank or/and space), Q_{in} is the heat absorbed from the heat source (e.g air or ground), and W_c is the work consumed by the compressor. By considering the efficiency of the compressor (η_c) and the temperature range of the heat engine, the COP of the ideal heat pump cycle can be further written as:

$$COP = 1 + \frac{Q_{in}}{W_c/\eta_c} = 1 + \frac{\eta_c T_1}{(T_2 - T_1)} \tag{2}$$

where T_1 is the temperature at the inlet of the compressor, which is determined by the evaporation temperature; and T_2 is the temperature at the outlet of the compressor, which is closely associated with the condensation temperature.

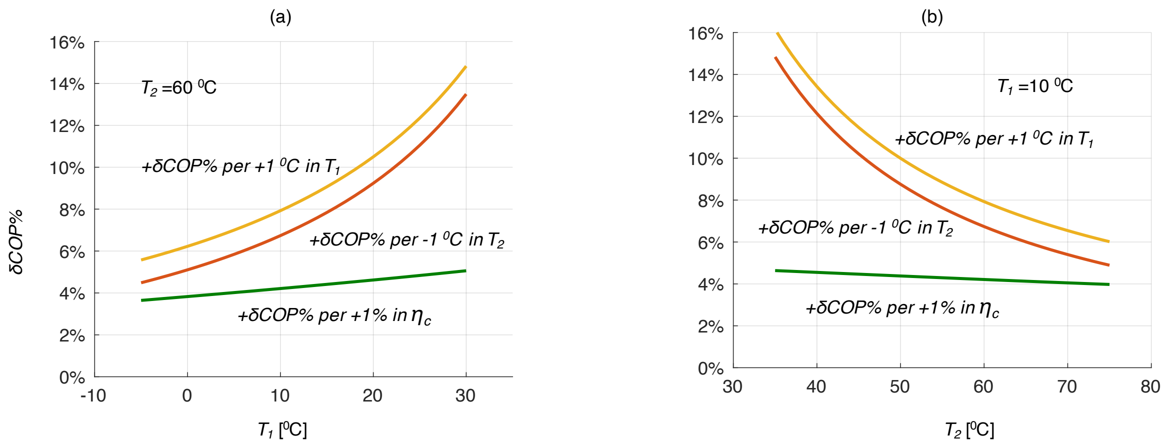

Figure 3: Impacts of the evaporation temperature, the condensation temperature and the compressor efficiency on the COP of ideal heat pumps in theory. (a) and (b) plot the sensitivity results of the evaporation temperature, the condensation temperature, and the compressor efficiency, in the systems with condensation temperature at 60 °C and evaporation temperature at 10 °C, respectively.

For the ideal heat pump cycle, if the efficiency variation of well-designed compressors is negligible at different evaporation and condensation temperatures, the difference of COP due to the three factors can be

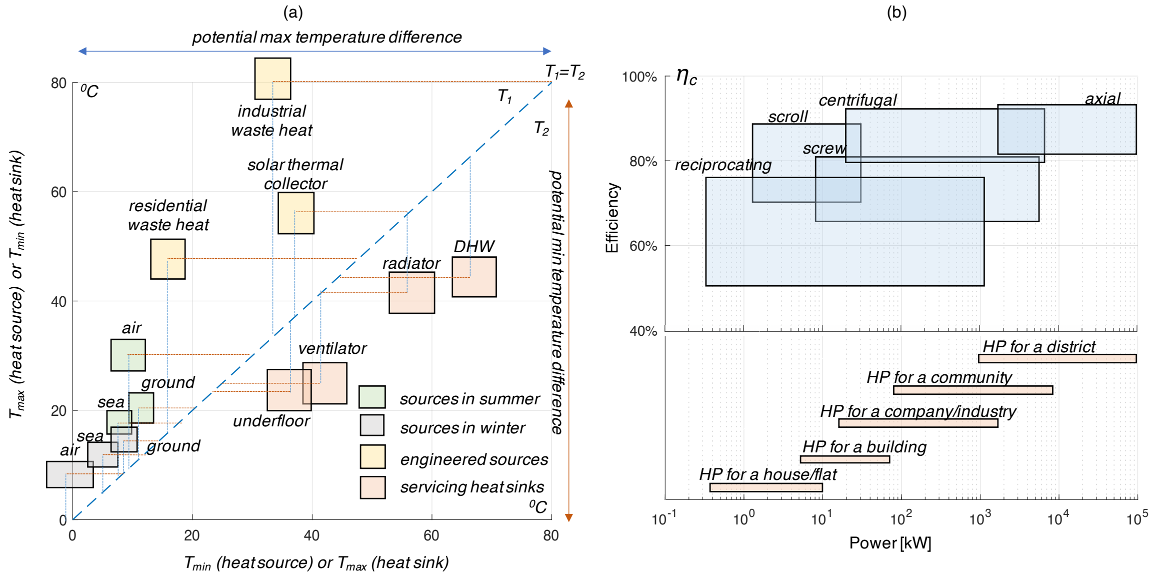

Figure 4: Temperature ranges of practical heat sources and heat sinks and technical performance of compressors. (a) illustrates the temperature range of common heat sources on the heat absorbing side and the temperature range of common heating distribution systems on the heat releasing side. (b) illustrates the common operational power and efficiency of various types of compressors. DHW: domestic hot water. HP: heat pump.

written as:

$$\delta COP = \frac{T_2\eta_c}{(T_2 - T_1)^2}\delta T_1 - \frac{T_1\eta_c}{(T_2 - T_1)^2}\delta T_2 + \frac{T_1}{(T_2 - T_1)}\delta\eta_c \tag{3}$$

Figure 3a and 3b plots the sensitivity analysis of the variations of the evaporation temperature, the condensation temperature, and the compressor efficiency in the ideal heat pump cycle, respectively. Two cases are considered here, in which one has a fixed condensation temperature at 60 °C and the other has a fixed evaporation temperature at 10 °C. It was found that increasing the evaporation temperature enhances the efficiency of the heat pump more so than decreasing the condensation temperature by the same degree. If the fixed condensation temperature is lower or the fixed evaporation temperature is higher, these positive impacts on the COP strengthen.

2.2. Approaches to improve heating efficiencies of heat pumps

Although analysis of the ideal heat pump cycle can help engineers quantitatively understand the effects of temperature and efficiency on the COP, these impacts may vary system by system in practice. This is due to the highly complex thermodynamic designs of heat pumps, unlike the simple ideal cycle analysed in Figure 3a and 3b, and numerous non-ideal effects such as non-utilised heat from superheated or supercooled refrigerant and dynamic performance of components involved. Panaras et al. derived a regression equation to estimate the COP of an ASHP system in which the impact of the heat sink temperature on the COP is more than five times the impact of the ambient air temperature [21]. Another experimentally regressed COP correlation indicated linear dependence of the COP on the temperature difference between the heat source and the sink [22, 23]. These different relationships between COP and the temperatures of heat sources indicate the complexity of predicting the performance of practical heat pump systems.

2.2.1. Operating temperature of various heat sources and sinks

Figure 4a plots the temperature range of common heat sources and heat distribution methods used in heat pumps. Most widely available "infinite" heat sources such as ambient air, ground, and surface water sources often can provide heat with a temperature from −5 °C up to 15 °C in winter and from 10 °C up to 35 °C in summer for the UK's climate. Other heat sources found in the literature include, as plotted in Figure 3c, solar thermal, residential and industrial waste heat. These heat sources usually require advanced engineering work to collect and sometimes store the heat for use in a heat pump system and so are defined as engineered sources in this study.

Hybridising these engineered sources with the conventional air, ground, and water source heat pump systems could increase the evaporation temperature of heat pumps and improve the COP [24]. In GSHP systems with a photovoltaic-thermal (PVT) collector and a borehole heat exchanger, every 3 °C increase of the evaporation temperature can lead to an increase in the COP by 9% on average [25]. Due to this additional heat from solar, the required heat from the original ambient air, ground or water source can be mitigated. Rad et al. showed that the integrated GSHP system with a solar thermal source reduced the geothermal heat exchanger length by 15% and increased the average entering fluid temperature and COP by 18.26% and 2.84% respectively, comparing to the original GSHP system [26]. This benefit of improving the COP by integrating heat pumps with solar thermal sources has also been demonstrated in ASHPs in which a 35-70% efficiency increase could be achieved [27, 28].

As the ambient air may fluctuate seasonally and spatially, these engineered sources can also be used to stabilise and improve the seasonal performance of ASHPs. Even in very cold regions where the ambient temperature is less than -30 °C, solar assisted ASHPs can have a steady COP between 2.5-3 [29], some 2-3X higher than the performance of traditional ASHPs in winter [30]. Additionally, residential and industrial waste heat sources have also been used to improve COP, including waste water from oil fields [31] and bathrooms [32], waste heat from pharmaceutical plants [33], drying systems [34], and vehicles [35], and many other waste heat sources [36].

On the heating side (i.e. the condensation side) of the heat pump system, by selecting different heat distribution methods, the condensation temperature can be varied, potentially leading to an increase in the efficiency of heat pumps. The temperatures of three thermal distribution systems are plotted in Figure 3c, including underfloor, air ventilation, and radiator systems, in which underfloor and radiator systems usually use water as the heat transfer fluid; while the air ventilation system uses air for distributing heat. Compared to traditional heating with radiators, underfloor heating can reduce the condensation temperature by about 50% due to the enlarged heat transfer area. A reduction in the condensation temperature could be achieved in heating using air ventilation but with different heat transfer performance in the exchangers.

2.2.2. Compressor selection and its performance

The third main factor directly affecting the COP of heat pumps is compressor efficiency. Figure 4b illustrates the ranges of efficiency and power capacities of various compressors, in line with the power range of heat pump systems in various scales of heating systems. Different compressors usually have quite different characteristics due to their unique geometric designs, which also results in different operational ranges. To maximise the performance of heat pumps, an appropriate compressor type is preferred.

However, selecting an appropriate compressor type and optimising compressor design are not straightforward, as more than one compressor option is normally technically feasible for a specific application. By analysing 135 combined solar thermal heat pumps for domestic heating, provided by 88 companies from 11 countries, Ruschenburg et al. [37] found that the scroll compressor dominates in the surveyed heat pump systems. Fernado et al. [38] compared scroll and reciprocating compressors in a two-stage heat pump system operating under extreme conditions. They showed that the system with the scroll compressor performed more efficiently with higher COP than the system with the reciprocating machine for pressure ratios below 7.5; for higher pressure ratios, the system with the reciprocating compressor has better efficiency and higher COP. In order to maximise the system efficiency of heat pumps in cold climates, variable-speed compressors were found to have good efficiencies at high ambient temperatures with a significantly reduced use of backup heaters at low ambient temperatures; tandem compressors, with the nominal capacity rated at low speeds, would be the second best choice [39].

Compared to volumetric compressors, velocity-based compressors usually offer high-efficiency gas compression at relatively large power capacity on the scale of tens to hundreds of kilowatts [40, 41]. These machines have been used in small-scale heat pumps for domestic heating on the scale of kilowatts to tens of kilowatts. Due to the nature of their continuous operations, velocity-based compressors have the potential to reach higher efficiencies than volumetric compressors currently used and the potential to achieve oil-free compression in these small-scale systems [42]. Schiffmann and Favrat [43] developed prototypes of the radial turbine (pressure ratio 3.3, efficiency 78%) by balancing various trade-offs for adapting the seasonal heat demand, mechanically balancing the machine, and optimising the rotor dynamics for stable operations.

2.2.3. System designs and practical implementations

Overall efficiencies of heat pump systems are integrally determined by all the factors discussed above. Table 1 lists several reviewed heat pumps in the literature, including their heat source & sink, compressor type, and the optional use of thermal energy storage (TES), which could indicate the selection of components for improving the heat pump's efficiency. Other methods to improve the system efficiency of heat pumps include advanced system designs [44], improved working fluids [24], integrated use for combined heating and cooling [45], and control for improving performance (e.g. defrosting in ASHPs) [46].

Table 1: Selective prior studies in the literature to show the different system settings for a heat pump.

Author	Heat source&sink	TES	Compressor	Sim/Exp	Findings
Arteconi et al. (2013) [47]	Air source & underfloor and radiator	Hot water	Not specified	Simulation	Using underfloor heating, room comfort can be maintained while the heating was off even without any additional heat storage unit. For houses with low thermal inertia (like radiator systems), a TES system needs to be coupled with the heat pump when a DSM strategy involves.
Plytaria et al (2019) [48]	Solar & Underfloor	PCM	Not specified	Simulation	1 Simulated COP is in the range of 5.5-6.5 approximately. 2 The use of PCM reduces the heating loads of the building by 40%, and improves the thermal comfort conditions inside the building. 3 The solar thermal plus PCM has the lowest total cost among the other systems with PCM, but with a 15-20% total cost increase.
Yao et al (2020) [49]	Solar PVT & Underfloor	PCM	Not specified	Simulation	1. The heating COP can reach 5.79 which is 70% higher than the conventional air conditioning system. 2 A 2 m^2 PV/T panel can meet the power demand of the system and heating demand of a 10 m^2 room with potentially additional power output when the solar radiation intensity is 500 W/m^2
Zhou et al (2019) [50]	Solar PVT & DHW	Hot water	Rolling-rotor compressor	Experiment	The average value of heating power, unit thermal efficiency andsystem heating COP are 4.7 kW, 120% and 6.16 respectively
Latorre-Biel et al (2018) [51]	Air source & Underfloor and radiator	N/A	Not specified	Simulation	The energy savings from the replacement of ASHPs to electric boilers compensate the environmental impact of the ASHP. This trend is more evident with underfloor heating than radiators.
Thalfeldt et al (2016) [52]	Air source & Underfloor	N/A	Not specified	Experiment	1 The heat balance of rooms was disturbed with internal gains introduced to several rooms in cycles, however during all tests, the average temperature fluctuations are minimal during night time. 2 COP during day time 2.52-2.6 and COP during night time 2.37-2.72.
Szreder (2014) [53]	Ground source & Underfloor	Hot water	Scroll	Experiment	1 COP is 3.55-3.75 with different heating systems and heating areas. 2 The heating capacity can be adjusted to match the heat demand for space heating by controlling the duration of compressor operation. 3 The heat pump failed to meet the expectations as regards the heating of hot domestic water above 45C

Wang et al (2017) [54]	Ground source & DHW	N/A	Not specified	Experiment	1 A field test was carried out for deep boreholes with 2000 m depth. 2 The average COP of the heat pump unit and the heat pump heating system are 6.4 and 4.6 respectively.
Aira et al. (2017) [55]	Ground source & radiator, DHW and pool heating	DHW	Not specified	Experiment	During the first year the average SPF is 3.94 in heating mode, 3.24 in DHW mode and 4.11 in pool mode. In the second year 3.39 in heating mode, 3.21 in DHW mode and 4.18 in pool mode.
Lu et al (2017) [56]	Ground source & Air ventilation	N/A	Not specified	Experiment	1 COP of 3.8 and 3.6 for heating and cooling were measured. 2 GSHP systems are more economical to operate than other alternatives. 3 ASHP is marginally more financially attractive than GSHP for an analysis of 20-year lifetime; however, for a design life of 40 years, GSHP provide considerably more savings than other alternatives including ASHP.
Luo et al. (2015) [57]	Ground source & Underfloor and air ventilation	Hot water	Not specified	Experiment	1 COP is estimated to be 3.9 for a typical winter day and 8.0 for a typical summer day, indicating a higher efficiency for cooling than heating. 2 The thermal imbalance needs to be seriously considered in design in order to avoid reducing in GSHP's efficiency over long-term operation
Liu et al (2019) [58]	Ground source & water from cooling tower & Air ventilation	Hot water	Not specified	Simulation	1 The use of additional water from a cooling tower in the GSHP system can remain stable soil temperature and outlet temperature of buried pipes during ten-year operation. 2 The annual average COP of the jhybrid GSHP system is 7.12% higher than that of conventional GSHP system.
Weeratunge et al (2018) [59]	Ground source & solar & Air ventilation	Hot water	Not specified	Simulation	1. Operational optimisation can reduce the operational cost using time-of-use electricity tariffs. 2 Integration of the solar hot water storage tank is beneficial to ensure the heat supply with improved performance
Zou et al (2017) [60]	Surface water & Air ventilation	N/A	Screw compressor	Simulation	1 COP of 2-6 and 3.5-4.5 were found for cooling and heating respectively. 2 A linear relationship between the daily average lake-water temperature and daily air temperature was established. 3 River water is more conducive to improving the energy efficiency of chiller unit than lake water
Kahraman et al (2009) [61]	Waste water & Air ventilation	Hot water	Hermetic compressor	Experiment	COP of 3.36-3.69 was measured.
Liu et al (2016) [62]	Ground/surface water & DHW and air ventilation	Hot water	Scroll compressor	Experiment	COP of 2-4.5 was found among different DHW temperatures.

Liu et al (2017) [63]	River water & Air ventilation	Ice storage for cooling	Screw compressor	Experiment	1 A linear relationship between the temperature of the river water and ambient air temperature. 2 The average COP of heat pump units and river water source HP system were about 7.4 and 5.2 for heating, respectively; 6.5 and 2.6 for cooling, respectively.
Zhang et al. (2019) [64]	Waste heat & Heat network	N/A	Not specified	Experiment	The total energy consumption for heating decreases with the increase of outdoor temperature, which presents a good linear relationship
Zhang et al. (2010) [65]	Waste heat & DHW	N/A	Reciprocating compressor	Experiment	1 COP was measured over 3.4. 2 M1B (37%R152a and 63%R245fa) was proved to be a suitable refrigerant for a moderately high temperature water-to-water heat pump

In general, systems operated at higher evaporation temperature and lower condensation temperature with efficient components (e.g. compressor and heat exchangers) have higher energy efficiency for heating. However, the ability to use higher quality heat source and distribute heat at lower temperature and the use of efficient components usually increase the complexity of system designs and require higher capital costs. For example, retrofitting or replacing current central heating systems (e.g. radiator heating) for fossil fuel boilers to low-temperature heating systems (e.g. underfloor heating) may need to re-plan and -install piping, both of which cause disruptions to customers. Although high heating efficiencies result in reduced operational costs, it needs time to compensate the high upfront costs. For example, Lu et al. [56] pointed out in the lifetime of 20 years, ASHP may marginally be the most cost-effective heat pump system, but GSHP has much lower heating cost if the cost analysis extends to 40-year lifetime.

Furthermore, the available space to exchange heat with the targeted heat source and sink also affects the efficiency of heat pumps. In particularly, heat sources such as geothermal and solar are space extensive, i.e. the amount of heat supplied by the heat source to the heat pump is subject to available roof or ground area in the premises of the building or household [66]. Depending on the type of heat exchangers used for extracting heat, the space requirement varies. For example, heat pumps with horizontal ground heat exchangers, trenches, helixes, baskets are highly space intensive, which are usually only appropriate for rural households and inappropriate for urban buildings. Compared to GSHPs, ASHPs require much less space for installing the outdoor unit for heat exchanges [67]. On the other end for heating distribution systems, underfloor heating systems require much larger heating transfer areas than those required by conventional radiator systems. It is also recommended to have larger radiators if the conventional heating distribution is used with heat pumps. A study indicated about 13-38% of UK homes have limited internal space for heating, which pose challenges and potentially limit the installation of low-carbon heating systems [68]. For using efficient heat pumps potentially at these space constrained households, research and innovations are needed to mitigate the space constraints.

In practical implementations, heat pumps may operate inefficiently and loss considerable energy due to a number of installation faults. Domanski et al. [69] focused on a single-family house and found that duct leakage, refrigerant undercharge, oversised heat pump with nominal ductwork, low indoor airflow due to undersized ductwork, and refrigerant overcharge have the most potential for causing degraded performance and increased annual energy consumption. These improper installation practices seem to be plausible to increase energy use by 30% [69]. The selection and installation heat distribution system also affects the heat provision. Major inefficiencies of heat distribution systems are due to poor hydraulic balancing, the building up sludge, trapped air in the system, and the formation of scales on radiator surfaces, all of which can reduce the performance of heat distribution by as high as 50% [70]. Field trials of heat pumps in the UK in the early 2010s showed some 40-50% lower COP than the brand labeled values [71], which were partially due to wrongly sized and incorrectly for set up systems for the properties, which led to operation in sub-optimal modes [72]. Additionally, the heat pumps may be damaged by extreme weather events (such as flood) or accidental activities (such as like crushing, perforations) [73]. Active maintenance and performance monitoring are needed to ensure the high energy efficiency over the systems' lifetime.

3. The development of high-flexibility heat pumps

In addition to energy efficiency, electrical flexibility is another valuable feature of heat pumps that could help facilitate decarbonisation of the power system by shifting towards the use of variable renewable energy sources [74]. The benefits of demand side response (DSR) have been recognised in improving the operation of generation as well as transmission and distribution networks, and mitigating the system balance challenges posed by rapidly increased generation from variable renewable sources [75]. The role of DSR in power decarbonisation is critical and has also been recognised as such by transmission system operator, such as National Grid in the UK, which aimed to procure 30-50% of the balancing services through demand-side measures by 2020 [76].

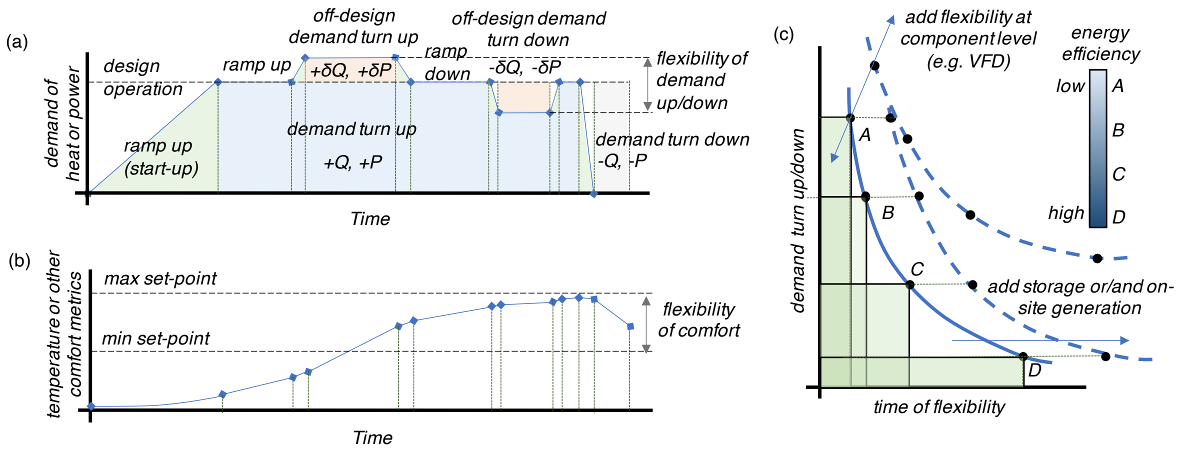

Figure 5: Factors that define and affect the electrical flexibility of heat pumps. (a) and (b) illustrate the flexibility of demand turn up/down and the flexibility of comfort, respectively. (c) visualises the power capacity, time of flexibility, and shiftable energy capacity of heat pumps with different thermal insulation levels.

3.1. Theoretical aspects of heat pump's flexibility

To understand the operational dynamics and bounds for DSR, Figure 5a and 5b illustrates the electrical and thermal operational characteristics of heat pumps. The flexible operations may include,

- ramp up/down [W/s], i.e. how fast the system can shift from its current steady operational point to another steady operational state. In particular, start-up describes how fast the system reaches the design operation from the "off" status. The ramping rates, as an electrical constraint for the flexibility, affect the dynamics of heat pumps in the participation of DSR. The electrical ramping rate of a heat pump system depends on the compressor design and the system scale. Small-scale heat pump systems that use a volumetric compressor have very fast dynamic response to power control or speed control signals. The system can ramp up to full-load within seconds [77]. Large-scale compressors can achieve a ramping rate of 10-20% per min, and ramp up to full-load within minutes of start-up [78].
- design demand turn up/down [W], i.e. how much power can be increased or decreased by turning on or off a heat pump system, which is determined by the system design. The on-off control leads to two operational points: $P \in [0, P]$. With additional flexible control such as variable speed drives (VFD), off-design demand turn up/down could be added to the flexible operation. The ability of flexibly operating the system from its design operation, resulting in a flexible operational range of the electrical power in $P_{min} \sim P_{max}$ in which P_{min} and P_{max} are the minimum and maximum power of the heat pump can operate, respectively. For volumetric compressors, the off-design range could be close to the full-range from zero to maximum power capacity; in contrast, the operational range of velocity-based compressors is limited by the surge and choke limits.

3.1.1. Differences between heat pumps and battery storage for demand side response

Heat pumps as thermal loads on the demand side potentially can offer flexibility to the power system. The thermal load's flexibility could be further improved with the use of thermal energy storage. However, DSR faces several challenges in using these electric heating loads. Unlike using battery storage in DSR, first, heat pumps, as demands or loads, are constantly constrained by their original energy service - providing heating for the thermal comfort of users. The heating performance of heat pumps should therefore not be compromised by their participation in DSR [79]. As a result, the designed thermal comfort levels strictly constrain the operational boundaries of heat pumps for DSR. As illustrated in Figure 5b, the acceptable thermal comfort levels measure out the flexibility of comfort, also called the elasticity of comfort, which determines the time for offering flexibility in a DSR event by turning up/down a heating demand. For example, in domestic heating, when heat pumps are switched off at the maximum temperature set-point, the maximum time for the DSR participation before the indoor temperature falls below the minimum temperature set-point constrains the flexible operation time for a demand turn down.

The second major difference of heat pumps from battery storage is that the thermal constraints vary from system to system (e.g. due to thermal insulation performance and user thermal behaviours) and are strongly affected by weather conditions. These factors that are external to the heat pump system, and are either difficult to control or expensive to retrofit, add complexity to aggregate or control heat pumps for participating DSR. Weiß et al. [18] showed how different types of residential buildings in terms of different construction materials and other factors, have significantly different energy flexibility. In addition, variations in heat-use patterns (e.g. occupancy in space heating or patterns of using hot water) lead to differences in flexibility of comfort [80, 81, 82], which affects electrical flexibility. The constrained comfort bounds could be significantly lifted during periods of unoccupancy [18], leading to a longer time of demand turn down at the rated power level.

The third major difference is the need for planning a commonly immediate follow-up payback energy usually after the flexibility offering. Compared to battery storage, the period between a DSR event and the payback is usually much shorter in order to ensure users' comfort level. For example, the space or water needs to be reheated back to the acceptable temperature range immediately after the DSR event. Zhang et al. [83] indicated that payback behaviours varied in different types of dwellings: the power payback is negligible in high thermal inertia dwellings (e.g. underfloor hydronic distribution); while the power and energy payback can reach 10% and 50%, respectively, in dwellings with low thermal inertia. The trials of 46 events for payback energies (35 hotel events, 11 office) showed that the payback energy is less than the turn-down energy thermal loads (the primary source of payback) produced, which is approximately 20% of the turn-down energy on average, showing an approximately 80% demand decrease [84]. However, the payback periods were sharp and narrow and such payback peaks, if synchronised, could easily cause local overloading in the distribution network [84]. Therefore, heat pump payback activities also need to be well arranged, adding complexity to the operation of heat pumps for DSR.

3.1.2. A visualised electrical flexibility of heat pumps

Figure 5c illustrates the demand turn up/down for heat pumps and the time of flexible operations in systems with different thermal insulation performances. The curve with four systems (i.e. system A, B, C, and D, representing systems with different insulation levels) indicate the trade-off between the power capacity of demand turn up/down and the time of flexible operation. The shaded area underlining the curve at each point represents the (maximum) shiftable energy for a DSR event. These systems are generic systems, which can represent buildings with varied thermal conditions, hot water tanks, and other heating applications hypothetically to meet same heat demands. Systems with a lower level of thermal insulation (e.g. system A) have a higher demand turn up/down but less time of flexible operation as they require higher heating power to compensate for the high thermal loss, and the temperature drops faster after the demand switch-off. In contrast, systems with a higher level of thermal insulation (e.g. system D) have a lower demand turn up/down but longer time of flexible operation. Similar analyses of system flexibility with various thermal insulation levels were reported with regard to domestic heating in buildings [18] and hot water tanks [85].

Therefore, variations in the flexibility of heat pump systems can be visualised by the movement of the curve. Weiß et al. [18] showed that the demand for space heating can provide at least three times the shiftable energy in spring compared to a cold winter week in January, as the flexibility curve is shifted to the right during warmer periods. The use of energy storage (including both thermal energy storage and electrical battery storage) can increase the time of flexible operation or even reduce the peak demand for heating, as indicated in Figure 5c. The demand turn down time increases with the installed thermal energy storage capacity. Adding operational points for heating, such as using a variable speed pump or multiple operational modes, can also offer significantly higher flexibility than just switching off heat pumps, which is the most common practice today [86]. These flexible operations and advanced controls can potentially move the flexibility curve to the upper right with longer time of flexibility and higher demand turn up/down, as illustrated in Figure 5c.

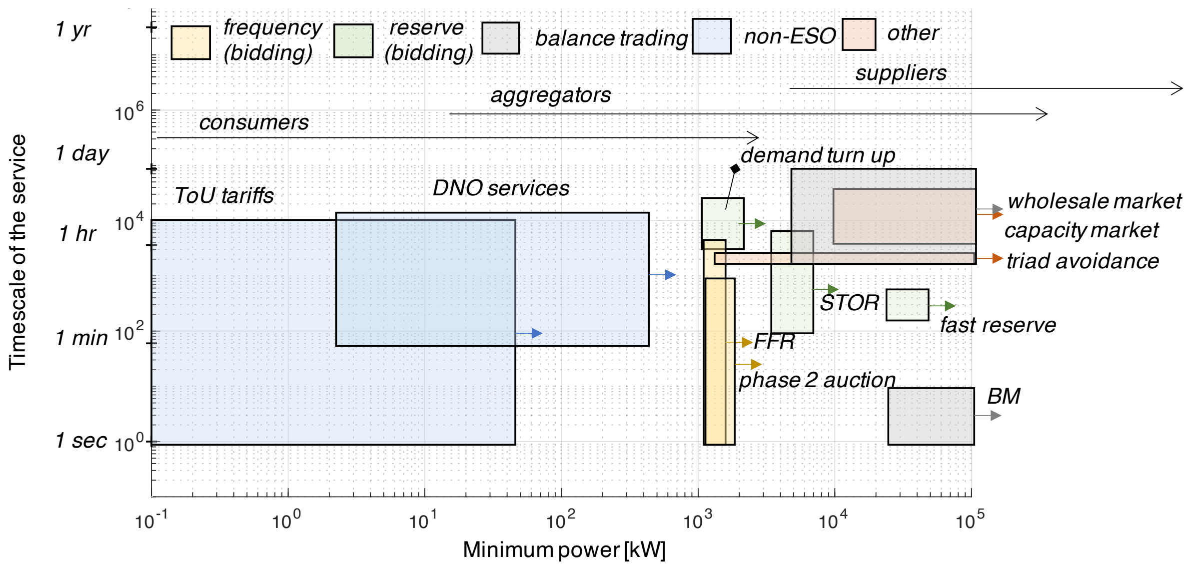

Figure 6: Potential electricity markets and DSR activities for heat pumps. STOR: short-term operating reserve. BM: balance mechanism. FFR: fast frequency response. ToU: time-of-Use. DNO: distribution network operator.

3.2. Electrical market opportunities for heat pumps

Electrical flexibility is valuable to the power system as it can mitigate the system balance difficulty and potentially reduce the cost of short-term balance and long-term infrastructure investment. Therefore, the markets are incentivising the flexibility offering through various forms of engagement. Figure 6 shows current market opportunities for heat pumps to participate in DSR in the UK (detailed information of these services can be found in Appendix A.2). The participation can be either explicit or implicit in the form of tenders (e.g. bids with offered sale prices), trades and/or contracts. Generally, heat pumps can potentially take advantages of variable electricity pricing via engagements with energy suppliers, provide services in electrical markets for ancillary service (including frequency and reserve) potentially by working with demand aggregators, and offer DNO services to support the distribution network operation. Electrical flexibility offered by heat pumps usually is not directly used for trading in the electrical market (such as the wholesale market), but the potential engagements with energy suppliers, demand aggregators and system operators will implicitly contribute to the electricity trading for balancing the power system.

3.2.1. Electrical market opportunities for heat pumps via energy suppliers

For end-users, the easiest way to participate in DSR is to contract with suppliers using time-of-use (ToU) tariffs or other similar price-based dynamic pricing rates. In particular, the ToU tariffs allow users to pay for electricity per unit consumption that varies in different blocks of time. The rate during peak periods is higher than the rate during off-peak periods. Time-based electricity rates are simple to use and make it easy to evaluate the potential savings due to energy use. The schemes can potentially also derisk energy suppliers' energy trading by increasing their prediction accuracy via smart metering devices and thereby reducing the costs associated with system imbalances. Thus, ToU tariffs have been widely exploited by operating heat pump systems smartly to reduce energy costs. Pallonetto et al. [87] minimised the electricity costs of a house using a heat pump for heating under ToU tariffs and achieved up to a 20% saving in energy bills and a 27% reduction of carbon emissions . Arteconi et al. [47] indicated that TES is very important for heat pumps with low-inertia heating distribution systems, e.g. radiators, to offer flexibility for DSR and ensure heating performance during high-price periods. Renaldi et al. [23] indicated that the CapEx (capital expenses namely the capital cost) and OpEx (operational expenses that include all operational costs such as energy and maintenance) of a heat pump system without TES are significantly higher than in a conventional system, but the integration of TES and ToU tariffs can reduce heat pump costs considerably. This reduced cost, in combination with subsidies for renewable heating, make heat pump systems economically competitive with conventional systems [23].

For energy suppliers, time-based electricity tariffs also enable them to share the price volatility in the electricity wholesale market with end-users, and particularly low-cost electricity during off-peak periods. This access to low-cost electricity can also incentivise end-users to shift their peak load to off-peak times, mitigating the balance challenges on the grid. In particular for heat pumps, innovative services or contracts for heating were proposed and trialed recently. Energy System Catapult in the UK proposed a Heat-as-a-Service model and trialed it with several energy suppliers in the UK where instead of buying units of energy in kWh, consumers buy hours of warmth for their homes [88]. This new business model could potentially create opportunities for energy suppliers to engage energy operators (e.g. exploit the electricity markets), end-users (e.g. learn about their heating behaviours), and system engineers (e.g. improve designs to adapt to the flexible setting) to provide heating services more affordably and environmentally. This new service also face challenges arisen from data communications, the coordination between different stakeholders, and the engagement of end-users. Alternatively, there are emerging pioneered ToU tariffs developed by energy suppliers that directly link the wholesale electricity market with end-users by providing a half-hour-based variable electricity pricing scheme [89]. This novel electricity pricing may improve connections and communications between various stakeholders by being influenced by the same temporally volatile electricity price in the wholesale market.

3.2.2. Electrical market opportunities for heat pumps by aggregating demands

Compared to providing demand flexibility via energy suppliers, instead, users of heat pumps may directly offer the demand flexibility by participating in the electricity markets by themselves. As shown in Figure 5c, taking the UK as an example, the ancillary services market (including frequency and reserve), balancing mechanism (BM), and capacity market accept flexible demands as independent participants but subject to their requirements of ramping rate, power capacity, and response duration. The required minimum power capacity to participate is from 1 MW to 100 MW depending on the market. This could be a large-scale heat pump system, which is a centralised heating system with a district heat network for heating buildings or communities [90], or an aggregate of many small-scale residential heat pump systems in kilowatts. Compared to the ToU tariffs, however, for all heat pump systems in residential, industrial, and commercial heating, participating in these electricity markets is much more difficult. Until now, these electricity markets have been dominated by conventional power plants, as the market designs are complex and new players face various entrance barriers. Particularly for heat pump end-users or system owners, the difficulties may include a lack of knowledge and expertise regarding trading/tendering in the complex procurement process [91], high investment for system retrofitting and prequalification for market participation [92], uncertain heating performance [93], and invisible revenue generation [92, 94]. Also, current price premiums in the electrical market may not be enough to overcome these negative impacts and uncertainties and stimulate users to shift their demands. As a result, the engagement of small-scale flexibility providers is low.

Companies that aggregate small electrical loads as a whole and professionally offer value in the markets through scale and portfolio effects, often called aggregators, can play an important role for overcoming some of these barriers. Aggregating heat pump loads seems straightforward, but it is difficult to evaluate and predict the techno-economics of the systems aggregated, as the flexibility of different heat pumps varies according to various physical (e.g. weather conditions, building envelopes, individual heat pump dynamic characteristics, and must-do payback heat), digital (e.g. smart metering and communication) and social factors (e.g. end-user behaviours). Zhang et al. [83] showed that the maximum utilised percentage of available aggregated ASHP flexibility for the Short-Term Operating Reserve (STOR) service is less than 50%. This inefficiency of the flexibility offering by heat pumps is due to the predefined standard for the flexibility procured in STOR and the variability of the aggregated ASHP clusters [83]. Heat pumps can be also aggregated with other electrical demands including battery storage as a whole to participate in ancillary services [95]. Martirano et al. [96] showed a power peak reduction up to 20% by aggregating commercial and residential units. Tacscikaraouglu et al. [97] indicated a 22% reduction of the energy demand by controlling aggregated HVAC loads with battery storage for DSR. Challenges for aggregating (heating) demands include the lack of widespread smart metering and the unadapted market design for DSR [98], which likely will be mitigated with the development of electrical markets and digitisation of the grid. However, aggregating demands for DSR events potentially lead to lowered thermal comfort and degraded performance of the systems [99]. These potential negative impacts and mitigation approaches should be further investigated .

3.2.3. Other electrical market opportunities for heat pumps

Besides aggregators and suppliers, heat pumps can also be aggregated and contracted with system operators such as transmission system operators (TSO) or distribution network operators (DNO) through direct load control. A TSO is an operator that transmits electrical power from generation plants over the electrical grid to regional or local electricity distribution operators; then a DNO is an operator that distributes electrical power further to end-users. Fischer et al. presented a pool of 284 Smart-Grid-Ready (SG-Ready) heat pumps that are controlled in four operational modes ("Off", "Normal Operation", "Recommended On", and "Forced

On") under network signals in the direct load control [86]. It was concluded that the SG-Ready controlled heat pumps offer significantly higher flexibility than conventional heat pumps [86]. Through the direct control of heat pumps by the system operators, grid frequency deviations and required reserve capacities of generators could also be effectively reduced by controlling variable speed heat pumps [100, 101].

The use of heat pumps potentially can provide other benefits to power systems. As one major strategy in electrification of heat for sector coupling, using heat pumps has the potential to support the integration of low-carbon technologies on the power network and mitigate the investment for decarbonisation. At the national level, studies have been developed to show how sector coupling by using heat pumps for heating potentially can lead to lower cost for power system decarbonisation [102]. Ashfaq et al. [103] showed that heat-pump coupling provides more benefit than the coupling using electrical-resistance heating, with 4 times more heat-storage energy and 38% less requirement for the gas-boiler energy. Coupling heating sectors through electrification can also enable a faster and deeper global CO_2 reductions before the required use of large-scale electrical energy storage for power systems with high penetrations of variable renewable energy sources [104]. This benefit is particularly important in the transition to low carbon energy systems for maximising existing energy infrastructures and available relatively mature technologies (such as heating), which may also lead to a lower cost pathway for meeting the climate goal [105]. Households can contribute about 10% of the total demand flexibility in countries with high share of electric heating or heat pumps, e.g. approximately 1-2.7 GW in Norway and 1-1.5 GW in Finland [106]. These flexibility potentially can economically substitute the investments on power generations [107]. At the distribution level, heat pumps are demonstrated to provide extra flexibility by enabling higher local PV self-consumption than the case with no heat pumps [108]. Challenges for distribution networks also emerge when the number of heat pumps are used. Protopapadaki et al. [109] indicated a greater issues of loading and voltage magnitude caused ASHPs on the studied feeders than PV and potential overloading and voltage issues could appear from 30% heat pumps in the studied region.

3.3. Approaches to use and improve heat pump's flexibility

The services that heat pumps usually provide mainly belong to ancillary services, including frequency services (such as FFR), and reserve services (e.g. demand turn up), either by directly controlling large-scale centralised heat pumps or aggregating various small-scale distributed heat pumps. To provide these ancillary services, optimal controls of these aggregated loads of heat pumps without compromising occupants' comfort are essential. Vrettos et al. [110] presented a hierarchical control scheme to enable provision of frequency control reserves using aggregated heating loads. The framework sequentially estimates reserve capacity that is allowed by the aggregated heating loads, minimises the heating loads' energy consumption for meeting the reserve provision, and dynamically optimises the heating load by tracking the changing frequency signal during the service provision. The framework was further improved by modeling the reserve uncertainty, and considering multiple actuators providing reserves in each building [111]. The framework was used to demonstrate the robust flexibility provision of aggregated heating loads (about 100 buildings) for minimising the net cost of buying electricity in the retailing market and selling band in the ancillary reserve market. Iria et al. proposed a set of stochastic optimisation frameworks for extending the biding range of aggregated loads to both demand and supply sides of the energy market [112], to the secondary reserve market [113] and the tertiary reserve market [114]. Shen et al. [115] proposed a progressive load control strategy which enables residential HVAC loads to implement primary and secondary frequency regulation. Muhssin et al. [116] proposed a decentralized dynamic frequency control algorithm for the provision of the frequency response service using a population of heat pumps and fridges. It indicated that the use of the aggregated load control can reduce the need for spinning reserve generators by 50%.

Novel demand flexibility indicators were developed to analyse the collective patterns of residential demand aggregations by using the statistical features of demand variations [117], which help aggregators to select suitable time slots during the day to initiate DSR events. New algorithms were developed to reduce the computational burden of the optimisation of bids from the aggregated loads in the electricity market [118] or to automate heating schedules intelligently [119]. Aggregates of electric heating can also be self-controlled locally to participate in the ancillary markets by using new thermostat designs [120].

Practical implementations of these advanced controls for ancillary services by aggregating heating loads is necessary to build confidence for widespread applications. Kim et al. [101] demonstrated the control of variable speed heat pumps can effectively reduce grid frequency deviations and required reserve capacities of generators using a data-driven dynamic heat pump model in a lab-scale system. Vrettos et al. [121, 122] implemented their developed hierarchical control framework for controlling commercial building to trade in the ancillary services. The real-world testing results demonstrated the ability of the proposed framework for controlling HVAC systems of commercial buildings to track a fast-moving frequency regulation signal with high accuracy and minimal occupant discomfort. Baniasadi et al. [123] proposed and implemented a model predictive control framework to schedule the uses of a DHW tank, the building thermal mass through preheating, and residential GSHP loads to off-peak periods. The experimental tests showed that the control can significantly reduce the total energy cost and overall cost by shifting up to 100% of the heating loads while maintaining the indoor temperature within a desirable comfort range. Cai et al. [124] proposed and tested a control for lab-based assessments of power frequency regulation service using variable speed HVAC (including a heat pump subsystem).

4. The values and costs of heat pumps for approaching net zero

As described in the sections above, the value of heat pumps lies in their ability to reduce carbon emissions for heating by using low-carbon electricity and their potential to support power decarbonisation efforts by offering flexibility at a scale, and reduce costs for balancing the power system and consuming energy for heat at the users' end. Therefore, heat pumps could be an enabler and facilitator of decarbonising both heat and power at their roots. Given the huge number of potential heat pump users from residential, businesses, and industry accounts, the use of heat pumps, even only partially replacing gas boilers, is essential to mitigate climate change and to help countries whose heating currently on fossil fuels, such as the UK, reach their ambitious carbon emissions goals in the mid of this century.

4.1. Benefits of heat pumps but with high costs

The technical value of high efficiency for heating not only reduces the energy bills of end-users but also help increase the efficiency of the primary energy use of the entire power system. First, the high efficiency of heat pumps can lead to less electricity being required for heating if electrified and therefore reduce the electricity generation capacity needed [125]. Secondly, because heat pumps can integrate with solar power or other renewable power sources in distributed systems, the use of heat pumps could increase the self-consumption of these distributed generations (e.g. solar PV) and reduce the need to expand current distribution networks [126]. This could improve primary energy use efficiency from the bottom up. Also, the use of heat pumps for demand-side management can help provide balancing and ancillary services, leading to avoided investment on the network infrastructure. Heat pump loads, as virtual generators, could minimise the use of conventional peaker generators that have much lower energy conversion efficiency and higher carbon emissions.

The value of the flexibility offered by heat pumps is to arm system operators with useful tools to balance the system as well as various other purposes. The total power capacity of heat pumps could be huge, on the scale of gigawatts or even over ten gigawatts. This potential power capacity is immense, which may have a huge impact on the power system. The heat pump demand has a significant diversity of power dynamics and shiftable energy capacity across different system designs, building types, regions, and user behaviours, which is challenging to manipulate but beneficial to potentially use for reducing the peak demand [127, 128]. Also, the large number of diversified heat pumps may enable system operators to explore combinations of options to solve a variety of imbalances and technical issues on the grid.

However, the major barrier preventing the adoption of heat pump technology is their high cost. As much expensive assets for heating to purchase than gas boilers, customers are likely less motivated to use heat pumps. Heat pump systems are CapEx-intensive with potentially low OpEx during their lifetime compared to currently widely used gas boilers. In the UK's market, for example, the cost of an ASHP is approximately £6,000-£8,000 and a GSHP can cost approximately £10,000-£18,000 [129], compared to the cost of a gas boiler at £1,500-£4,600 [130]. The current average gas rate and electricity rate are about 4p/kWh_{gas} and 16p/kWh_{e}, respectively. Considering a COP of 3 and 4 for ASHPs and GSHPs, respectively, the thermal efficiency of gas boilers is 90%, and with yearly heating thermal energy consumption of 15,000 kWh_{th}, the yearly operational costs for heating are £800, £600, and £667 for ASHP, GSHP, and a gas boiler, respectively. Given a 7% interest rate and 20 year lifetime, by conducting a net present value analysis over the lifetime, levelised cost of heat (LCOH, see Appendix A.3) is about 9-10p/kWh_{th}, 10-15p/kWh_{th}, 5-7p/kWh_{th}, for ASHP, GSHP, and a gas boiler, respectively. As indicated by these numbers, the lifetime cost of current heat pump systems, including ASHP and GSHP, is about 30-114% higher than current gas boiler systems. The energy efficiency benefits of heat pumps are compromised by the high cost of electricity, as the preliminary analysis in the UK indicated. This result aligns with prior studies in the literature. Similar results were obtained by Barnes et al. [131] by comparing costs of six heating systems (i.e. gas boilers, ASHP, GSHP, hybrid heat pump, direct electric heating and storage-based heating) in a typical semi-detached house in the UK. ASHP and GSHP were found to have 5 times and 9 times of the upfront cost and almost similar operational costs, compared to an equivalent gas boiler [131]. Therefore, to reduce the cost, further development and innovations for facilitating the uptake of heat pumps are needed.

4.2. Approaches to reduce the costs of heat pumps

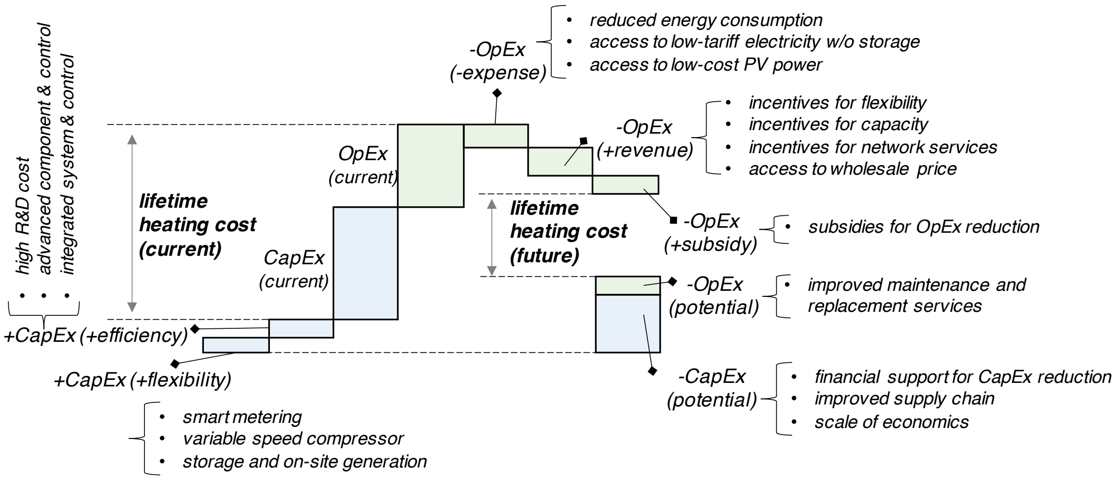

Figure 7: Breakdown of the CapEx and OpEx of current and future heat pumps.

Potential technical developments and financial supports may help improve the cost-effectiveness of heat pumps. The improved efficiency can help reduce the operational energy costs of heat pump systems. As reviewed and discussed in Section 2, there are several ways to improve the heating efficiency of heat pumps, such as advanced system design and control, e.g. integrated systems with engineered heat sources and/or well-designed compressors. However, these improvements may increase the CapEx of heat pump systems. As illustrated in Figure 7, if the reduced energy consumption with improved COP can lead to more reductions on the OpEx over the long term than the added CapEx, the overall lifetime costs of heating could be reduced. Another way to reduce the expense of electricity consumption for heat pumps is to use low-tariff electricity. In the UK, one typical ToU tariff is Economy 7, in which the minimum electricity rate is about 8p/kWh — about 20% less than the normal electricity rate. Another potential low-cost electricity is from renewable energy sources such as solar and wind. The LCOEs of these sources can be as low as about 3p/kWh$_e$ [132], and its weather-dependent nature could even reduce the dynamic price from energy suppliers to zero or even negative at times when the sun is shining or the wind is blowing strongly but there is low electrical demand. Using this lower-cost electricity during off-peak or periods with "overproduced" renewable power to heat space and water could directly translate into significantly lower energy bills for heating.

The use of these low-cost green electricity can be improved by enhancing heat pump's flexibility. Devices for receiving real-time price signals and monitoring time-variant electricity usage need to be added to heat pump systems for enabling the flexible operation of heat pumps [133]. Other options including new components such as VFD compressors, thermal and battery storage, and rooftop solar panels could be used to boost system flexibility and enable systems to participate in the DSR markets with improved power dynamics and enhanced energy capacities. On the one hand, these retrofits will necessitate increased system CapEx, which needs an optimisation to cost-effectively balance various energy needs. For example, specifically for heating, thermal energy storage is usually cheaper than storing electricity in batteries for heating, but batteries are versatile for other end-uses. On the other hand, the significantly enhanced flexibility that can potentially be actively offered in electricity markets could lead to new revenue generation mechanisms for heat pumps. These revenues could potentially reduce the lifetime cost of heat pump systems significantly. Cai et al. [124] used PJM's historical wholesale energy and frequency regulation prices, and estimated up to 48% of the electricity costs as credits gained by providing frequency services. A Heat-as-a-Service like new business model between end-users and aggregators was proposed and analysed by Kircher and Zhang [134], in which end-users buy heat or cooling outputs while aggregators own heat pumps. A developed case study of a typical US home based in the new model shows a doubled value of a heat pump investment, in which two thirds of the new value comes from accessing the lower electrical energy prices available on wholesale, and one third comes from selling ancillary services [134]. A bi-market (wholesale market and frequency regulation market) strategy of using building's thermal loads was indicated to increase the credit by 118% and reduce the net electricity cost by 14% [135]. However, with the decarbonisation progress and the increase of variable renewable on the grid, the structure and products in electrical markets may change. The potential revenues depend on on-going electrical market development in which current services and markets were mainly designed for conventional fossil fuel generators. Further case studies are needed to develop detailed techno-economic analysis for understanding the economics of heat pumps with different system designs (e.g. VFD compressors, energy storage, and rooftop solar panels) used in evolving electricity markets.

Another crucial factor for reducing the user expenses involved with heat pumps are subsidies, at least for a foreseeable future, which are essential for growing the market and encouraging mass adoption of heat pumps to reduce the carbon emissions associate with heating. Taking the UK as an example, the Domestic Renewable Heat Incentive (RHI) subsidises about 11p/kWh_{th} and 21p/kWh_{th} to users that have installed ASHP and GSHP respectively for seven years. These subsidies favor heat pumps by potentially covering all the energy costs and partially reimbursing the CapEx of ASHP and GSHP during the subsidy period (i.e. the first seven years). In the example case above, the expenses of heat pumps spent by end-users are substantially lowered by the RHI scheme, potentially resulting in similar or lower lifetime costs to gas boilers. However, barriers like high capital cost and slow administrative processing time mitigate the impact of RHI for accelerating the heat pump installation. The progress of heat pump uptake has been slower than it was expected. A new subsidy, Clean Heat Grant, which is currently on consultation to the public, is to be delivered through an upfront grant scheme for heat pumps [136]. The new subsidy scheme will reduce the upfront costs of heat pumps and reshape the cashflow of owning a heat pump. A subsidised ASHP under Clean Heat Grant may have a similar price to an equivalent gas boiler. This improved "affordable" upfront cost may encourage wider adoptions of ASHPs among end-users.

If electrification of heat steadily progresses in the next 1-2 decades in countries such as the UK, with the growing market for heat pumps and the wider adoption of the technology for heating on the demand side, the cost of heat pumps could be reduced as a result of greater economies of scale in manufacturing them and an improved supply chain. During the scale-up process, the learning of system design, installation, control, and maintenance by manufacturers, vendors, engineers, and users could also substantially improve the heat pump's onsite performance closed to their brand labelled values which will reduce OpEx and likely reduce the installation and maintenance costs.

5. Other factors that affect the use of heat pumps for supporting heat and power decarbonisation

Not limited to the UK, electrification of heat is emerging as a technologically feasible and scalable solution to reduce the reliance on fossil fuels for heating in many regions across the world. Waite et al. [12] indicated 53% of U.S. space heating energy can be electric without exceeding current peak loads and the use of heat pumps can reduce fossil fuels to as low as 20% of total heating energy supply (currently 70%). Ruhnau et al. [137] indicated the importance to plan for the significant additional demand for renewable electricity for heat and to pave the way for system-friendly direct heat electrification, in order to meet Germany's 2050 climate goal. A mix of using heat pumps, expanding district heating networks and improving building efficiency was indicated to be able to reduce the aggregated CO_2 emissions from heating by 80% in Switzerland [138]. Heat pumps are also found to be options for lowering the cost of energy system decarbonisation in Europe and across the world [139, 140]. In this context, the benefits of approaches to improve the energy efficiency, electrical flexibility and economic costs are applicable to other regions, although this study focuses on the UK's heating demand, power system, and electrical markets. These insights will help researchers and policy-makers develop technical, policy and market solutions for facilitating the uptake of heat pumps in the transition to a low carbon future.

Although electrification of heat using heat pumps seem a promising pathway to decarbonise the current gas-dominant heating infrastructure, it relies on the progress of the power decarbonisation. Formidable challenges to the power system's capacity and operations would also remain in this 'all-electric' pathway with the uncertainties arisen from the scale and progress of using variable renewable energy sources for power generation. Significant electricity generation capacities from low-carbon sources are needed to decarbonise the current electrical demands, as well as potentially added large-scale demands due to electrification of heat and transport. Many studies investigated potential decarbonisation scenarios at different locations and indicated the feasibility of using solar and wind power for having a low-cost decarbonised energy system. The National Grid (UK) [141] indicated that a double or triple of current electrical capacity is needed to meet electrical demand in a net zero, with significant generation capacities from solar and wind. Tröndle [142] estimated that the European electrical system could be supplied wholly with solar PV and wind power at a cost effective rate. Jacobson et al [143] presented a 100% renewable US grid for 2050 – 2055 only with solar, wind and hydro for power generation. Although the generation capacities are sufficient to meet the demands, such systems with high proportions of renewable generations from wind and solar would require substantially expanded capacities of electrical energy storage and interconnection to mitigate the challenges posed by the intermittence of solar and wind, which heat pumps could help mitigate the associated balancing challenges as discussed in previous sections. Further studies are needed to investigate the evolving role of heat pumps in future decarbonised systems.

Additionally, the social acceptance and recognition of heat pumps also affects the replacement of current heating systems. Compared to gas- and oil-fired boilers, the current use of heat pumps is low globally, although the uptake in the UK is even far behind that in Europe and the US. Despite the high upfront costs of heat pumps that negatively affect the low-carbon heating switching, Pan et al. also indicated that non-economic factors (including supply chain competency, market and statutory acceptance, and the reputation of manufacturers) have affected the house-builder's selection of technology for heating [144]. These factors could be improved by regulating the market and establishing high standards for the product, but it will require manufacturers, suppliers, engineers, and policymakers to remove the barriers and keep abreast of the market changes and technology development. A recent study showed a positive house price premium associated with installations of ASHPs across 23 states in the US where houses with ASHPs have a 4.3–7.1% (or $10,400–17,000) price premium on average [145]. This market-driven incentive may be strengthened with the increasing value of the whole low-carbon business sector. In addition to the increasing environmental conscious of the public, these social factors may positively affect the use of heat pumps.

Opportunities to massively use heat pumps are triggered by the urgency to decarbonise heat. Electrification of heat through the use of heat pumps is certain to be more efficient than other low-carbon approaches such as hydrogen. For delivering the same amount of heat, heat pumps are about 6-14 times higher energy efficient than using hydrogen [146]. Therefore, replacing current natural gas heating systems with direct electrification in regions if possible will lead to significantly reduced use of electricity for heating. Where direct electrification is not feasible (e.g., due to poor building insulation or poor electrification), hydrogen-based or other low-carbon fuel-based heating could provide a decarbonisation solution; however, it would require investment and development of an established hydrogen grid, with the existing natural gas grids either retrofitted or replaced, and could face considerable public perception and safety challenges [147]. Therefore, compared to building a new low-carbon gas infrastructure, improving energy efficiency of households and buildings in electrified regions likely lead to less uncertainty for the heat decarbonisation. This would reduce the heat demand and improve energy efficiency for heating at the energy end-use. The reduced heating demand by enhancing the thermal insulation of households and buildings will also positively improve the cost-effectiveness of heat pumps.

6. Discussions and conclusions

To approach the goal to substantially reduce carbon emissions toward a net zero, the heat pump is a promising solution as it could support the decarbonisation of both the heat and power industries in a reciprocative manner. Thanks to the falling carbon intensity of electricity, the carbon footprint of heat pumps has been substantially reduced over the last decade in many regions across the world. For example, the carbon intensity of electricity in the UK is about one third of the emissions per unit thermal energy produced by gas boilers. This environmental benefit will keep growing in line with ongoing decarbonisation in the wider power sector. At the same time, massive use of heat pumps could offer flexible demands on the scale of gigawatts or even beyond ten gigawatts, providing cost-effective and useful tools for system operators to balance the unprecedentedly high penetration of variable renewable energy sources in a decarbonised power system with electrified heating.

To achieve this benefit for facilitating decarbonistion of heat and power, high-efficiency and high-flexibility are essential performance goals for heat pumps. Using the definition of demand-side management that is "everything that is done on the demand side of an energy system" [148], improved efficiency could be regarded as a permanent DSR. Thus, an increased COP could translate into reduced electrical consumption, reduced carbon emissions, and potentially reduced costs over the lifetime. In contrast, greater flexibility could enable heat pumps to achieve such environmental and economic benefits by facilitating the power system balance across timescales from seconds to hours and underpinning the power decarbonisation.

However, to realise the potential of heat pumps as efficient and flexible demands on the grid, there are still many challenges. As reviewed and discussed in this paper, these may include but are not limited to complicated design and control of the components and system; high upfront cost; compromised benefits of energy efficiency due to the high electricity price; space constraints that potentially limit the installation of heat pumps; conflicts between the heat provision and the flexibility offering; and user-dependent constraints for both heating and flexibility. Tackling these challenges requires technological, economical, social, and political innovations from all the stakeholders by developing efficient systems with efficient components, smart monitoring and optimal control, innovative system integration, aggregation, and servicing.

Our specific recommendations to accelerate the development and use of high-efficiency and high-flexible heat pumps are as follows:

- To develop highly efficient component-level and system-level designs for accessing enhanced-temperature heat sources and improving the energy use efficiency for heating.
- To develop universally accepted standards for measuring heat pump electricity flexibility dynamics and energy capacity. Such standards would help to coalesce both the thermal and electrical technical communities and industrial fields in their understanding and approach to tackling the challenges in the decarbonisation of both heat and power.
- To develop autonomous monitoring and control methods and architectures for heat pumps that ensure high-efficiency heating for users and high-flexible demands for system operators. To date, most of investigations or case studies have been based on individual systems or individual aggregated systems far below the potential power capacity that heat pumps could offer. Methods and architectures for sorting and optimising these collective thermally constrained heating loads could be a game-changer.
- To develop technical solutions and innovative business models that can improve the coalescence of heat and power on the operational level for deep decarbonisation of heat and power.
- To develop new schemes (e.g. electricity tariffs) and improve market designs for encouraging the use of heat pumps and other flexible demands for offering flexibility that supports the power system operations.
- To support the growing uptake of heat pumps by providing financial supports for improving the cashflow of owning a heat pump by end-users. This supports could be direct incentives to end-users for using low-carbon heating, regulations for reducing non-commodity costs of electricity (e.g. levies and taxes), and wider supports to various stakeholders in the supply chain for building professional skills (e.g. system sizing and installation) and manufacture scales required for electrification of heat.

After all, as reviewed and discussed, there are a number of technologies that have the potential to cost-effectively mitigate these decarbonisation challenges, paving the way towards developing heat pump technologies, tackling the significant global carbon emissions from heating in buildings, providing useful DSR tools with greater demand diversity in the electricity markets, and fundamentally facilitating decarbonisation of heat and power.

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Appendix

A.1 Carbon footprint estimation and calculation

The carbon intensity of the power system is calculated based on every 5-min data of all supplies and demand in 2019 from GridWatch [149]. Therefore, the carbon intensity of the power system is,

$$CI_{sys} = \frac{\sum_i CI_i E_i}{\sum_i E_i} \tag{4}$$

where CI_{sys} is the carbon intensity of the power system, CI_i is the power density of an energy source, and E_i is the energy generation from an energy source.

In this study, the energy generation considered includes coal, biomass, combined cycle gas turbine (CCGT), open cycle gas turbine (OCGT), oil, solar, wind, solar, hydro, power from inter-connections, and other sources. The parameters of the carbon emissions of these generation methods are listed in Table 2. Although the carbon intensity of the imported electricity varies from time to time due to the relatively small amount of imported electricity in the UK power system, this estimation is reasonable as a ballpark calculation.

Parameter	**Value**
Coal [kg MWh^{-1}]	937
Biomass [kg MWh^{-1}]	120
CCGT [kg MWh^{-1}]	394
OCGT [kg MWh^{-1}]	651
Oil [kg MWh^{-1}]	935
Electricity from French [kg MWh^{-1}]	53
Electricity from Dutch [kg MWh^{-1}]	474
Electricity from Ireland [kg MWh^{-1}]	458

Table 2: Parameters used in the estimation of carbon intensity.

Therefore, the carbon footprint of heat pumps, electric heaters, and hydrogen heating can be estimated as,

$$
\begin{aligned}
CO_2^{HP} &= \frac{CI_{sys}}{COP}; \\
CO_2^{E} &= \frac{CI_{sys}}{\eta_{E-T}}; \\
CO_2^{H_2} &= \frac{CI_{sys}}{\eta_{E-H_2}\eta_{H_2-T}}
\end{aligned}
\tag{5}
$$

where COP is the COP of heat pumps, η_{E-T} is the electricity-heat conversion efficiency of electrical heaters, and η_{E-H_2} and η_{H_2-T} are the electricity-H_2 and H_2-heat conversion efficiency, respectively.

A.2 Introduction to some electricity markets in the UK

Operators in the ancillary services market, that requires minimum power capacity of 1 MW or higher to participate, are procured via a tender process. When bids are accepted, participant are paid the market price in the form of an availability fee (/hour) and a utilisation fee (/MWh), respectively, for committing to be available and providing demand flexibility if it is used. Other payments may also be available to incentivise participation.

The balance mechanism (BM) allows the system operator, i.e. the National Grid, to accept offers/bids of electricity, including generation increase/reduction and demand down/up, to balance the supply and demand in each half-hour trading period of every day at very short notice close to real time. A primary BM Unit (BMU) is the smallest grouping of generation and/or demand that can be independently metered for settlement [150]. A primary BMU usually is above 50 MW in England and Wales, 30 MW in South Scotland or 10 MW in North Scotland [150].

The capacity market is designed to ensure that sufficient reliable capacity is available by incentivising capacity to be available. Demand such as heat pumps can participate in the capacity market by providing pre-specified load reductions when system contingencies arise. Participants are paid for being available at /kW/year and for providing demand down for /kWh. Potential capacity market participants can bid for contracts in auctions held every four years or one year ahead of the delivery date, and contract for 1-year, 3-year, or 15-year agreements. DSR can only bid for 1-year agreements. Three-year agreements are for refurbished power plants and 15-year agreements are only open to new power plants [151].

According to the definition by the National Grid ESO, Triads are "the three half-hour settlement periods of highest demand on the GB electricity transmission system between November and February (inclusive) each year, separated by at least ten clear days" [152]. The National Grid identifies three Triads each year in order to apply the Transmission Network Use of System (TNUoS) charges to organisations with half-hour meters. The TNUoS charges can be reduced if demand is decreased when a Triad Alert is expected.

For more information, Albadi and Saadany presented a summary of possible DSR programs [153]. More information of the electricity markets can be found on the Nation Grid ESO's website [154].

A.3 Levelised cost of heat (LCOH)

To assess the overall cost of heat pumps, similar to LCOE (levelised cost of electricity), LCOH (levelised cost of heat) is developed, based on the present value analysis, which is

$$\text{LCOH} = \frac{\text{lifetime cost of the heat pump system, } C_{HP}}{\text{lifetime heat generated, } E_{th}} \tag{6}$$

in which

$$C_{sys} = CapEx + \sum_{i} \frac{OpEx_i}{(1-r)^i} \tag{7}$$

where $CapEx$ is the upfront cost, $OpEx_i$ is the annual running cost, r is the interest rate, and i is the year number during the lifetime.

The $OpEx_i$ can be estimated,

$$OpEx_i = \frac{c_{unit} E_{th,i}}{COP} - E_{th,i} RHI_{ASHP/GSHP} \tag{8}$$

where c_unit is the electricity rate, $E_{th,i}$ is the thermal energy consumption, $RHI_{ASHP/GSHP}$ is the subsidy rate under the RHI scheme.

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