



Hot stuff: Research and policy principles for heat decarbonisation through smart electrification

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ABSTRACT

There is a need for major greenhouse gas emission reductions from heating in order to meet global decarbonisation goals. Electricity is expected to meet much of the heat demand currently provided by fossil fuels in the future and heat pumps may have an important role. This electrification transformation is not without challenges. Through a detailed narrative review alongside expert elicitation, we propose four principles for heat decarbonisation via electrification: putting energy efficiency first, valuing heat as a flexible load, understanding the emission impacts of heat electrification and designing electricity tariffs to reward flexibility. As a route to heat decarbonisation, when combined, these principles can offer significant consumer and carbon reduction benefits. In the short term these principles can encourage the smooth integration of heat electrification and in the longer term these principles are expected to reduce the scale of required infrastructural expansion. We propose a number of policy mechanisms which can be used to support these principles including (building) regulation, financial support, carbon standards, energy efficiency obligations and pricing.

1. Introduction

The requirement for rapid decarbonisation that goes beyond existing EU targets for greenhouse gas (GHG) reduction [1] has been recognised by both academics [2] and the EU itself which is now proposing GHG emission cuts of at least 50% compared to 1990 levels by 2030 [3]. The new 'green deal' proposals from the EU recognise the requirement for a 'renovation wave' of buildings [3] reflecting the fact that around a third of energy consumption in Europe is within buildings and that 75% of heat consumption is provided by fossil fuels [4].

The European Commission has suggested that around three quarters of the required energy investment needed to meet the 2030 energy goals would need to be targeted at energy efficiency, renewable heat and power generation on or in buildings [5] highlighting the scale of the heat challenge.

A key element of European heat decarbonisation is expected to be achieved through increasing the share of electricity used for heat with electricity meanwhile being decarbonised. This is reflected in European Commission reports [6], EU funded analysis [7] and analysis at member state level (e.g. Germany [8], The Netherlands [9] and the UK [10]).

The scale and required speed of heat decarbonisation together mean the heat challenge appears to be transformative in nature and closely connected to other non-heat elements of the energy system including the power and transport sector [11,12]. So far, progress on this heat transformation is limited with a 'renewable energy gap in heating' [13] and policy support will be needed for households as low carbon heating costs are expected to be higher than fossil fuel alternatives (e.g. Netherlands [14] and UK [15]). The current German heat transition appears to be slow [16] and in the UK, it is not clear the transition has started [17]. However, as others have pointed out, heat transitions have happened before but suitable social and governance frameworks are required [18,19]. In Sweden, heat pumps are now so widespread that they are considered a key and dominating part of the heating regime [20].

In recognition of limited heat decarbonisation progress in some countries and in anticipation of the EU delivery of a 'strategy for smart sector integration', this article provides principles which can support environmentally and socially beneficial heat decarbonisation through electrification.

The article is structured as follows: following a brief explanation of

Abbreviations: COP, Coefficient of performance; ECF, Effective Conversion Factor; EPBD, Energy Performance of Buildings Directive; GHG, Greenhouse gas; PV, Photo-voltaic; RHI, Renewable Heat Incentive; SPF, Seasonal performance factor

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our research design (Section 2), the paper firstly considers potential low carbon heat technologies and the importance of electrification and heat pumps alongside flexibility in heat systems (Section 3). It goes on to consider the whole system nature of heat decarbonisation by presenting principles for how 'smart' electrification, which integrates whole systems thinking, demand reduction, demand flexibility and developments in information and communications technologies (Section 4). Section 5 considers current and relevant policies which can support the principles and Section 6 considers the key outstanding issues for heat electrification and summarises and concludes the paper. While we focus on the EU, many of these principles may be globally applicable.

2. Research design

Based on the most up to date research, the overall aim of this paper is to derive a set of principles and highlight relevant policies for integrated heat decarbonisation using electrification. These policies and principles can inform energy research and policy making in this area and support immediate decarbonisation.

This paper is effectively a 'narrative review' defined by Sovacool et al. [21, p22] as (compared to other literature review approaches) an: 'exploratory investigation of literature, involving less precise research objectives, a less systematic approach to article inclusion and allowing more in-depth qualitative insights to be obtained'. In order to reduce concerns over author bias associated with narrative reviews we have combined this review with expert elicitation. By focusing on such a timely and policy relevant topic and through providing some fundamental foundational knowledge around heat decarbonisation technologies, we also hope that this analysis is both socially useful (to policy makers and researchers) and improves basic understandings around heat electrification, a combination of attributes that may be rare in energy social science research [21].

The research design was as follows:

Firstly, relevant literature around heat electrification, policy and integration was reviewed. This included both peer-reviewed literature and grey literature using platforms such as Scopus and Google Scholar. Grey literature was selectively used as important case studies or modelling results are included in non peer-reviewed publications that could provide important and recent insights into heat electrification.

Secondly, we synthesised across the evidence identified and derived key learnings from experiences with heat electrification so far. Those learnings have then been framed as principles that can be used to either frame future research and/or future policy making.

Finally, we asked a number of heat decarbonisation experts to review the four principles developed and provide feedback on the usefulness and appropriateness of these principles¹. Expert elicitation has been used previously to consider energy innovation and futures [22,23]. Experts were chosen based on the research teams a-priori knowledge and included academics and representatives from non-governmental bodies and research organisations all with an interest in heat decarbonisation. Based on the feedback received we iteratively refined the justification and framing of the four principles and the policy options to support these principles.

There are limitations to our approach. The literature review was not exhaustive, and we have not identified all of the evidence that exists, particularly if it is in languages that are not English. While narrative reviews are known to have value, [24,25] the approach is unlikely to be exhaustive.

However, at the risk of simplification there is merit in our endeavour as it allows others to scrutinise and engage with the four principles. It also enables policy makers to pay close attention to what researchers understand are important issues to consider. A literature

¹ The six people included academics, policy experts, building and appliance experts and energy experts from non-governmental organisations.

review that relies more heavily on professional judgement, as we use, may also have value in creating responses and encouraging discussions in order to unpick key issues [26].

3. Low carbon heat technologies

By considering low carbon heating technologies, this section highlights the importance of heat electrification, in particular heat pumps, for heat decarbonisation. While a number of approaches including demand reduction can reduce emissions from heating exist, there are few methods to produce ultra-low carbon² heat for space and hot water heating and geography can have significant impacts on availability of resource. Firstly we consider a number of non-electric potential low carbon heating options.

3.1. Alternative heating options

Bio-energy suffers from various availability, land-use, and sustainability issues [27], local pollution issues [28] and has varying carbon reduction potential depending on feedstock and use [29]. Demands for biomass in high temperature uses, where limited low carbon options are available, such as industry may limit availability further. Overall, this suggests the availability of sustainable biomass for heating may be limited.

While able to produce ultra-low carbon heat, solar thermal technologies are limited by their ability to produce heat on-demand and are expected to play only a limited role in Europe [7] and higher latitudes unless combined with inter-seasonal storage or a back-up heat source [30,31].

Deep geothermal technologies require access to suitable heat sources [32] and suitable heat demand, often along-side district heating networks [33] suggesting limited geographic potential for this technology.

Converting gas grids to hydrogen is seen by some including the UK Government to be a possible low carbon heat technology [34] but a lack of sufficient practical experience alongside a requirement for carbon capture and storage for cost-effectiveness [10,15] means this option is uncertain. Concerns have also been raised over the promotion of hydrogen by gas industry incumbents³ at the expense of other options [35]. But even in light of this uncertainty, and in light of questions over the availability of 'excess-electricity' for hydrogen production and the future availability of hydrogen imports, there are still areas where clear heat decarbonisation options exist such as electrification in off-gas grid areas [36].

While the ideal future heat technology mix is uncertain, Chaudry et al. (2015) [37] suggested that for the United Kingdom some common emerging messages from heating analysis can be identified including:

- A need to reduce heat demand;
- Growth in district heat networks;
- A substantial level of electrification.

Chaudry et al. (2015) [37] also suggest the three essential elements for reducing emissions in heat are:

- Reducing heat demand;
- Reducing the carbon intensity of the energy carrier;

² The term ultra-low carbon is used here to describe technologies which have the potential to reduce emissions compared to fossil gas combustion by over 80% based on analysis of heat technologies from POST, (2016). 80% is seen as a significant GHG reduction potential which can support goals for net-zero emissions.

³ A working definition of the term incumbent can be found in Lowes et al. (2017)[139]

- Deploying low carbon heat technologies.

We focus on the current potential of heat electrification using heat pumps, explored in the following sub-section and build on the elements highlighted previously.

3.2. Electrification and heat pumps

As described in Section 1, electricity is widely expected to become an increasingly important energy vector which can decarbonise heating. Heat electrification requires an expansion of the electricity sector alongside its decarbonisation.

Through a near 100% conversion efficiency, resistive heating technologies which can convert electricity directly to heat will almost directly reflect the carbon intensity of the electricity they use. Heat pumps, through their effective conversion factor (ECF) or 'coefficient of performance'⁴ (COP) can effectively reduce the carbon intensity of the electricity they use by a factor of the COP and are seen to be particularly important.

Heat pumps can extract waste heat, heat from water sources (hydrothermal or water source) ambient heat from the ground (ground source) or heat from the air (air source or aerothermal). Using a refrigeration cycle, heat is transferred from environmental sources into areas where it can be used for useful work such as heating spaces or hot water. As the heat produced from heat pumps is classed by the EU as renewable, heat pumps can contribute to recast 2030 Renewable Energy Directive. The directive requires 32% of all EU energy consumption to come from renewable sources and 40% of this renewable energy is projected to come from heating and cooling [38].

Global market data on heat pumps is complex as it often also considers air-conditioning data. Heat pumps can vary in scale with large heat pumps feeding district heating networks and small heat pumps providing heat to single buildings or even single rooms. EU market data suggests a growing heat pump market with highest levels of heat pumps sold in France, Italy, Spain and Sweden⁵. The majority of the existing EU heat pump stock is air source heat pumps which provide warm air (air to air) followed by air source heat pumps connected to wet heating systems and then ground source connected to wet central heating systems⁶.

Heat pumps can also be used to provide cooling. This function can be performed through the reversal of the refrigeration cycle. Because heat pumps simultaneously produce a heating capacity and a cooling capacity as part of their cycle, if heating and cooling demand is needed at the same time, system efficiencies can be increased by combining these energy functions [39]. While this may improve the economic efficiency of heat pumps, its practical uses may be limited to buildings with high simultaneous cooling and heating demand. As shown below in Fig. 1, the emissions intensity of electricity across Europe and in relevant Northern EU countries has reduced significantly over the past two decades as a result of the growth of renewable electricity generation and the removal of coal generation. With further renewable electricity capacity deployment, including but not limited to wind (including offshore) and solar photovoltaics (PV), the carbon intensity of electricity it is likely to reduce further⁷.

UK electricity carbon intensity has reduced to less than 200gCO₂/kWh which is now below carbon emissions from natural gas combustion

at 204gCO₂/kWh [41]. At an extremely conservative seasonal performance factor (SPF) of 2⁸, a heat pump operating in the UK and across many EU countries can already offer significant carbon benefits compared to a gas boiler and electricity emissions are likely to reduce further.

For the EU, it is not apparent that any existing technologies other than heat pumps can be delivered to buildings which can provide their entire heat demand across the year while also decarbonising heat. Solar thermal could also be deployed rapidly. As described previously however, for most households and in particular those at higher latitudes, a reliable source of heat such as a heat pump will be needed and this and the associated system will need to be sized to ensure heat demand can be met on a day with low solar irradiation. This could then negate the value of solar thermal. While solar (PV) may face similar issues to solar thermal in that maximum generation may not be during the months where heat demand is highest [42], PV may be better suited to buildings/energy systems which include heat pumps because any excess generation can be exported to the wider grid at times when it is sunny and warm.

Further still, if low carbon gas can be delivered at scale, even in the UK, a country with large gas network infrastructure, a significant proportion of heat electrification is expected for decarbonisation [43].

Heat electrification may also be important for the future development of district heat networks. The growth in district heating networks, whereby heat is transferred directly to buildings in steam or hot water, is expected to be an important element of heat decarbonisation. The Heat Roadmap Europe studies suggested that across the 14 European countries considered, district heat networks could cost-effectively provide over half of heating demand [7]. Electricity and heat pumps appear likely to be an important source of heat for low carbon heat networks with heat pumps and electricity already used for heat networks in Sweden [44] and their usage is likely to grow in order to replace fossil fuels [45].

For these reasons, and because of the expected continuation of the reduction in the carbon intensity of grid electricity, our analysis focuses primarily on decarbonisation using heat pumps.

3.2.1. Electrification integration

The large scale deployment and use of heat pumps will have system impacts but these impacts can be minimised. Nonetheless, heat pumps are at least initially, likely to have higher upfront costs than boilers and require heating systems and buildings to be suitable for lower flow temperatures than associated with boilers [46].

Heat electrification also introduces an array of wider energy system issues. As well as increasing electricity demand in general, the unmanaged electrification of heat, alongside significant utilisation of renewable sources for power generation will result in variability and uncertainty in electricity supply as well as substantially higher peaks for electricity demand [47].

A number of studies have been carried out to investigate the impacts of the heat electrification on the electricity supply infrastructure. Lund (2018) [48] projected that the total electrification of heat in Denmark would require a 2–4 times expansion of the electricity grid and significant investments in electricity storage capacities unless heat decarbonisation also included thermal storage and the use of heat networks. Strbac et al. (2018) [10] estimated that the electrification of the heat in GB to achieve a zero emission energy system could lead to an

⁴ COP is measured as a positive number reflecting the total heat output compared to electrical input. E.G. a COP of 3 means for each unit of electricity input, 3 units of usable heat are produced.

⁵ This includes heat pump systems which can definitely provide heating but may also provide cooling.

⁶ Thanks to the European Heat Pump Foundation for providing market data.

⁷ Optimal electricity technology mixes will vary significantly depending on renewable resource/climate.

⁸ 'SPF is a measure of the operating performance of an electric heat pump heating system over a year. It is the ratio of the heat delivered to the total electrical energy supplied over the year'. This includes the electricity used for pumps and direct electric heating which can be a significant element of demand [140]. 2 was the lowest recorded SPF in the most recent heat pump UK field trial [141]. Seasonal Coefficient of Performance (sCOP) refers to only the performance of the heat pump over the course of a year and does not include associated electricity use.

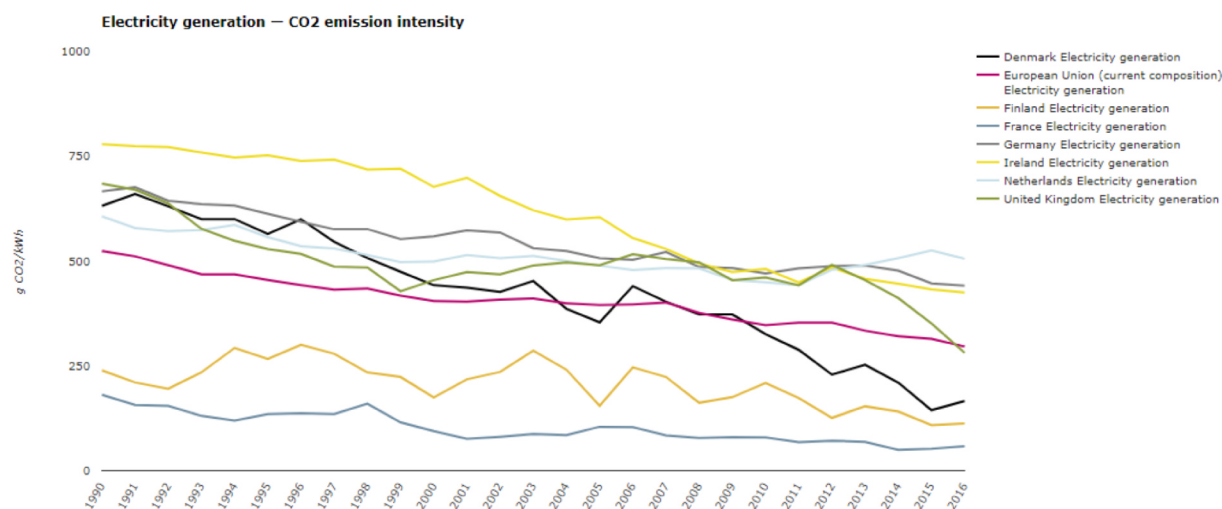


Fig. 1. Average annual emissions intensity of electricity across EU and various EU countries gCO_2/kWh [40].

annual system cost of £92.2 bn (lower than the cost of widespread deployment of hydrogen (£121.7 bn)). However, Strbac et al. (2018) [10] concluded that a hybrid approach in which electricity and hydrogen work together in a complementary way could result in an even lower annual system cost of £88bn.

Fundamentally, prior analysis suggests that utilising flexibility already present in energy systems can reduce the costs of heat electrification. Costs could be reduced by employing system flexibility (e.g. energy storage, demand side response) enabling peak shaving and supporting demand and supply balancing [11].

As well as being used within electricity systems, if flexibility can be used around heat (and hot water) demand there are likely to be further system benefits. One study alone suggests that employing smart heat pump control in combination with thermal storage in 50% of buildings in north west of England could result in the avoided cost of £3.2bn for upgrading the local electricity network [49].

Exploring these integration issues, and investigating how best to manage and maximise the benefits of heat decarbonisation is the focus of much of the rest of this article.

4. Principles for smart heat decarbonisation

Based on our review, and subsequent expert elicitation, the following sub-sections propose four policy and research principles for smart heat decarbonisation. The principles can be applied to immediately drive heat decarbonisation through electrification while minimising energy system impacts and costs for consumers. These principles can inform readers and researchers and can also be employed by policy makers working to decarbonise heat systems. The principles are supported by a detailed literature review. Specific policy measures which can support these principles are considered in Section 5.

4.1. Principle 1: Fabric efficiency should be a primary objective

The deployment of energy efficiency measures can offer numerous energy system benefits. By reducing heat demand, emissions can be directly reduced. Additionally, energy efficient buildings can be heated using lower flow temperatures which can lead to further efficiency benefits of both low carbon and fossil fuel based systems further lowering emissions [50].

Heat pump based systems also generally operate at lower flow temperatures than boilers [51] and so relatively energy efficient buildings are a pre-requisite for electrification based on heat pumps. Furthermore, the more energy efficient a building, the less quickly it will lose heat. Efficient buildings may therefore be able to be 'charged

up' (warmed or pre-heated) in order to become significant sources of flexibility.

Through focusing on heat demand reduction, taking an 'efficiency first' approach can cost less or deliver more value than investing in infrastructure or supply side measures [52]. This idea has become a pillar of EU energy and climate policy [53]. Indeed it's apparent for the UK that reducing demand for heat and then electrifying demand would be much cheaper than only electrifying heat because this reduces the need for additional generation and network capacity [54]. This view is also reflected in a recent IEA analysis which proposes three principles for buildings; firstly create 'sufficiency' through avoiding unnecessary energy demand in new buildings, secondly deliver radical advances in efficiency using fabric measures (i.e. physical modifications to buildings which reduce heat losses) and finally replace fossil fuel heating systems with low carbon solutions [55]. Modelling of four EU countries (Czech Republic, Croatia, Italy and Romania) suggests that 30–50% of heat demand could be avoided through energy saving measures for heat decarbonisation [56].

Nationally focused studies suggest a similar requirement for the deployment of energy efficiency measures in order to support heat decarbonisation and electrification. In Germany the cheapest heat decarbonisation route appears to employ significant energy savings through energy efficiency [57] and as well as reducing costs, energy efficiency can reduce wider technological challenges [58]. UK statutory advisor the Committee on Climate Change has previously stated that houses in the UK are not 'fit for the future' and decarbonisation requires major renovation works [17]. Even ignoring decarbonisation, 25% of current UK domestic energy use could be saved cost effectively by 2035 [59] and there is likely to be cost effective energy efficiency potential elsewhere.

4.2. Principle 2: The flexibility of heat loads can provide significant energy system value

That the electrification of existing fossil fuel heat demand would increase the peak capacity and throughput requirements for electricity systems should come as no surprise and indeed, expanding electricity systems are a principle feature of global decarbonisation [60]. However, with this expansion for heating there will be challenges and specific issues around electricity generation and network capacity have been highlighted by various (often incumbents and fossil fuel) interested parties in the Netherlands and the UK [35,61].

Through reducing heat demand, and reducing the capacity of heating systems, Principle 1 can reduce both throughput and capacity requirements on the electricity system compared to a counterfactual

where no energy efficiency measures are installed. However, energy system flexibility can potentially reduce or even eliminate potential capacity issues associated with heat electrification by utilising existing system headroom⁹. If possible, flexibility can increase electricity asset utilisation rates, support renewable electricity integration and therefore potentially reduce consumer costs.

Analysis of the UK energy system has shown that flexible power system operation which balances demand side response, interconnection and peaking plant can produce lower cost electricity decarbonisation [62]. Further UK analysis has highlighted the benefits of flexibility at high levels of heat and transport electrification with potential multi billion pound annual savings [11]. Flexibility is also potentially able to support greater levels of intermittent renewable electricity integration providing cross-system benefits [10]. Specific attention has also been paid to pairing heat pump demand with wind energy across Europe [63].

While most past attention has been paid to specific within-electricity-system flexibility, the scale of heat demand as a proportion of total demand means that it could become increasingly important. Further still, the storage of heat within the thermal mass of buildings or as hot water in water cylinders (tanks) can be much cheaper than storing electricity [64]. Others have also highlighted the potential for energy storage within heat networks which contain high volumes of water [65].

A comprehensive review of '4th generation' heat networks conducted by Lund et al. (2018) [66] shows that lowering the supply temperature of heat networks opens up opportunities for utilising large scale heat pumps. Furthermore, as a result of the availability of large scale and cheap thermal storage in heat networks, the electricity consumption of power-to-heat technologies can be decoupled from the heat demand supporting the operation of the wider electricity system. Within these networks, the potential for trading of heating and cooling could further optimise local systems.

Fischer and Madani (2017) [67] propose three key routes through which heat pumps can offer services to flexible electricity systems: grid benefits such as capacity reductions and voltage control, price benefits through making the most of variable pricing and support for renewable electricity integration through load shifting. Analysis of Denmark has suggested that a high penetration of heat pumps in an electricity system dominated by wind generation can reduce peak load requirements providing system and consumer benefits [68].

While electricity demand for heat pump systems can potentially be flexed, this is not necessarily the case for many systems installed and based on standard current user practices, if 20% of UK homes were fitted with heat pumps this could add 14% (7.5GW) to peak electricity load [69]. It should be noted that often heat pumps are not set up to deliver on demand i.e. at morning and evening peak but instead they provide heat to homes across the day and night [69]. This implies that heat pumps could smooth heat demand across the day and suggests the potential for flexible operation of many heating systems. Muhssin et al. (2018) [70] demonstrated how thermal inertia of buildings equipped with heat pumps can be used to control the electricity consumption for heating and consequently provide dynamic frequency response to the GB power system.

Reducing heat demand as proposed through principle 1 increases the capability of buildings to act as thermal stores [71]. The general requirement for hot water storage tanks in heat pump systems which do not normally produce instantaneous hot water increases the potential for load shifting as hot water can be heated at a different time to when it is used. Ignoring hot water, it has been reported that heat pump heated buildings can have heating turned off for multiple hours without affecting thermal comfort [72]. Data synthesis for the UK Government has suggested significant potential for heating 'off' periods in more

energy efficient buildings based on measurement elsewhere including:

- Denmark: 5–6 h at 5 °C outside temperature and 2–3 h at –12 °C outside temperature;
- Switzerland: all house types considered could achieve off-blocks of more than 6 h, with the most highly insulated buildings achieving off-blocks of more than 12 h;
- Austria: length of off-blocks at temperatures above –7°C were between 5 and 10 h but fell rapidly below –7°C [73].

In order for heat pumps to be operated flexibly, it's likely that some sort of advanced control and possible user engagement will be needed. The remote control of heating systems has reached significant market penetration levels, however, understanding the consumer interaction with such controls and their use to support flexibility appears an area where further research may be required.

Combinations of technologies in households such as solar PV, electricity batteries and heat pumps may be able to provide further system flexibility but the performance and economics are complex and vary depending on the size of various elements of the system such as storage and PV capacity [74]. Domestic scale heat batteries based on phase change materials may also be able to provide heat demand flexibility [75] and these technologies are currently being supported by the Scottish Government [76].

Overall, through valuing the potential flexibility of heat load, system benefits associated with renewable power integration, flexibility and asset use maximisation could have significant system and consumer (cost) benefits.

4.3. Principle 3: How and when heat is electrified can have significant emission impacts

As shown previously in Fig. 1, electricity greenhouse gas emission intensities are reducing across Europe. However, increasing electricity loads through electrification will lead to power sector impacts and understanding how heat electrification could best be managed in order to maximise carbon reduction is vital.

GHG emissions associated with a unit of electricity vary depending on what type generation plant is connected to the system and what is generating. Fossil fuel generating technologies have higher GHG emissions than renewables and while coal generation may be the most GHG intensive, followed by oil then gas, emissions from specific fuels can vary significantly [77]. As shown in Fig. 2 which shows the changing UK electricity generation capacity, a rapid growth in renewable capacity has taken place since 2010 at the same time as conventional fossil fuel capacity has reduced. Overall this means that the UK carbon intensity of electricity has fallen but it also means that the short-term emission intensities of power generation vary significantly which much of this variation a result of renewable output.

In electricity systems with a high proportion of renewable generation, renewables tend to always generate when they can and because of their short run marginal costs (low opex), wholesale electricity prices can be lower when there is a high degree of renewable electricity generation [78]. Because renewables tend to run when available and at these times power prices can be depressed and fossil fuel plant may be displaced, times of low pricing are likely to also be times of low emission intensities¹⁰.

GHG emission intensities are also affected by the type and quantity of fossil fuel generation. While coal generation has largely been removed from electricity generation in the UK and the system is primarily comprised of renewables and gas, gaps are also filled by coal

¹⁰ This is assuming that renewables always have lower life-cycle emissions than fossil fuel which may not be the case for certain technologies classed as renewable such as biomass power generation [142].

⁹ This is certainly possible under initial limited electrification.

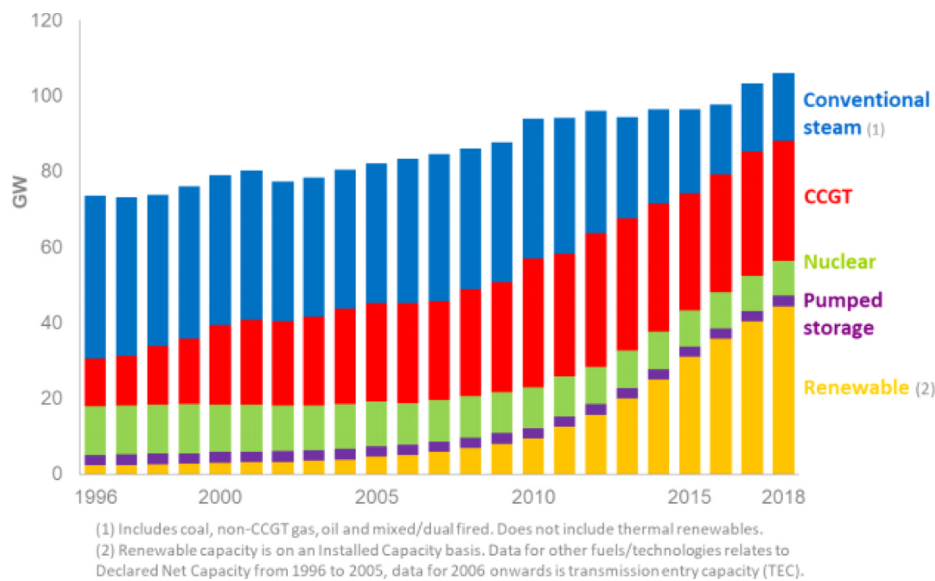


Fig. 2. UK electricity system installed capacity [79] (p29).

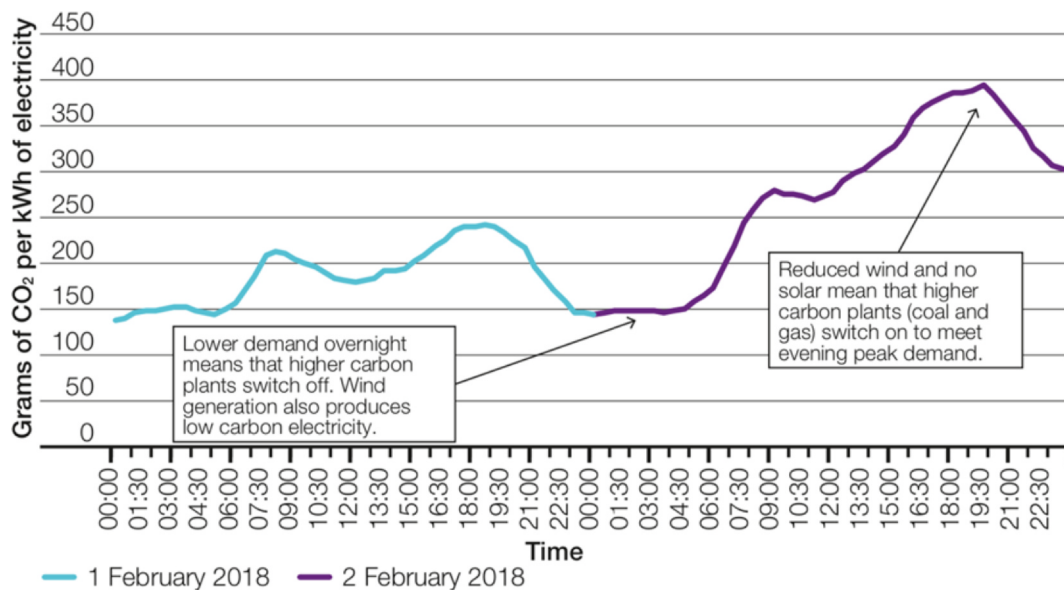


Fig. 3. The variation and causes in changes in UK electricity CO₂ emissions intensity over two days in 2018 [81].

generation, open cycle gas turbines and oil generation [80]. The GHG emissions associated with electricity can therefore vary greatly over time. Fig. 3 shows the variation in emissions over two days in the UK with both morning and evening peak demands resulting in higher intensities on both days as well as wider changes linked to renewable generation.

The flexibility of heat highlighted by principle 2 could be used to optimise heating systems based on the carbon intensity of the grid as well as prices although both may be related. The potential for smart and remote control of heat pumps is already possible with products designed in countries with smart tariffs already able to take advantage of time of use pricing e.g. in Sweden [82] and third parties creating software and hardware platforms for heat pumps to respond to market signals (e.g. Homely Energy, 2020).

While the current dynamic response of heat pumps is linked to price and carbon intensity may be reflected in time of use prices as a result of carbon taxes [84], it will be possible for heat pumps and/or their owners to respond to emissions signals, as well as or rather than solely pricing and this could drive further emissions savings.

4.4. Principle 4: Tariffs can be designed to reward flexibility

Variable time of use (ToU) tariffs which can reflect changing wholesale prices (and potentially electricity greenhouse gas intensity) can financially encourage consumers to move electricity demands outside of certain periods. If utilised, they can reduce consumer bills directly and support wider energy system cost reduction through for example, greater asset utilisation [85]. Price can have significant impacts on when electric vehicles are charged at home [86] and UK electric vehicle users are already moving electric vehicle charging out of peak hours [87].

Eid *et al.*, (2016) [88] highlight 3 approaches to time based pricing options.

- Fixed electricity prices for different time blocks within a time period, such as a day;
- Variable pricing which can reflect day ahead market prices;
- Critical peak pricing to discourage demand on certain days of extreme demand (generally aimed at industrial users, e.g. ‘Triads’ in

Great Britain).

While variable ToU tariffs appear to offer important technological and financial benefits, their uptake by consumers remains relatively limited and willingness and ability to shift heat demand appears uncertain. Trials of remotely controlled heat pump systems linked to ToU tariffs have seen success but have recognised some issues with overheating where houses become too hot for residents as systems attempt to effectively charge up houses and ensure buildings are warm enough at peak price times when systems turn off [89]. However, overall it has been suggested that time of use tariffs can be an important tool to incentivise load shifting using heat pumps (and electric vehicles) and therefore reduce electricity system stress and limit peak demand [90].

Commercial trials combining domestic heat pumps with variable tariffs alongside sophisticated machine learning and controls are already underway in the UK although performance data is not available [83]. Understanding the consumer response to and interaction with such automation may be an area of further research which could be considered within large heat electrification trials such as that currently underway in the UK (i.e. [91]). Further performance data associated with these sorts of flexible heat pump systems would also be of value.

5. Policies for smart heat decarbonisation

The four principles we have identified can support immediate heat decarbonisation with potentially limited system impacts and should be a key consideration for policy makers looking to decarbonise heating. However, significant policy intervention will be required to deliver these principles in energy systems. This section reviews some of the key approaches which can support these principles for 'smart' heat electrification.

5.1. (Building) regulations

Regulation can be used to simply determine what type of heating source is or isn't used in buildings as well as to determine other energy characteristics of buildings such as demand levels or thermal properties of particular components. While countries are likely to have their own national standards, at an EU level supra-national standards exist with the Energy Performance of Buildings Directive (EPBD) requiring all new buildings from 2021 (public buildings from 2019) to be nearly zero-energy buildings (NZEB). This should result in an increasing share of new buildings fitted with low carbon heating systems [92].

Through building regulations, fossil fuel heating is being banned in UK homes from 2025 [93], the Netherlands effectively banned the connection of homes to the gas grid on 1st July 2018 [94] (subject to permitting) and the Republic of Ireland is banning gas boilers from 2025 in new buildings [95]. Oil heating has been banned from new Norwegian buildings since 2017 [96] and is being banned from Austrian new buildings after 2020 [97], in Germany by 2026¹¹ [98] and Ireland by 2025 [95].

While building regulations often target new buildings, regulatory schemes can also target existing buildings. Existing buildings are likely to make up a significant proportion of the housing stock in a decarbonised energy system and are seen as a priority area for the EU [99]. For existing buildings, the EPBD only applies where significant building work is taking place but there are opportunities to introduce stricter national minimum standards for existing buildings. For example, minimum standards could be introduced which are applicable at the point of sale or rental [100], something the UK has recently introduced for rental properties [101]. Energy performance requirements could also be placed on social housing and the Scottish Government has mandated social housing providers to meet certain energy efficiency

standards for their buildings by 2020 [102]. Poland has announced a ban on the use of coal for heating in both new and existing buildings [103] and Norway has done the same for oil [104].

Regulations can provide a valuable policy approach to drive immediate integrated heat decarbonisation in new buildings through the requirement for high standards of energy efficiency and the use of low carbon heating which can provide flexible heat load supporting our first and second principles. However, it is unlikely that building regulations alone can drive fully integrated heat decarbonisation, particularly for existing buildings and therefore further measures will be necessary.

5.2. Financial support schemes

The deployment of both low carbon heating technologies and energy efficiency represent capital heavy investments with both long asset lives and long (and potentially negative) paybacks¹². Therefore, financial support may be required to support investment in buildings. This is in part reflected by the European Investment Bank which now sees buildings renovation and energy efficiency as a priority [105]. Financial support can take many forms including loans, grants and ongoing payments such as feed in tariffs and some examples of financial support which support smart heat decarbonisation are considered below.

5.2.1. Loans

Loans can be used to eliminate the issue of building owners requiring access to capital to pay for energy efficiency and low carbon heating measures. The German KfW bank programme is well established and provides up to €100,000 for energy efficiency and renewable energy measures at 0.75% annual interest rate [106]. The Scottish government and French government provide interest free loans for energy efficiency and renewable energy measures up to £15,000 and €30,000 respectively [107,108]. Bulgaria also provides a specific loan fund which requires an equity contribution from a developer and must deliver energy savings [109]. While loans may be particularly valuable for homeowners, loans are not suitable for all individuals including renters and those on low incomes.

5.2.2. Grants

Grants provide capital to householders which can offset some of the costs associated with energy efficiency and low carbon heating systems. These grants are likely to come from Government spending. Prior to the current Renewable Heat Incentive (RHI) in the UK, the Renewable Heat Premium Payment provided cash to householders who installed renewable heating systems [110]. Grants were also provided by the previous 'Clear Skies' programme for various domestic renewable systems [111]. The Scottish Government currently provides grants alongside its zero cost loans [107].

5.2.3. Tax rebates

Tax rebates can provide building owners with a reduction in income tax following the installations of certain measures with the size of the rebate linked to the type of measure installed. This approach is currently used in France [112] and Italy is currently offering 110% tax rebates for the installation of heat pump systems as part of its Covid-19 response package alongside other incentives [113] (article 119).

5.2.4. Feed-in-tariffs style policies

Feed-in-tariff style policies which provide ongoing income across part of the life-time of a project can be used to support the deployment of renewable heat as is the case with the GB Renewable Heat Incentive. It should be noted that this policy has deployed below expected levels

¹¹ Subject to technical feasibility.

¹² Low carbon heating systems are likely to cost more to install than fossil fuel boilers e.g. a heat pump compared to a gas boiler.

[114]. While not currently used, feed-in-tariffs could potentially be used for the deployment of energy efficiency measures [115]. The limited experience of these policy measures for heat mean it is unclear what benefit an ongoing tariff provides over a grant.

5.2.5. Auctions

Auctions can be used as competitive processes through which energy efficiency and in some cases low carbon heat can be procured by governments. Competitive bidding through an auction is used in Portugal and Germany to procure energy efficiency [116,117] and, in Switzerland, low carbon heating systems (heat pumps) are supported as energy efficiency measures [117]. Limited international experience of these approaches has shown only restricted deployment [118].

5.2.6. On-bill finance programmes

These programmes allow the repayment of a loan via a surcharge on the energy bill. While such programmes have had some success outside of Europe, European success is limited [119] with the GB Green Deal seen as a particular failure [120].

Various financial support schemes can support smart heat decarbonisation and these schemes vary significantly. However, all are based around either removing or reducing the need for capital or returning some capital to households post investment. The suitability of schemes is likely to vary depending on the type of consumer who needs support and the existing market framework in the relevant country.

In order to support our first and second decarbonisation principles, where further thermal demand reduction is possible, financial schemes should support demand reduction and the deployment of heat pumps simultaneously. This is already the case for Scottish Government loans which provide finance for both [107] and the GB RHI requires minimum standards for insulation [121].

5.3. Carbon intensity standards

In many countries in the EU, the cost of carbon is not reflected in the prices of fossil fuels used for heating of buildings [122] despite the fact that carbon costs are (in part) reflected in electricity prices as a result of the EU emissions trading scheme [123]. This effectively provides an economic disincentive to heat electrification despite carbon reductions associated with electricity and the need to electrify heating.

This issue (alongside a locally increased carbon price on electricity) has led UK energy innovation body the Energy Systems Catapult to call for a potential rebalancing of policy costs to support electrification [124]. However, it has also been suggested that obligations could be set on energy consumers, suppliers or producers to over time, reduce the carbon intensity of heat use or heat supply; schemes like the Low Carbon Fuel Standard which over time obliges upstream fuel producers to reduce the carbon intensity of vehicle fuel in California could be re-designed to cover heating fuel [124]. More detailed consideration of these carbon standards has suggested that under these schemes, carbon savings could be traded as carbon credits in order to increase competition and overall costs as has been the premise behind the EU ETS [125]. This approach could also give energy companies flexibility to prioritise different heat measures.

However, for heat decarbonisation this approach is untested and questions remain over the complexity of administration relative to benefits compared to other more regulatory approaches such as technology bans. There is also a potential issue whereby the most cost-effective 'low-hanging-fruits' are initially targeted when significant changes to buildings are actually required immediately. It is also unclear on who a standard should be set and how this tool may interact with other policy and regulatory measures. For reasons of simplicity, it may make sense that an industry wide carbon tax is introduced to cover heat as is used elsewhere and has been a major driver of heat pump deployment in Sweden, although this tax will need to be high and sustained to encourage technology change [126].

Through requiring companies to reduce the emissions across their portfolio of customers and with an incentive to carry this out at as low cost as possible, carbon standards could potentially lead suppliers to deliver integrated decarbonisation solutions comprising fabric efficiency measures, low carbon heating systems and time of use offerings. In doing so, this approach could support all four of our principles. However, a lack of experience of this model suggests further trials and analysis may be required.

5.4. Energy efficiency obligations

This policy approach obliges companies, including suppliers and network operators, to deliver a specific amount of energy savings. There are 16 such schemes operating across the EU driven in part by the EU Energy Efficiency Directive [127]. These schemes can support renewable heating measures such as heat pumps as the UK 'Energy Company Obligation' does. Like carbon intensity standards, these energy efficiency obligations can give companies flexibility on how energy efficiency reductions are made. If designed well, these obligations can support the deployment of heat pumps through either a specific technology focus or through promotion of the more efficient use of electricity as heat as heat pumps provide more useful energy than direct electric heating.

Typically, energy efficiency obligations have supported technologies with low capital costs rather than low carbon heat systems [118] however if these policies are combined with others, in particular financial support such as loans or tax rebates, energy efficiency obligations could play an important role [128]. The similarity of energy efficiency obligations to carbon intensity standards means that potential hybrid carbon intensity standards/energy efficiency obligations could play an important role in both the deployment of demand reduction measures and low carbon heating. This could support our first and second principles of reducing demand and increasing heat demand flexibility. Again, further testing and analysis of this approach appears to be needed.

5.5. Electricity pricing

We explained in Section 5.3 that energy prices, particularly for gas, may not reflect carbon intensity. In order to support our third principle around carbon intensity, as well as ensuring that all heating fuels reflect carbon intensity, it should be recognised that the carbon intensity of electricity can vary, often relative to the level of demand. Our fourth principle explained that electricity tariffs can be designed to reward flexibility. If time of use tariffs can be used by consumers alongside the shifting of heat demand, this can potentially reduce the cost of low carbon heat for consumers and simultaneously encourage the use of lower carbon off-peak electricity.

Current policy structures in the UK appear to have exacerbated the cost differential between electricity and gas, potentially reducing incentives to electrify heat [129], and so as a first step policy should ensure that electrification doesn't face an unfair and unplanned structural cost disadvantage.

As a next step, energy supply regulatory regimes should allow consumers to have access to time of use tariffs which reflect varying wholesale costs and/or network constraints, something which is supported by the EU 'Clean Energy for all Europeans' package [130]. In advance of widespread dynamic tariffs, existing time of use tariffs which may provide lower cost power overnight can provide cost benefits to consumers with electric heating for example through pre-heating hot water and policy could encourage suppliers to engage consumers around these approaches.

6. Conclusions and policy and research implications

The challenge of heat decarbonisation requires an immediate policy

and research response. Through this analysis, we have shown that approaches exist which can immediately decarbonise heating while minimising energy system impacts and limiting consumer costs and requirements for capital outlay. These approaches are supported by recent developments in automation and communications but nonetheless require physical system changes such as energy efficiency measures and new heating systems. Over the longer term, the impacts of heat electrification on energy systems can be limited if electrification is carried out in a coordinated fashion which takes into account our principles and wider technology developments.

The path to a decarbonised global heating system has not yet been fully determined however, even if it had, technological innovation means that what appears to currently be the optimal pathway is likely to change. It is however apparent that in many countries where space heating demand is significant, some combination of energy efficiency alongside electrification appears important and wider innovation around electrification may further support this pathway. Furthermore, the electrification of heating demand is likely to provide an important route to increase the quantity of renewable energy in energy systems.

Recognising the expectation of the need for a significant level of heat electrification using heat pumps in many countries (with electricity simultaneously being decarbonised), this paper has explored how synergies between different elements of whole energy systems can support heat decarbonisation through electrification. Smart and well-coordinated heat electrification can reduce both system and consumer impacts while maximising greenhouse gas emission reductions.

Further technological innovation including cost falls in the price of lithium batteries [131] and the associated use of vehicle to grid technologies [132] could provide support for electrification more widely and reduce integration costs. The use of vehicle to grid technologies could have particular value for heating integration if the energy stored in electric vehicles can be used at times of peak heat demand. This could reduce costs for consumers by allowing the use of off-peak electricity for heating and potentially, subject to existing infrastructure, reduce the need for network capacity upgrades.

Based on our narrative review of best available evidence, four policy and research principles for smart heat decarbonisation are:

- a) Fabric efficiency should be a primary objective;
- b) The flexibility of heat loads can provide significant energy system value;
- c) How and when heat demand is electrified can have significant emission impacts;
- d) Tariffs can be designed to reward flexibility.

Clearly, further research and policy development in this field is needed but the principles in this paper can drive immediate and widely beneficial heat decarbonisation, at least in the short term. With such transformative change required associated with large financial flows, we also recognise significant equity issues associated with how heat decarbonisation is governed, what policies are used and how the transformation is financed; this issue is worthy of significant further investigation.

We also add that in general, to enable smart and integrated heat decarbonisation, we support the proposed technology steps of Chaudry *et al.* (2015) [37] which we introduced in Section 3 whereby heat demand is reduced through energy efficiency, the energy carrier, electricity is decarbonised and low carbon heat technologies which use electricity are deployed. However, as shown in Fig. 4, we suggest an additional step which supports the flexible operation of heating systems. As well as supporting energy system change and reducing system impacts, the adoption of flexibility can limit immediate and long-term consumer costs associated with heat electrification [133].

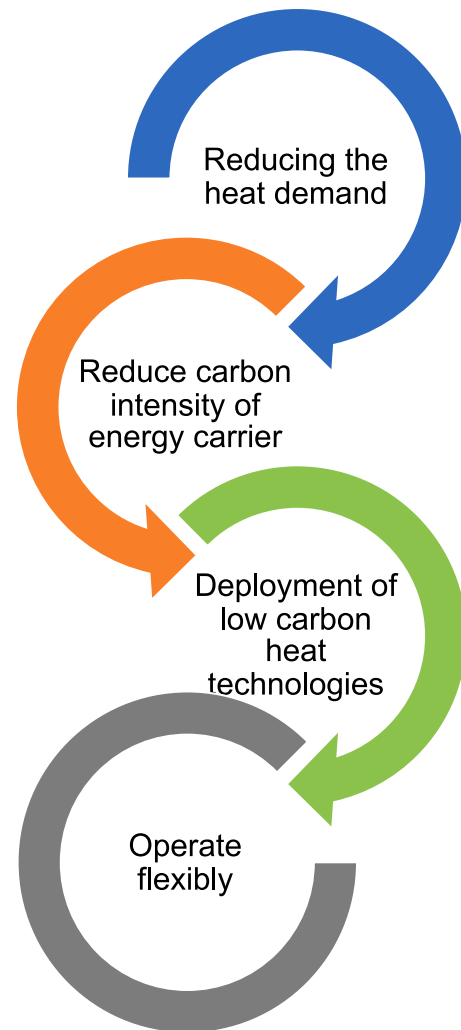


Fig. 4. Four inter-related steps towards smart heat electrification. Adapted from Chaudry *et al.* (2015) [37] figure 5 p626.

6.1. Policy and research implications

This article has highlighted a number of policies which can drive the four heat decarbonisation principles. These include increasing the rate of energy efficiency upgrades of existing buildings, the phase out carbon-intensive heating systems through regulation, the implementation of well-designed and well-funded financing mechanisms for energy efficiency and low carbon heat, a fairer distribution of costs between different fuels, and the encouragement of flexible use of heat through time-varying prices.

With rapid cost falls in the price of renewable electricity and storage and developments in ICT, this is an important and rapidly developing time for socio-technical change associated with heat. If applied in isolation, none of the principles and policies proposed in this paper can deliver progress at the scale needed to meet EU climate targets. When harmonised however, the various elements of heat decarbonisation can be harnessed to bring significant benefits for both the energy system and associated actors.

This harmonisation will require regulatory, policy and political coordination across scales and across actors which does not appear to be currently in place. The importance of complex and integrated poly-centric governance has been previously highlighted by scholars examining past heat transitions [19]. Coordination of heat decarbonisation governance and policy could also support the development of entirely new business models to provide heat [134], an extremely

interesting and active area of research.

While there appear to be clear opportunities for heat decarbonisation, some uncertainty exists. We have noted already that further understandings of the interaction of citizens and households with flexible heating systems and their controls would be of value. Details on the performance of existing flexible heating systems could also further support policy development in this area. There is also a gap for further research into how policies can drive heat decarbonisation while ensuring equitable outcomes for citizens. In particular for heating, further analysis of how financial models and obligations and standards on actors could support change would be of great value.

Significant uncertainties also remain around how energy systems with very high proportions of electrified heat demand and renewable electricity penetration are balanced inter-seasonally without large volumes of hydro-power which has supported a high penetration of heat pumps in France and Sweden [44]. Recent techno-economic modelling considering the UK has suggested that in various heat scenarios, while significant electrification is important, hydrogen, as a storage and balancing medium, could play some role to reduce system costs [10,135]. However, we note that developments in thermal storage mean that various options exist [136] and indeed existing technologies, such as large hot water storage may have value.

If hydrogen does have a role for heating, it is unclear where this hydrogen has most value. Hydrogen could be used in homes in hybrid heat pump systems comprising a hydrogen boiler and a heat pump (promoted by the gas industry in both the UK and The Netherlands [137,138] and by academic researchers [10]) or hydrogen could be used to produce electricity at times of peak demand in order to provide flexibility in electricity systems [10].

Further research on mitigating or managing this issue of inter-seasonal balancing and the potential role for hybrid heat pumps could support international progress towards decarbonised heating. This should however not detract from the requirement for immediate deployment of known low carbon heating technologies.

Declaration of Competing Interest

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

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