

Smart and Flexible Electric Heat



An Energy Futures Lab Briefing Paper

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Energy Futures Lab

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List of Acronyms

ASHP	Air-source Heat Pump
BEIS	Department of Business, Energy and Industrial Strategy
BYOD	Bring-your-own-device
CAD	Consumer Access Device
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CES	Community Energy Storage
CHP	Combined Heat and Power
CoP	Coefficient of Performance (of heat pump)
DHW	Domestic Hot Water
DR	Demand Response
dRHI	Domestic Renewable Heat Incentive
EPC	Energy Performance Certificates
EV	Electric Vehicle
GB	Great Britain
GCH	Gas Central Heating
GSHP	Ground-source Heat Pump
HaaS	Heat as a Service
HHP	Hybrid Heat Pump
HP	Heat Pump
IC	Internal Combustion
ICT	Information and Communications Technology
kWh	Kilowatt Hour
kWhth	Kilowatt Hours of Heat
LPG	Liquid Petroleum Gas
MHCLG	Ministry of Housing, Communities and Local Government
MVHR	Mechanical Ventilation with Heat Recovery
MWh	Mega-watt Hour
PCM	Phase-change Material
PMV	Predicted Mean Vote
Prosumager	Households that consume, produce and store energy
Prosumer	Households that produce as well as consume energy
PV	Solar Photovoltaics
PVT	Solar photovoltaic-thermal (solar thermal/PV hybrid panels)
RdSAP	Reduced Data Standard Assessment Procedure
SAP	Standard Assessment Procedure
SAP	Standard Assessment Procedure
TCR	Targeted Charging Review
TCS	Thermo-chemical Storage
TES	Thermal Energy Storage
TOU	Time-of-use (electricity tariffs)
TWh	Terawatt Hour
UFH	Underfloor Heating
UV	Ultra-Violet

Executive Summary

Heating in residential, commercial and industrial settings makes up almost half of final energy consumption in the UK, more than the energy consumed for electricity or transport.

The electrification of heat is anticipated to play a major role for the UK's efforts to reduce emissions to net-zero by 2050. Heating demand is highly variable between seasons and time of day. To take maximum advantage of low-carbon generation, and to respect the limitations of the distribution grid, electricity loads for heating will need to be flexible. This Briefing Paper explores the potential for smart flexible low-carbon electric heating in UK homes and the challenges for consumer engagement. This paper considers four key elements for enabling smart, flexible and cost-effective electric heating in UK homes: low-carbon heating systems; cost-reflective electricity pricing; thermally efficient buildings; and smart storage devices.

Heat pumps have a key role to play in the electrification and decarbonisation of heating, but currently take-up is low in the UK – only 4% of homes have low-carbon heating installed, compared to 85% on gas central heating. Furthermore, implementing cost-effective solutions for the millions of older homes with high heat losses will be more challenging than new builds. Moving to electrification of heating produces two major challenges – firstly, delivering a potentially large increase in low-carbon power through renewable generation and, secondly, delivering demand flexibility, both on a diurnal and seasonal level. As with smart-charging of electric vehicles, *automation and storage technologies* offer the possibility of facilitating and managing load-shifting for heat.

Heat pumps work most efficiently when coupled with larger heat emitters such as underfloor heating and oversized radiators that can maintain thermal comfort using lower temperature water. Smart controls are important for delivering efficiency through automation, zoning and the integration of several technologies, such as smart-enabled hybrid heat pumps or various emitter and storage technologies. Smart controls also allow optimised operation by automatically responding to smart tariffs or other cost-reflective flexibility services. The ownership of smart devices has risen dramatically in recent years but developing interoperable standards for smart heating devices, appliances and controls would help to support increased consumer uptake.

Thermally efficient building fabric supports low-carbon heating in three ways: reducing consumption, enabling flexibility by pre-heating the home, and allowing low-carbon heating systems to operate efficiently. 70% of UK homes do not meet the Energy Performance Certificate rating of C and improvements to housing stock have stalled. Retrofitting the 27 million existing homes therefore has a much greater potential than new-builds for cutting emissions, driving commercialisation of products and improving comfort and wellbeing. Building efficiency retrofitting could lower barriers to adoption of low-carbon heating systems and storage technologies and play a significant part within a green recovery plan post COVID-19.

Smart storage devices have a significant role to play but more data, modelling and analysis is needed to further understand which combination of technologies best suit which applications and households to deliver flexible low-carbon electric heating in the most cost-effective manner. Installation of storage devices may be less disruptive than building fabric improvements but barriers to household engagement include cost and unfamiliarity.

Executive Summary

Recommendations

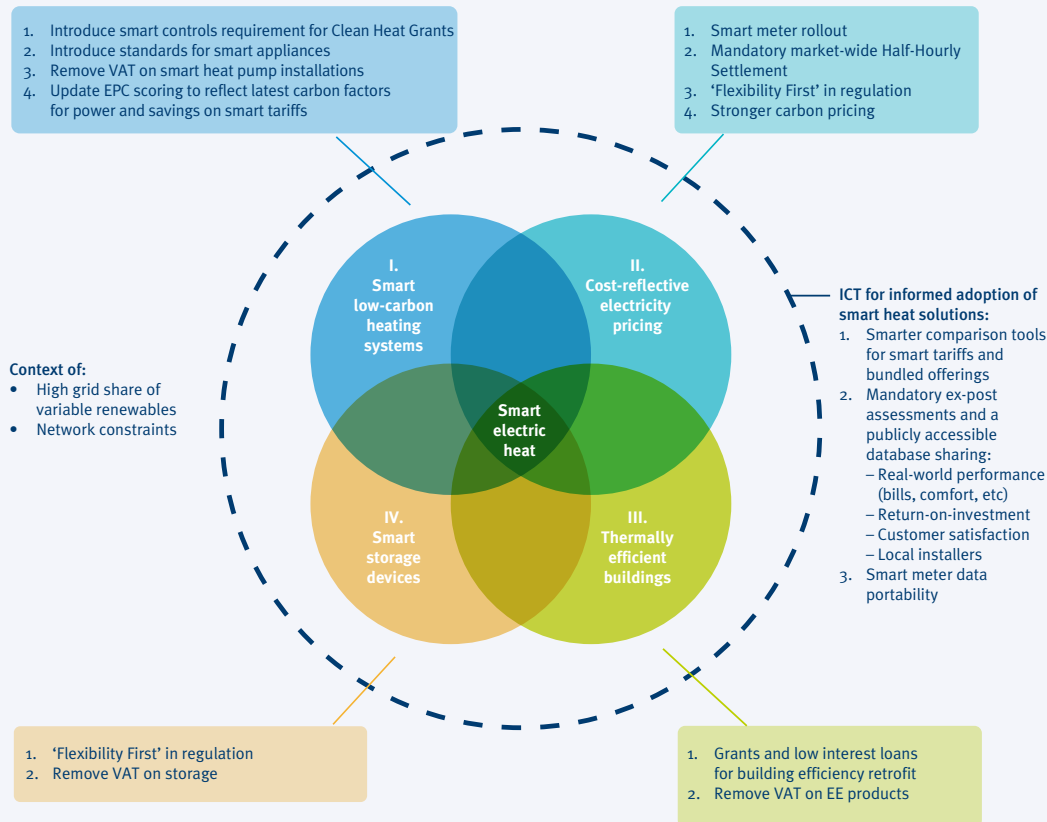
Decarbonisation of domestic heat will require a coordinated approach across buildings, heating systems, the power sector and infrastructure. This will take considerable time to implement so significant progress is urgently needed. Figure 1 summarises recommendations for each of the four major elements of smart electric heat: Low-carbon heating systems to replace fossil fuel use; cost-reflective electricity pricing to incentivise load-shifting; thermally efficient buildings to reduce consumption and enable pre-heating; and smart storage devices to facilitate load-shifting.

Key recommendations for smart low-carbon heating systems are to include smart control systems as a requirement for Clean Heat Grants, as well as setting interoperability standards for smart appliances and for heat pump smart controls. VAT reductions on heat pump and storage installations as well as energy-efficiency measures should be considered, as should an update to Energy Performance Certificates to reflect both more recent carbon factors for power and the potential for properties to utilise smarter tariffs to further reduce carbon intensity of electricity and lower energy bills.

Heat has considerable scope for load-shifting, especially when facilitated by smart controls and pricing incentives for flexibility. The continued rollout of smart meters, coupled with the planned introduction of a mandatory market-wide half-hourly settlement regime, will help to unlock this flexibility. A ‘flexibility first’ approach to new regulation that improves access to the full market value of flexibility in household electricity demand could make investment in heat pumps, storage and building fabric more cost-effective, although Ofgem’s ongoing Significant Code Reviews have so far reduced the business case for storage. Greater support could also incentivise suppliers to offer new cost-saving demand response services including the bundling of smart tariffs with hardware, such as heat pumps and storage, to offer households an integrated solution and reduce up-front costs.

The range of heating technologies, tariffs and other supplier offerings for smart electric heat will necessarily involve consumers navigating new and more complex choices. ICT technology and data-led digital services could play a crucial role in supporting informed consumer adoption. There is an important opportunity for price comparison websites to support informed consumer adoption of smart flexible heat solutions by including smart energy services and bundled offerings in their market comparisons, thereby lowering barriers to adoption. Further, ‘Try-before-you-buy’ is not possible for heat and building technologies, but digital comparison tools offer the potential to mitigate this low *trialability* and uncertainties caused by this. A second opportunity for ICT to support adoption is by leveraging evaluations of how smart electric heating solutions perform in households that have adopted them. Making such *ex-post* assessments of real-world performance mandatory and allowing interested consumers to access them via a public database would reduce uncertainty about running costs, comfort level, usability and general customer satisfaction with these solutions and help to normalise these technologies and services by making their adoption *visible*. However, if these tools are to operate effectively, better arrangements are required to enable consumers to share their smart meter data with third parties offering these services.

FIGURE 1: FOUR ELEMENTS FOR SMART FLEXIBLE ELECTRIC HEAT WITH SUGGESTED POLICY AND ICT INTERVENTIONS



Introduction

The UK has now set a binding target to achieve net zero emissions by 2050 and a number of other national governments have set, or are proposing, similar targets (Energy & Climate Intelligence Unit, 2020). Reaching these targets will require greater efforts across all energy sectors and will include changes for households. Decarbonising heat is recognised as perhaps the greatest challenge to achieving the UK Net Zero target (CCC, 2019a).

Heating contributes almost half of final energy consumption in the UK, more than the energy consumed for electricity or transport. 57% of this heat is used for space and water heating in UK homes (DECC, 2015 in Ofgem, 2016). Domestic heating accounts for about 25% of total UK energy (CCC, 2019a) and 15% of UK greenhouse gas emissions (CCC, 2018a). Heat has, for some time, however, been treated as the ‘Cinderella’ of energy policy, with her siblings, transport and power, receiving far more attention.

Decarbonising heat will involve moving away from central heating powered by boilers running on fossil fuels, and in particular natural gas, which have made up the vast majority of UK heating systems since gas central heating was widely adopted from the 1970s (Gross & Hanna, 2019). Achieving zero and low-carbon heat will almost certainly be complex, costly, and involve households engaging with new technologies, products and services. This will take time and so there is an urgent need to begin:

“Even though most whole systems analyses, including those from ETI3, show the bulk of heating decarbonisation occurring after 2035, the scale and complexity of the transition requires an almost immediate start” (ETI, 2019).

There are various pathways to decarbonising heat but a shift to the electrification of heat will be an important part of solutions. Only around 8% of homes in Great Britain are heated by electricity and the majority of these use heating systems with thermal storage (Ofgem, 2015). The mass switching to electric heating, in particular through the widespread installation of heat pumps, raises the prospect of much greater peaks in electricity demand in mornings and evenings. This would require not only significant growth in the generation of low-carbon electricity, but also expensive upgrades to the power grid. Flexibility in electricity loads for heating will be required and might be delivered reliably and easily using smart-enabled energy technologies.

This briefing paper explores the potential for smart, flexible low-carbon electric heating in UK homes and the challenges for consumer engagement and offers recommendations for accelerating the adoption of products and services to deliver it.

Chapter 2 explores the challenge of decarbonising UK residential heating and considers heat demand, current UK heating systems, possible decarbonisation scenarios and the challenge of balancing demand from new heating loads with supply of low-carbon electricity.

Chapter 3 looks at the smart electric heating technologies that could supply flexible low-carbon electric heat and discusses barriers to their mass adoption.

Chapter 4 lays out the important role for improved thermal performance of UK housing for enabling reduced demand and more efficient and flexible electric heating.

Chapter 5 discusses flexibility in heating loads via dedicated smart storage devices within the home.

Chapter 6 presents a summary and offers a range of recommendations for policy and other support for consumer engagement with smart flexible low-carbon heat.

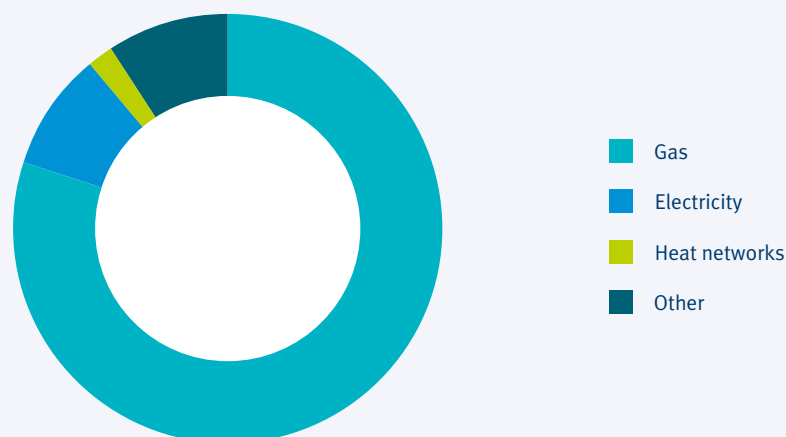
2. The Challenge of Decarbonising Heat

Within UK homes, space heating and domestic hot water together account for 80% (62% and 18% respectively) of total household energy use (Palmer & Cooper, 2013). In terms of carbon, heating accounts for approximately 31% of an average UK household's carbon emissions (Energy Systems Catapult, 2019). In contrast, demand for cooling through air conditioning in the domestic sector is very small in the UK. This could change in the long term however, with hotter summers and better insulated buildings, and consideration of future cooling requirements will need to form a part of decarbonisation decisions (Ofgem, 2016). A statutory requirement for reducing overheating risks in new builds is needed (CCC, 2019c).

2.1 Current heating systems and emissions

Around three-quarters of heating in GB buildings is provided by natural gas (CCC, 2019a) with the majority of this being used in the 28 million GB households, 85% of which are connected to the gas grid (National Grid, 2019). An average household with a gas-powered boiler and central heating through radiators spends around £750 per year on space heating and hot water (ETI, 2019). Only 2% of GB households receive heat through a district heating network (ADE, 2018), around 8% use electricity (typically with thermal storage) as their main source of heating, and 4% of homes use heating oil (Palmer, Terry and Kane, 2013; Ofgem, 2015). In Northern Ireland, however, around 68% of homes are heated by oil-fired boilers (The Consumer Council, 2019). Around 4% of UK homes (one million households) have low-carbon heating, mostly wood stoves or biomass boilers as opposed to heat pumps (CCC, 2019c).

FIGURE 2: CURRENT HEATING SYSTEMS IN UK HOMES (SOURCE: OFGEM, 2016)

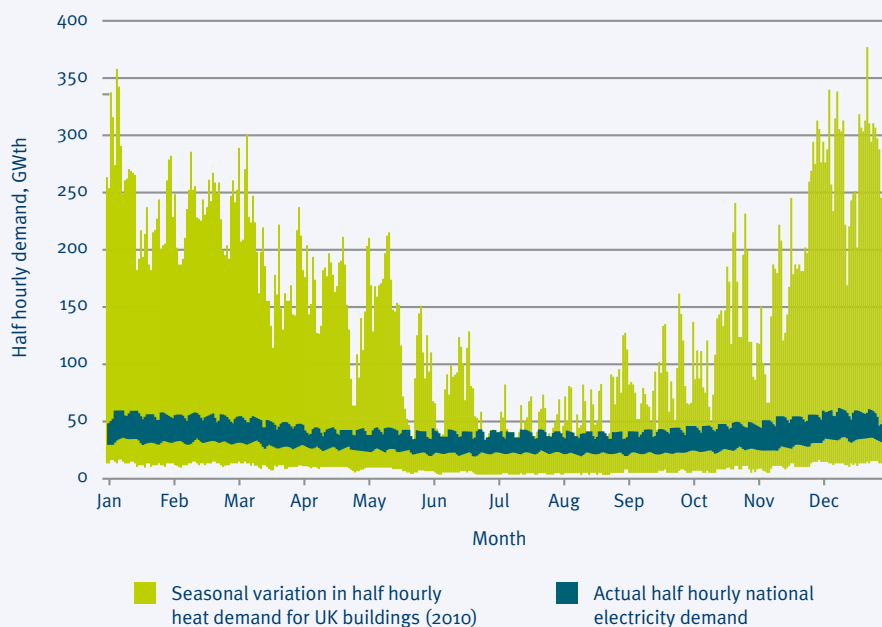


2.2 Variation in UK heat demand

One strength of the gas network is its ability to meet large variations within daily and seasonal demand. On a winter peak day, gas demand can be around 5 TWh – more than five times the energy that the electricity grid will supply in a day (National Grid, 2020).

Winter peak demand varies from year to year depending on severity of weather; for example, winter 2010-11 was unusually cold (Watson, Lomas, & Buswell, 2019). Existing UK household electricity consumption is also already higher in winter (though to a much lesser extent than gas). Satisfying winter peak demand for heat in a cost-effective manner will be a major challenge for the electrification of heat (Regen, 2020).

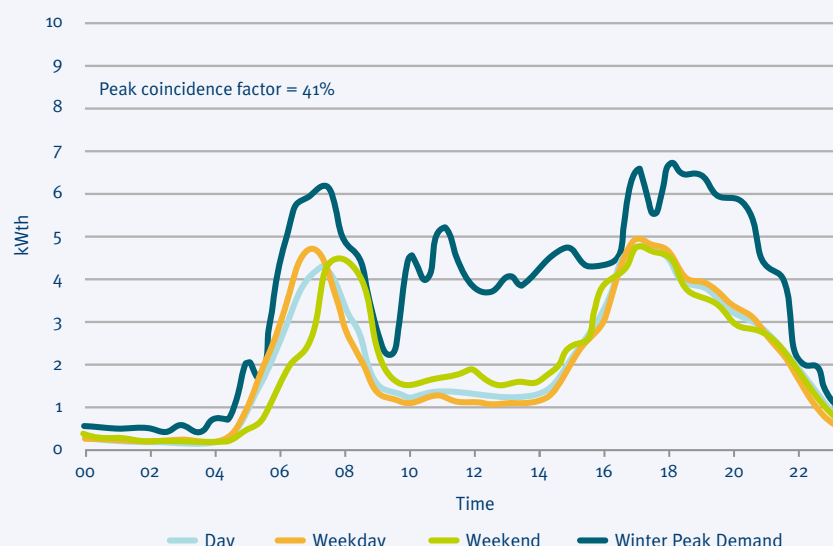
FIGURE 3: SEASONAL VARIATION IN HALF HOURLY HEAT DEMAND FOR UK BUILDINGS (2010) AND ACTUAL HALF HOURLY NATIONAL ELECTRICITY DEMAND (SANSOM, 2014)



Diurnal variation (over the course of 24 hours) in heat demand is characterised by a short morning peak and a longer evening peak (see Figure 4) and also presents significant, though different, challenges for electrification. A diurnal pattern of morning and large evening peaks is seen in both gas and electricity consumption and in relation to UK household activities in general (Sansom, 2014; Torriti, Hanna, Anderson, Yeboah, & Druckman, 2015).

2. The Challenge of Decarbonising Heat

FIGURE 4: DAILY HEAT DEMAND FOR GAS CONDENSING BOILER -DATA FROM 19 UK HOMES 2006/7 (SOURCE: SANSOM 2014)



2.3 Heat decarbonisation strategies

Whatever heat sources will replace fossil fuels, demand reduction through greater energy efficiency also has an important role to play in reducing carbon emissions associated with heat in homes (Rosenow & Lowes, 2020). In the UK, the greatest opportunity for lowering demand is through reducing the heat lost from poorly-insulated and draughty housing stock (UKACE, 2015). Chapter 4 discusses the benefits of, and opportunities for, improving the thermal performance of building fabric.

Even with greater energy efficiency and lower overall heat demand, new sources of low-carbon heating will be needed to replace fossil fuels. Scenarios for decarbonising UK residential heat incorporate alternative mixes of district heating, reuse of the gas grid for biogas and hydrogen, and electrification via heat pump technology (CCC, 2018b; National Grid, 2019; Strbac et al., 2018). Unlike electricity, which is largely generated centrally at grid level and distributed to the point of use, heat is typically generated

within the home, by a gas or oil boiler, solid fuel stove or direct electric heater. Decarbonising heat will, therefore, not just involve change ‘upstream’ from the consumer but will entail a shift of some kind away from familiar heating systems and towards using end-user technologies in the household that are currently unfamiliar to most people (Gross & Hanna, 2019).

New-build homes will soon no longer be permitted to use fossil fuel gas boilers. In 2019 the UK Government announced plans for a Future Homes Standard that would mandate the end of fossil fuel heating systems in all new houses from 2025 (Hammond, 2019). From this date, new-build houses will not be connected to the gas grid but will be required to have low-carbon heating systems. This will be made more feasible by the superior thermal efficiency of these new buildings. Implementing cost-effective solutions for the millions of older homes with much greater heat losses will be much more challenging. Overall, a combination of emerging and potential options for heat decarbonisation will be required, and several of these are discussed below:

Further development of heat networks

The ~2% of UK homes on district heating networks is very small compared to countries such as Iceland, Denmark, and Sweden where at least 50% of citizens are serviced by heat networks (Euroheat, 2016). Increasing the contribution of district heating in the UK would be best suited to areas of high heat demand such as high-density housing and would ideally take advantage of waste heat from industry. A detailed analysis for the CCC of the potential for UK district heating highlighted a key role for thermal storage but a more limited role was seen for gas combined heat and power (CHP), for which carbon savings diminish as the electricity grid decarbonises (Forster, Love, & Walker, 2015).

The key immediate challenge for heat networks is not the heat source but developing the infrastructure of hot water distribution pipes (which can be switched to low-carbon source at a future time). However, “the ubiquity of existing water, sewage, power, gas and telecoms networks make it challenging to modify or install any network, since this can have a significant impact on large numbers of people and businesses during the process.” (MacLean, Sansom, Watson, & Gross, 2016, p.3).

Blending more biomethane into the natural gas supply grid

Increasing the levels of biomethane injected into the gas grid is one of the CCC's low regret measures for heat (CCC, 2016). Current gas boilers and cookers could continue to operate up to a certain concentration of biomethane. According to the CCC, “its potential is limited to around 5% of current gas consumption” (Ibid, p.9).

Developing hydrogen networks

Unlike the methane in natural gas (fossil gas), hydrogen does not release carbon dioxide when combusted. But like biomethane, blending hydrogen into the mains gas supply is not entirely new: “When the UK used town gas there

was as much as 50% hydrogen by volume in the grid. Work is needed to confirm the safe upper limit of hydrogen that is compatible with the gas grid and, importantly, gas appliances” (Carbon Connect, 2017).

Hydrogen could be especially useful as a form of low-carbon, inter-seasonal storage to supply winter peak heat demand (Samsatli & Samsatli, 2019). The existing gas grid is not fully able to transport hydrogen without leaks and so new high pressure pipes would be required (Dodds & Demoullin, 2013). Ninety percent of the distribution network is expected to be converted to polyethylene by 2032 under the ongoing Iron Mains Replacement Programme (Carbon Connect, 2017). Households' gas boilers and cookers would also need to be replaced if the gas grid was converted for use with hydrogen instead, and it is very early days for understanding public awareness, attitudes and acceptance regarding appliances that run on hydrogen.

However, the “most important precondition for using hydrogen would be the development of large scale, low cost production facilities” (MacLean et al., 2016) and doubts about its feasibility persist (CCC, 2018b). Uncertainty over production is linked to future costs of carbon capture and storage (CCS) if producing ‘blue hydrogen’ from electrolysis, and the availability of surplus renewables power for producing ‘green hydrogen’. Hydrogen may also be in demand from the electrification of transport and shipping (CCC, 2018b).

Solar photovoltaic and solar thermal panels

Solar thermal panels are a simple technology and a relatively inexpensive low-carbon source of heat. Solar photovoltaics (PV) can be used as a low-carbon source of electricity for electric heating (including heat pumps). Typically for residential scale systems, solar hot water has a shorter carbon payback period than solar PV, but both technologies provide net carbon benefits over their lifetimes. For example, Allen, McManus and Staffell (2015) found that solar hot

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water and solar PV microgenerators had carbon payback periods of 1-2.5 years and 4-7 years respectively, i.e. significantly less time than their expected operational lifetimes. Although the potential for solar energy to contribute to heat decarbonisation is limited in colder countries that receive lower levels of solar irradiation, such as the UK, further reduction in the cost of storage could permit a greater cost-effective role (Rosenow & Lowes, 2020). Solar hot water and PV are discussed further in Chapter 3.

Electrification of heating through heat pumps

Although some combination of the above-mentioned heat decarbonisation scenarios and technologies is likely, it is anticipated that the electrification of heat using heat pumps will play a major role in displacing heat currently provided by gas and reducing emissions associated with heat in the UK:

“It is clear that electrification will have to play a significant role whether through individual heat pumps or renewable electricity used to power district heating networks via large-scale heat pumps” p.4 (Rosenow & Lowes, 2020a)

Indeed, for buildings not connected to the gas grid, heat pumps are likely to be the most feasible low-carbon option (CCC, 2016). Both air-source heat pumps (ASHP) and ground-source heat pumps (GSHP) are regarded as a proven technology and currently supported through the Domestic Renewable Heat Incentive (dRHI). As a key technology for electric heating, heat pumps are discussed further in the following chapter.

This briefing paper focuses on electric heat and the challenges for accelerating low-carbon and cost-effective electric heating solutions. The first challenge posed by the electrification of heat is how the huge increase in demand for low-carbon electricity would be satisfied. Great strides have already been made in the decarbonisation of UK electricity and the carbon intensity of power is

likely to continue to fall (Staffell, 2019). As noted above, heat accounts for 80% of total household energy consumption in the UK (Palmer & Cooper, 2013) and the electrification of transport will add further to new loads. For a typical UK household, the ETI (2019) states that:

“Notionally replacing their gas boiler with a heat-pump and their cars with fully electric ones would add around 5,000 kWh of additional electricity consumption for heat and 3,000 kWh of vehicle charging to the existing 3,100 kWh for other domestic uses of electricity. That is assuming that many households would reduce the heating bill with fabric efficiency measures. This level of electrification will present entirely new challenges, outside the historic experience” p.10 (Energy Technologies Institute, 2019).

The anticipated new loads from both transport and heating could see a doubling of overall electricity demand in the UK (Vivid Economics & Imperial College London, 2019). Producing all of the UK's power from low-carbon sources (from the current 50%) could require 75 GW of offshore wind by 2050 compared to the 8 GW today (CCC, 2019a). A second challenge, discussed below, is balancing highly variable demand for heat with variable supply from renewables and doing so within the constraints of the distribution grid.

2.4 Flexibility in electric heat

Within the UK, the Clean Growth Strategy (BEIS, 2017b) aims for a high renewables and flexibility approach to a low-carbon electricity system which is also secure, affordable and efficient. Large-scale rapid expansion of low-carbon generation through offshore and onshore wind and, in the longer-term, solar photovoltaics (PV) is envisaged (Bloomberg NEF, 2018; National Grid, 2019).

Flexibility in electricity demand is needed to balance variable supply and demand, and to avoid investment in reinforcing the transmission and distribution grid (Strbac et al., 2015). The value of flexibility in the UK has been estimated to be up to £8 billion per year, assuming that a smart energy system is developed with a high penetration of intermittent renewables while continuing to incorporate less flexible nuclear power (Carbon Trust & Imperial College, 2016; Heptonstall, Gross, & Steiner, 2017). System balancing options include grid interconnection, flexible generation, storage, demand side management and demand response (DR) (Strbac et al., 2012). Static time-of-use (TOU) electricity tariffs apply different rates at fixed time periods such as a higher rate during the evening peak-time. In relation to the Smart Metering Implementation Programme (SMIP), the UK Government's cost-benefit analysis assumed that 20% of consumers would switch to static TOU electricity tariffs by 2020, increasing to 30% in 2030 (BEIS, 2016a).

Flexibility of heating loads has hitherto received less attention than flexibility of EV-charging loads. The uptake of heat pumps for electric heating in the UK remains low compared to other northern European countries (Hanna, Parrish & Gross, 2016). A wider deployment of heat pumps has the potential to add significantly to the contribution of electric space and water heating to morning and evening peak loads. Love et al. (2017) estimate that if heat pumps were installed in a fifth of all GB buildings, peak electricity load would increase by 14%. Nevertheless, opportunities for system savings may be greater from flexible electric heating than from electric vehicle (EV) charging:

“Smart electric heat can provide enough flexibility to enable renewable generation from wind and solar to displace the need for both nuclear and CCS, whilst providing savings of up to £3.9bn/year” p.16 (OVO Energy and Imperial College London, 2018)

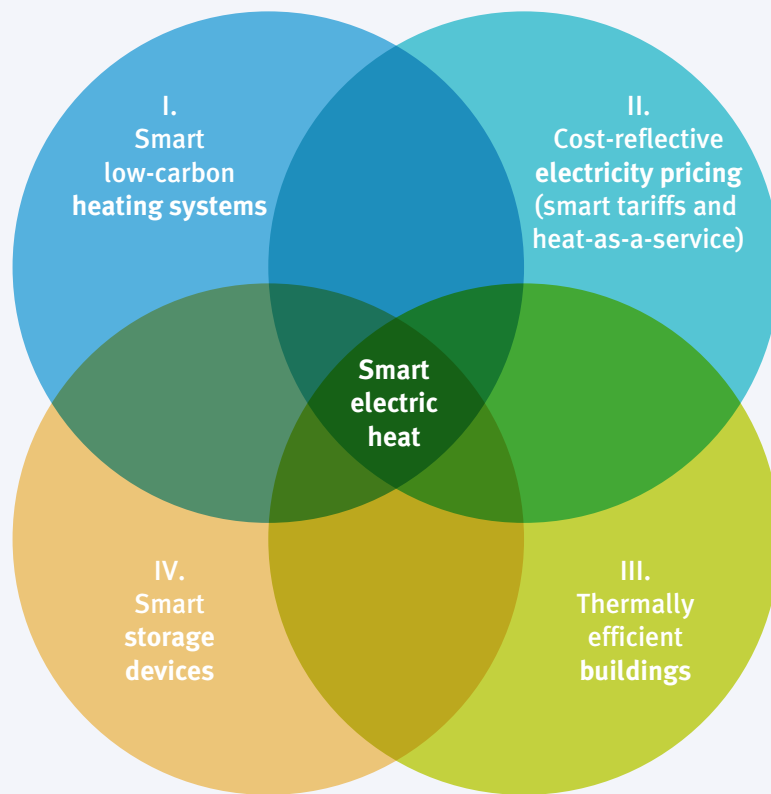
Flexibility in residential demand is expected to be delivered by incentivising households through a range of cost-reflective time-varying electricity pricing options. 8% of GB households use electricity as their main source of heating (Ofgem, 2015); these households are twice as likely to be in fuel poverty (Regen, 2020), so lowering heating bills through more efficient and flexible electric heat could reduce this hardship. Most UK trials of residential DR have focussed on manual DR (household occupants shifting energy-consuming behaviours to off-peak rate periods), but storage and automation technologies that enable the shifting of much larger loads promise far greater flexibility and cost-savings with more reliability and more convenience for consumers (Carmichael, Gross & Rhodes, 2018). As with smart-charging of electric vehicles, automation and storage technologies offer the possibility of managing load-shifting for heat.

Figure 5 depicts four elements that could enable smart, flexible and cost-effective electric heat in UK homes. The following chapters will explore each element in turn: Chapter 3 will detail smart heat technologies (I) and services (II); Chapter 4 the role of efficient buildings (III); and Chapter 5 behind-the-meter storage devices (IV).

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FIGURE 5: FOUR ELEMENTS ENABLING SMART, FLEXIBLE AND COST-EFFECTIVE ELECTRIC HEAT FOR UK HOMES

Context of: • High grid share of variable renewables • Network constraints



3. Smart Electric Heating Technologies and Services

3.1 Small-scale heating technologies

Most domestic properties in the UK (approximately 85%) are currently heated by means of hot-water central heating with heat generated by a natural gas boiler (CCC, 2017). Decarbonisation ambitions will require the widespread adoption of low-carbon heating sources in order to reach a net-zero 2050 target. This section outlines the characteristics of several small-scale technologies for low-carbon heating, which are relevant to the smart management of electric heating and/or demand.

Direct Electric Heating

Heat can be produced directly from electricity via thermal heating and fan convectors, as well as infrared and halogen elements. It can also be stored using electric storage heaters that heat up a dense set of ceramic bricks during periods of low electricity demand, usually at night-time, and then slowly reemit the heat during the day. Built-in electric heating tends to be unobtrusive and is simple to operate and maintain. However, running costs are generally higher than gas heating, due to the higher costs of electricity, and a heat-pump is, in most cases, a more efficient way to generate heat from mains electricity. In cases where a heat-pump would be impractical, effective decarbonisation of electric heating can be achieved via distributed renewable generation, usually domestic solar PV panels, combined with electricity storage or thermal storage heaters.

Heat pumps

A heat pump is an electric device that has the ability to transfer heat from one location to another, even if the original location is colder than the location to which the heat is moved. In this way, a heat pump can warm buildings during cold weather by taking heat from the colder outside environment and transferring it to the warm interior. The second law of thermodynamics prevents heat from flowing from a colder to a warmer area on its own, so an outside source of energy (in this case electricity) must be used in order to provide the work to transfer the heat.

A heat pump works along the same lines as a refrigerator or air-conditioning system (a heat-pump is basically an air conditioner running in reverse). This technology works by utilising an intermediate fluid known as a refrigerant. This absorbs heat from the outside in a heat-exchanging coil known as the extractor, causing the fluid to boil and become a gas. This then gets compressed by an electricity-powered compressor to a high pressure and circulated inside to another heat-exchanging coil, known as the condenser. In this coil, the gas cools to a liquid, giving off the excess heat into the inside environment, and is then depressurised and passed back to the outside. Many different refrigerant fluids exist, and the choice of which one to use is determined by the ambient temperature of the outside environment and the temperature differential the heat pump needs to bridge.

3. Smart Electric Heating Technologies and Services

Heat pumps are known for being more than 100% efficient – that is, they move more heat energy, often by a factor of several times, than they use electrical energy. The Coefficient of Performance (COP) of a heat pump refers to the number of units of heat energy moved per unit of electrical energy. This is strongly dependent on the outside temperature – as it gets colder, and the temperature differential between inside and outside increases, a greater pressure difference is required between the two coils, requiring more energy to compress the refrigerant. Thus, the COP falls as the outside temperature decreases. This observation also applies the other way – a heat pump will be less efficient at moving heat from the outside in order to heat hot water to 50°C for central heating than it will at directly transferring the heat into the building at 21°C. Heat pumps also operate more efficiently if run constantly, not interrupted (ETI 2018); this means that a smaller heat pump, sized appropriately for the building requirements, can run continuously and be more efficient than a larger heat pump. There are two common types of heat pump:

1. **Ground-Source Heat Pumps (GSHPs)**, or **Geothermal Heat Pumps**, which draw heat from the ground or groundwater. The refrigerant is circulated through tubes in a 'loop' arrangement buried below the ground. This ground loop can be installed in relatively shallow horizontal trenches or in vertical boreholes which can be between 15 and 100 metres deep (Green & Bradford, 2010). GSHPs therefore require a garden or other land large enough to install the ground loop and accessible to digging machinery. Ground-source heat pumps are relatively costly, with installation costs ranging from £14,000 to £19,000 in the UK (Energy Saving Trust, 2020b). However, the relatively constant temperature of the ground makes a ground-source heat pump work at a similar COP all year round.

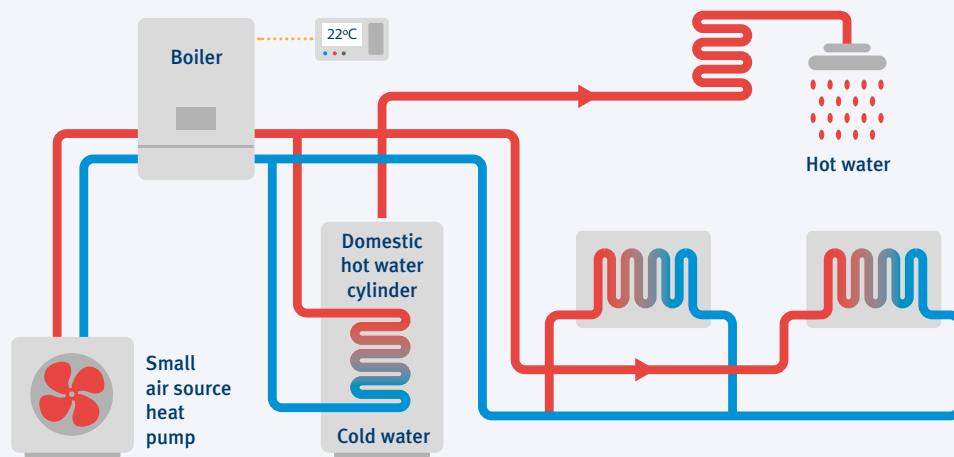
2. **Air-Source Heat Pumps (ASHPs)** utilise the outside air as a heat source, and as such are easier and much less expensive to install than a ground-source model. An air-source heat pump consists of two units, one inside and one outside. Installation costs are typically between £9,000 and £11,000 (Energy Saving Trust, 2020b). However, air temperature is considerably more changeable than ground temperature, and air-source heat pumps lose efficiency as a heating system as the air temperature cools in wintertime. Noise levels from the outside unit of an air-source heat pump are also greater than that of a ground-source heat pump.

Water-source heat pumps use water bodies (e.g. lakes or rivers) as a heat source, but they are not an available option for most homes.

Hybrid Heat Pumps

A hybrid heat pump is an integrated heating system comprising an electric heat pump and a gas- or oil- fuelled boiler. The system is designed to switch between the heat pump and boiler as heating sources dependent on which is most efficient at a given time - with the boiler typically being used at lower temperatures when the heat pump becomes less efficient or during peak-time electricity prices. Hybrid heat pumps can be designed so that both sources can run at the same time, which depending on the building being heated, may be more efficient.

FIGURE 6: A HYBRID HEAT PUMP SYSTEM TRIALLED AS PART OF THE FREEDOM PROJECT
(SOURCE: FREEDOM PROJECT, 2018)



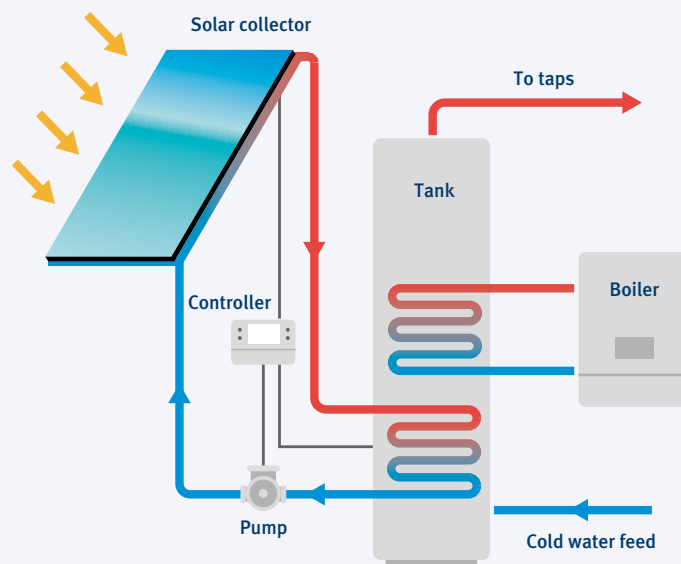
Hybrid heat pumps have a few advantageous characteristics, for both householders and the energy system, at least in the short term. Switching to gas can reduce use of electricity and networks during periods of high demand, especially during periods of very cold weather. They can also be used as energy arbitrage, switching between the two sources to take advantage of time-of-use price differences. Section 3.4 discusses the use of hybrid heat pumps in the Freedom Project trial and in relation to their potential to be offered to consumers via ‘Heat-as-a-service’ (HaaS) products.

Solar Thermal Systems

Solar thermal systems heat water by means of solar energy. Two typical types of solar thermal collector, flat plate and evacuated tubes, can be used to supply hot water in buildings. For flat-plate collectors, water or a heat-transferring working fluid is circulated via pipes embedded in rooftop-mounted panels, often made of copper and painted black to increase absorption of solar radiation and conductivity. In the more expensive evacuated tube format, a copper heat pipe is fed through an inner tube surrounded by a vacuum-containing glass outer tube. Solar radiation heats the copper pipe through the tubes, with the vacuum layer preventing heat loss through conductivity. This heat is then transferred to a working fluid, which will circulate to heat water in a separate tank. The advantage of this system is to minimise heat loss to colder external air, making it more efficient in cooler countries such as the UK.

3. Smart Electric Heating Technologies and Services

FIGURE 7: DIAGRAM OF SOLAR THERMAL WATER HEATING SYSTEM
(GREENFIELDS HEAT & POWER LTD, 2020)



In the UK, solar thermal technology is generally used exclusively for water heating, is less energy efficient or cost effective for space heating, and cannot directly replace electric or storage heaters. It is unsurprisingly more effective in summer months and may require boosting via a gas boiler or electric heater over winter. In most installations, solar thermal cannot be used with combi boilers due to the need for a hot water tank for exchange between the working fluid and the domestic water supply. It is less efficient and useful in the UK winter, when most heat is needed, but can provide the majority of domestic hot water (DHW) in warmer months.

In the UK, therefore, solar thermal is not a stand-alone solution for phasing out fossil fuels within buildings and will not be eligible for support in the Clean Heat Grants which will replace the domestic Renewable Heat Incentive (dRHI) (BEIS, 2020a).

Solar Photovoltaics

Solar PV use semiconductors to convert sunlight directly into electricity, and as a modular technology can be scaled from 1kW for small residential applications to over 1,000MW for some solar parks in countries with sufficient land and solar radiation (Jardine, 2015; Power Technology, 2020). First generation solar PV technologies are made of silicon and are still the most widely used. Second generation thin-film PV systems may be made of alternative materials, such as cadmium telluride or copper indium gallium selenide, and are cheaper but have lower efficiencies (Jardine, 2015; Staffell *et al.*, 2010). Third generation PV has been described as the “holy grail of PV technology development” (Jardine, 2015), with potential to attain greater than 20% efficiencies and benefit from low production costs. These comprise a diverse range of possible and competing materials and designs and are not yet fully commercialised.

Solar PV has a typical efficiency of 15% to 20%, although this is improving, with up to 40% achieved in some demonstration cases. This is significantly lower than residential solar thermal systems which can convert approximately 90% of solar radiation into heat (BP Lightsource, 2014). Output is affected by orientation, roof angle, solar radiation, and shading (e.g. nearby trees/satellite dishes). The installation cost for a residential scale solar PV system (typically 30m² of panels) can range from £5,000 to £8,000 (Energy Saving Trust, 2020a) (EST, 2020). The expected lifetime of solar PV modules is 25 years or more (Staffell *et al.*, 2010).

Solar thermal/PV hybrid panels ('PVT') such as DualSun (DualSun, 2020) increase the efficiency of PV by making use of the waste heat which reduces PV efficiency. Solar PV panels lose efficiency as they become warmer, e.g. a 0.5% efficiency loss for each degree of increased panel temperature (TheGreenAge, 2014). Solar PVT panels have reduced installation costs compared to two separate installations, use roof-space more efficiently, and the heat output is eligible for Domestic RHI support (provided the heat output of the system is separately rated in kWh). However, the dRHI will be replaced by the Clean Heat Grant in April 2022 through which the government is proposing to provide capital grants for heat pumps, but not PV, solar thermal or hybrid heat pumps (BEIS, 2020a).

Micro-combined heat and power (Micro-CHP)

Micro-CHP converts natural gas from the grid into both heat and electricity. It is more efficient overall than top performing gas power plants. Micro-CHP can be generated from internal combustion (IC) or external combustion (Stirling) engines, or from fuel cells (Staffell *et al.*, 2010; Staffell, Brett, Brandon, & Hawkes, 2015). The former engine-based technologies burn gas to generate heat and electricity at the same time. IC and Stirling engines are more typically used at larger scales (e.g. industrial or commercial), and their application to residential microgeneration

is relatively recent. Both engine technologies generate more heat than electricity. Their low electrical efficiencies reduce cost-effectiveness and CO₂ savings, and Stirling engines, for example, are best suited for older, larger retrofit houses with above-average heating demand (Staffell *et al.*, 2010).

Fuel cells run on pure hydrogen and can derive this from grid natural gas or liquid petroleum gas (Staffell *et al.*, 2010). The overall process is a direct, electrochemical conversion of hydrogen to electricity plus heat recovery. Fuel cells have an electrical efficiency in excess of 50%, compared to 10-25% for IC or Stirling engines (Staffell *et al.*, 2015). Fuel cell micro-CHP therefore has a greater ratio of electrical to heat output than micro-CHP engines, allowing a more flexible response to household electrical demand.

The UK market for residential micro-CHP remains small with comparatively low uptake of the technology (Staffell & Entchev, 2015). Fuel cell micro-CHP is still at an early stage of commercialisation; Japan owns 60% of global hydrogen fuel cell patents, and hydrogen cannot yet be distributed through the Japanese gas system (Vivid Economics & Imperial College London, 2019). Micro-CHP engines and fuel cells have an expected lifetime of up to 10 years (Staffell *et al.*, 2010, 2015).

3.2 Emitters

Heat emitters are used to distribute the heat generated and collected by thermal systems into the rooms and spaces of the property. Emitters can either transfer heat by radiation (the emission of electromagnetic waves) or convection (the transfer of heat via the movement of fluids or gases). Examples of convective emitters are hot water radiators, fan heaters and unit heaters. Examples of radiative emitters are UV lamps and underfloor heating.

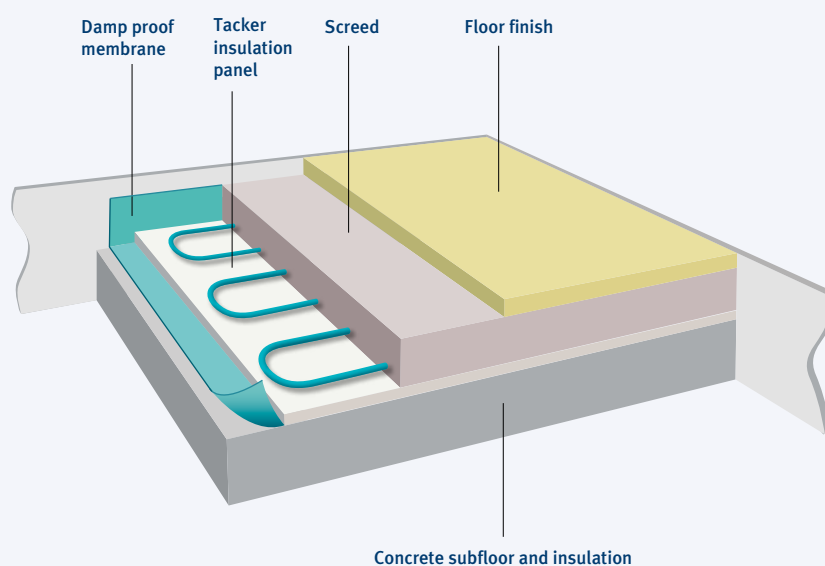
Radiators

Radiators contain constantly circulated hot water, which transfers heat to the metal surroundings and therefore out into the space surrounding it. Radiators emit the majority of their heat via convection, though approximately 20%, depending on design, is emitted via radiation. Water temperature in traditional radiators tends to be quite high – about 68-80°C. Smaller radiators, due to their lower surface area, need a higher temperature to achieve the same outputted heat. Larger or oversized radiators take up greater wall-space in rooms but can maintain comfortable room temperatures running at lower temperatures and so are compatible with heating sources which are more efficient at producing low-temperature heat, for example, heat pumps or solar thermal.

Underfloor Heating

Underfloor heating (UFH) involves heat being distributed by pipes or elements embedded in the floor, in effect making the entire floor a radiative emitter. Underfloor heating can be ‘wet’ (warm water circulating through pipes) or ‘dry’ (using electric elements) and is usually embedded in concrete floors. Underfloor heating typically has a lower temperature than radiators, averaging about 40°C; the larger surface area of the emitter compensates for this lower temperature and is sufficient to provide comfortable room temperatures. This makes it more suitable to use with heat-pumps, which typically generate hot water at a lower temperature than conventional boilers. It has several advantages – as the emitter is located underfloor, this frees up wall and room space which otherwise would be occupied by radiators, and the heat is distributed more evenly throughout the room, decreasing air movements and drafts and improving thermal comfort (see Box 1).

FIGURE 8: TYPICAL UNDERFLOOR HEATING INSTALLATION ON CONCRETE FLOOR.
(IMAGE CREDIT: HOMEBUILDING & RENOVATING)



UFH can provide good thermal mass storage especially if laid on concrete, although this is not very controllable and UFH tends to have low responsiveness, owing to the time it takes to heat up the surrounding flooring material. This requires a different heating cycle than traditional radiators – UFH may need to be turned on hours before the heat is required and will continue radiating heat for some hours after it is turned off, due to the thermal storage potential of the flooring. The thickness of the screed above the UFH determines the responsiveness and thermal storage potential, which may need to be altered in different rooms depending on purpose – a bedroom may require greater responsiveness than a living room, for example. Over 65% of domestic UFH installations are ground-floor only due to cost and weight considerations.

Thermal skirting

Due to the intrusive and disruptive nature of installation, underfloor heating is easier to incorporate into new-build houses and significant housing refurbishments. A less disruptive option for retrofitting existing housing stock is thermal skirting – a metal version of skirting board which radiates heat around the room. Compared to radiators, thermal skirting can, like UFH, free-up wall space for furniture and has a larger, more distributed surface area which again is conducive to thermal comfort. Thermal skirting will provide a smaller surface area than UFH however, so a higher water temperature may be needed for rooms of larger size and or greater heat losses. Thermal skirting should be more responsive than UFH, as it does not have to emit heat through floor coverings and has a lower thermal mass, but for this reason will also have less thermal storage capacity.

Air Fan Convectors

Fan convectors provide warm air when attached to a low- or -medium hot water system. Heat from water pipes passing through the convector are transferred to aluminium fins, which then heat air drawn in by the fan. These can operate effectively at lower temperatures than radiators (with a water temperature of approximately 35 °C being effective) and therefore can use the output of heat pumps relatively efficiently, though they lack thermal mass for energy storage, and are not supported by the dRHI (Energy Saving Trust, 2019).

Source/Emitter matching

Specifying a heating system for a given property must not only take into account the building's heat demand but also ensure the heat source and heat emitter are well matched. Matching is mostly influenced by the output temperature of the source and surface area of the emitter: lower-temperature heat sources require emitters with greater surface area than higher-temperature heat sources.

“Current incentives, such as the Domestic Renewable Heat Incentive, have encouraged suppliers to promote use of low temperature heat pumps (to maximize seasonal coefficients of performance), necessitating more expensive radiator and insulation upgrades and struggling to provide comfortable daytime temperatures without imposing higher night time temperatures.” p.113 (Energy Technologies Institute 2018)

» BOX 1: Thermal Comfort

Thermal comfort is the term given to an environment in which human beings do not feel uncomfortably hot or cold – where their bodies are maintaining thermal equilibrium with the surroundings. This is generally understood to be about 20-22 °C ('room temperature') in standard conditions and with typical levels of clothing, although drafts, humidity and activity levels can alter this.

The Fanger model, often referred to as Fanger's thermal comfort equation, was developed to understand the effects of skin temperature and sweat evaporation on thermal comfort rates, expressed as the predicted mean vote (PMV), a prediction of the response of a large number of people based on a sampling of responses in experimental tests. The model has a low predictive accuracy – predicting a given occupant's thermal comfort accurately only about one in three times (Cheung, Schiavon, Parkinson, Li, & Brager, 2019).

3.3 Smart Controls and Automation

Traditional domestic heating systems have relatively simple controls in which the user can schedule set time blocks for heating and hot water, often with a connected thermostat for heat control. Low-carbon heating solutions often have more complicated characteristics or benefit from more granular control. In addition, advances in digital technology have enabled automated heating systems which can utilise sensors and machine learning to provide a more efficient heating cycle. These two drivers are leading to an interest in automated, smart heating controls which can efficiently match the characteristics of heat generators and emitters to consumer use patterns.

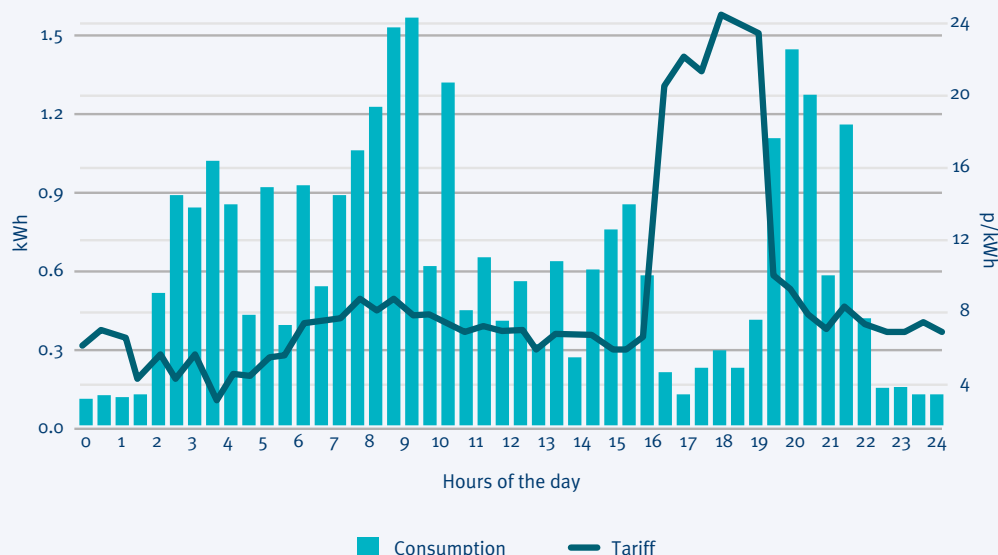
Properties of smart controls

Automation

Smart heating controls can lead to heating automation, where instead of the user setting timings for heat supply, algorithms can set heat generation timings based on occupancy, outside and inside temperatures and the characteristics of the heat generators and emitters. A gas boiler-radiator heating system, for instance,

will require less lead time for a room to reach a desired temperature than a heat pump-UFH system and will likewise cool quicker due to a lack of thermal mass. There are several brands of self-learning thermostats currently on the market that utilise a combination of occupancy sensors and self-learning algorithms based on when and how manual temperature adjustments occur to build a schedule that aims to automatically maximise thermal comfort and minimise energy consumption. Some smart heating controls can also be linked to smart meters to take advantage of time-of-use tariffs and schedule heating for times of low energy prices (see Figure 9 below). These are particularly effective when combined with heating systems which have an ability to store heat, either in hot water cylinders or in solid thermal storage. Smart controls are usually internet-enabled and come with companion mobile apps for users to control their heating from outside the home, for example to set heating on before arriving home or to turn it off due to absence.

FIGURE 9: EXAMPLE OF HEATING LOAD OF HEAT PUMP WITH AND WITHOUT LOAD-SHIFTING
(SOURCE: ROSENOW & LOWES, 2020)



Zoning

Many smart control models allow domestic properties to be divided into ‘zones’ in order to provide more granular control of heating supply based on the function and occupancy of the zones as well as the heating emitters present. Each zone can have its own thermostatically-set desired temperature as well as heating cycle. For example, living rooms may need to be kept at a relatively high temperature for most of the day and evening, whereas bedrooms could be heated only in the evening and morning with a lower desired average temperature. If part of a property is heated by UFH and the others by radiators, this will also benefit from a zoning scheme to take into account the different responsiveness of these technologies. Zoning can lead to greater energy efficiency and smarter usage of heating systems, though adds some complexity to heating controls.

Efficiency

Both automation and zoning deliver efficiency and cost savings. Smart controls can also produce greater efficiency by enabling several heating technologies and sources to operate in an integrated way. Examples of such ‘integrative design’ (Lovins, 2018) include the balancing of solar thermal panels and a gas boiler to provide hot water at a constant temperature, or the use of PV panels to generate electricity to drive a heat pump, with the addition of electric or thermal storage to provide heating during the night-time period.

3.4 Trials of low-carbon heating and smart controls

UK trials of low-carbon heating sources with smart control systems have shown several benefits to utilising smart and automated control with these sources. The Energy Systems Catapult has published findings from its Smart Systems and Heat programme, a combination of modelling, consumer engagement and

3. Smart Electric Heating Technologies and Services

demonstration installation (Energy Technologies Institute, 2019). This research identified several important areas to develop. Thermal comfort and cost are both very important to consumers, though there is a considerable variety in what consumers consider to be optimal thermal comfort and a large range in how often they manage their systems, from almost no management to significant micromanagement of temperatures in zones throughout the day. A smart zonal control system installed in consumers' houses led to a significant improvement in their perceived thermal comfort at either the same or lower cost of heating. Likewise, modelling showed the advantages of smart zonal heating controls – enabling high levels of thermal comfort with lower peak demand and smaller installed appliances than standard heating systems. While improvements to existing building fabric, such as greater levels of insulation, are important, the modelling finds that these need to be combined with smart controls in order to be effective. Fabric improvements without smarter controls could ironically lead to higher costs and lower levels of thermal comfort than before.

The Freedom Project, a joint initiative between Western Power Distribution, Wales and West Utilities and PassivSystems to trial hybrid heat pumps (Freedom Project, 2018) found that an optimally-managed hybrid system responding to appropriate market signals can provide heating that responds quickly to market signals (for cost or carbon intensity) while maintaining the same levels of thermal comfort as a conventional system. A new market and regulatory framework will be needed to fully realise this flexibility, though hybrid heat pumps already see a financial benefit for off-grid properties utilising oil heating. This type of automated flexible hybrid heating could be offered to consumers in a 'heat-as-a-service' product, where customers pay for a given level of thermal comfort and flexibility instead of metered units of energy (pay-per-use). Both the Freedom Project and Smart Systems and Heat trials saw consumer appetite for this model, which rose significantly among consumers who trialled the new technologies.

3.5 Barriers to uptake and solutions

A range of low-carbon heat technologies and solutions already exist but improving the consumer experience is key to increasing their uptake. Given the reliance of UK households on gas boilers for heating over several decades, low-carbon alternatives will at least need to match if not surpass current consumer offerings and experiences with gas boilers and central heating (ETI, 2018; ESC, 2018).

Fewer than 40,000 new heat pump installations were supported by the Renewable Heat Incentive from 2014 to 2019 (BEIS, 2020b). This low uptake is linked to various financial and non-financial barriers. The chief financial barrier is a relatively high upfront cost, which the RHI tariff-based payments have not effectively addressed. Non-financial barriers include low awareness of heat pumps, the inconvenience involved in installation and difficulties finding skilled and trusted installers (Balcombe, Rigby, & Azapagic, 2014); Richard Hanna, Leach & Torriti, 2018).

A broader challenge in terms of consumer engagement is low public awareness of heat as a priority area for climate action and of alternative low-carbon heating technologies. In a survey of 2,000 consumers covering public attitudes on low-carbon technologies, the Energy Systems Catapult (2020) found that: only 49% of respondents "identified gas boilers as a contributor to climate change"; less than 20% "would consider switching to low carbon heating"; and less than 2% "had switched their heating system to low carbon in recent years". While approximately half of those surveyed were aware of low-carbon heating solutions, there was a recognition that switching to these technologies would be costly and difficult (Energy Systems Catapult, 2020).

There is no need to wait for gas (or oil) boilers to come to the end of their lifetimes; if householders wait for their boiler to break down, this will very likely lead to the “distress purchase” of a replacement boiler. Replacing fossil fuel heating systems now can save significant carbon emissions if they are replaced by zero- or close to zero-carbon heating systems (Rosenow & Lowes, 2020; Finnegan, Jones, & Sharples, 2018).

Smart meters are a vital part of the infrastructure required to enable consumers to participate in more flexible electricity consumption. Households need to have a smart meter, or get one installed, if they wish to sign up to smart tariff offerings. The delay in the smart meter rollout progress is also impacting on the timeline for the introduction of a mandatory market-wide half-hourly settlement regime by Ofgem. This regime is intended to help provide the right ‘incentive framework’ to suppliers for “bringing forward new products, services and business models, supporting more dynamic competition, and helping consumers to manage and shift their consumption to cheaper periods” (Ofgem, 2018c, p.69).

The ‘connected home’ is a promising route for introducing consumers to smart technologies and engaging consumers with smart heat solutions (Energy Systems Catapult, 2018). Evidence suggests that consumer first-hand experience with smart technology and services leads to increased interest in other smart products via a ‘familiarity effect’ (Carmichael et al., 2018); this could also mean that adoption of smart charging for electric vehicles helps prepare consumers to engage with smart flexible heat. In this sense, advancing all flexibility services, and EV smart charging specifically, could make consumers more aware of savings and other benefits possible through flexibility and, therefore, more receptive to adopting smart heat.

The ownership rates of smart devices has risen rapidly in recent years. There is some emerging evidence that the use of smart home assistants could help to motivate purchases of other smart appliances for heating and lighting. Developing standards for smart devices could encourage consumers to buy their own hardware enabling flexibility, known as a bring-your-own-device (BYOD) business model (BEIS, 2018a; Chase *et al.*, 2017; Carmichael, Gross, & Rhodes, 2018). In order to reduce barriers to uptake, it has been suggested that the UK government should introduce and mandate common standards for smart appliances, including interoperability, grid-stability, cyber-security and data privacy (BEIS, 2018a). Interoperability would help consumers to avoid the cost of replacing incompatible appliances. At present, air source heat pumps and gas boilers do not typically have smart hybrid functionality. Manufacturers should be incentivised to provide this and Government support schemes such as the dRHI, and its replacement the Clean Heat Grant, could stipulate a requirement for smart controls in heat pumps and storage devices (Carmichael, 2019).

4. Building Thermal Efficiency for Reduction and Load-shifting

4.1 Benefits of thermally efficient buildings

A thermally efficient building fabric supports low-carbon heating in three ways. Firstly, a home with lower heat losses (through walls, roof, floors and openings) reduces the overall heat required for space heating and so reduces consumption, carbon and energy bills.

Secondly, this lower rate of heat loss enables flexibility by pre-heating. The home can stay warmer for longer even when the heating system is off for extended periods. The building effectively acts as a thermal store. For electric heat, this allows the living space to be heated during cheaper off-peak periods when renewable energy is plentiful; heat pumps can be turned off during periods of limited supply, high demand or grid constraint, further cutting costs for the household and system operator.

The length of the 'off-block period' - when heat pumps are not running - will depend on building thermal performance. The Annex 42 project (Delta-EE, 2018) aimed to understand the capacity of the UK building stock to provide flexibility when heated with heat pumps. The modelling showed that, "the level of flexibility is strongly dependent on the thermal characteristics of the building, with increased thermal mass and insulation levels having a positive effect on the switch-off times" (Delta-EE, 2018; p.4). Analysis for a Northern Ireland context also found that the scope for flexibility was strongly affected by the building thermal mass and that for heating systems with a low thermal mass, the presence of a thermal energy storage (TES) unit was important (Arteconi, Hewitt, & Polonara, 2013). More real-world data is needed but more efficient buildings clearly permit demand reduction and longer off-block

periods. Dedicated thermal storage devices, such as hot water tanks, will be discussed in the following chapter.

Thirdly, thermally efficient buildings allow zero and low-carbon heating systems to be specified and operate in an efficient and cost-effective manner not possible in homes with high heat loss (Hansen, Connolly, Lund, Drysdale & Thellufsen, 2016).

"The 'right' balance between energy efficiency and flexibility and low-carbon heat supply is highly context-dependent but in most, if not all, cases will include all three elements in order to avoid unnecessary overinvestment." (Rosenow & Lowes, 2020a)

» BOX 2: EPC and SAP energy efficiency ratings

An EPC, or Energy Performance Certificate, is a rating system used by the Government to assess and compare the energy and environmental performance of dwellings. For new buildings the EPC is calculated using the Standard Assessment Procedure (SAP). Existing buildings are assessed using the Reduced Data Standard Assessment Procedure (RdSAP).

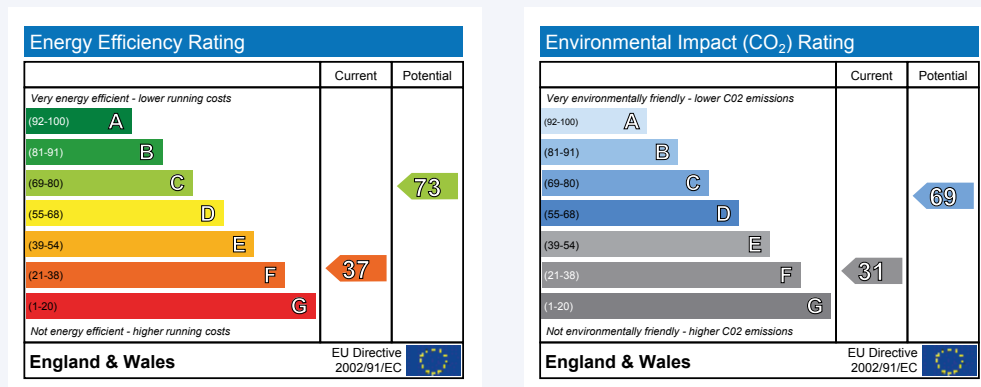
The SAP and RdSAP assessments are the basis for establishing compliance with Building Regulations as well as EPCs.

EPCs have two metrics for energy efficiency, both banded A-G (in both cases, a rating of A is equivalent to a SAP score of 92 to 100 points). EPCs also give recommendations for energy efficiency improvements. These are generated by the EPC software based on the current features of the building and cost-effectiveness criteria.

Energy Efficiency (the main 'EPC' rating) is based on estimated fuel cost (expressed in £/kWh/m²). A building with a score of 100 has no heating or hot water costs while dwellings with a rating in excess of 100 are net exporters of energy.

Environmental Impact (EI) ratings are based on estimated carbon emissions (expressed in CO₂/m²).

FIGURE 10: EXAMPLE OF ENERGY EFFICIENCY AND ENVIRONMENTAL IMPACT RATINGS SHOWN IN AN EPC



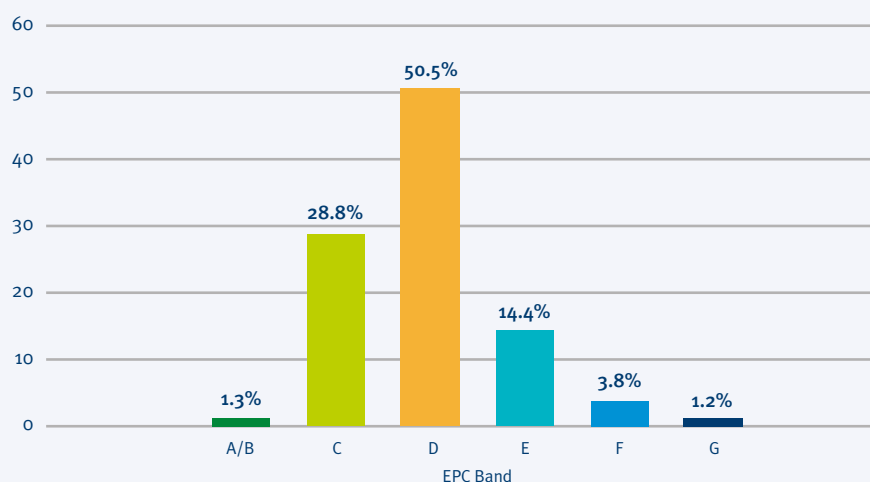
4. Building Thermal Efficiency for Reduction and Load-shifting

4.2 UK building stock

The energy performance of UK dwellings saw some improvement between 1996 and 2016 but progress has stalled in recent years. UK homes are among the oldest and least thermally efficient in Europe with only 29 per cent of homes today reaching EPC band C (Green Alliance, 2019). The most common EPC rating for homes across Great Britain is D and only around 1.5% of properties have A or B ratings (Stephens *et al.*, 2020).

Depending on the measure used, between 10% and 13% of households are considered to be living in fuel poverty. In Scotland, the figure is almost 25% (Regen, 2020) and this may underestimate the problem due to some households not being able to afford the heat they need. Poorly heated homes contribute to reduced physical and mental wellbeing and excess winter deaths and so heat decarbonisation must consider how solutions impact fuel poor and vulnerable households. Fuel poverty is closely linked to building energy efficiency (CCC, 2016) and homes using direct electric heating (National Statistics, 2019).

FIGURE 11: PERCENTAGE OF ENGLISH DWELLINGS IN EACH ENERGY PERFORMANCE CERTIFICATE (EPC) BAND A-G (2017 DATA). SOURCE: UK HOUSING REVIEW 2020
AT <https://www.ukhousingreview.org.uk/ukhr20/tables-figures/pdf/20-024.pdf>



4.3 Problems with EPCs and SAP

The EPC system regularly issues poor ratings for homes with heat pumps and installers have complained that EPCs do not recommend heat pumps as an energy performance improvement measure (Rosenow, 2019). One problem is that the main EPC efficiency rating is based on the financial cost of heating a property: as electricity prices are far higher than natural gas prices, heat pumps fare poorly on cost compared to gas boilers. Further, electricity running costs assume a flat-rate tariff for electricity, so the lower costs

available to heat pumps by operating on time-of-use tariffs are also not reflected in EPCs.

EPCs also assume a poorer operational efficiency for heat pumps than field trials suggest, affecting both cost and Environmental Impact scores. Moreover, official government figures now show that electricity is cleaner than gas (BEIS, 2019) but the SAP/RdSAP uses an outdated carbon factor for electricity dating from 2012, resulting in a lower rating for heat pumps (CCC, 2019c; Rosenow & Lowes, 2020). This has been recognised and the next version of the Standard Assessment Procedure will use

a corrected, lower carbon emissions factor for electricity of 0.233 kg CO₂ per kWh, compared to 0.210 kg CO₂ per kWh for gas. Rosenow (2019) recommends adopting “a dynamic carbon factor that can be updated as the power system gets cleaner”. Ideally, this would also recognise the fluctuation in carbon intensity of electricity (grid carbon factors) linked to time-of-use and the lower emissions associated with off-peak and flexible consumption. The EPC rating system is intended to encourage low-carbon buildings but is currently not supporting smart flexible electric low-carbon heating.

BEIS and MHCLG (Ministry of Housing, Communities & Local Government) are also currently considering ways in which the use of Energy Performance Certificates could be improved. One possibility is that smart meter and other building data could be used to improve the accuracy of the EPC ratings. BEIS’ SMETER (Smart Meter Enabled Thermal Efficiency Ratings) programme aims to develop, test and demonstrate technologies that measure the thermal performance of homes using smart meter and other data (BEIS, 2018). This work could feasibly contribute to making EPCs more compatible with, and supportive of, smart technologies and services for heat.

Another example of the EPC metrics holding back innovation concerns emitters (Chapter 3). At present there are three categories for emitters – radiators, oversized radiators and underfloor heating. Other emitters – for example thermal skirting – are not represented in the scoring system or recommended actions. As a general point, regulation intended to promote low-carbon energy should not act as a barrier to the adoption and commercialisation of innovative products and services.

4.4 New-build

Given that no new gas connections will be permitted to new-build homes from 2025, it will be vital that these buildings are energy efficient in order to be cost-effectively heated with heat

pumps. It is much cheaper to make a home zero-carbon at build stage than through retrofitting but policies to support low-carbon new-build have been weakened or withdrawn, including Zero Carbon Homes and the Code for Sustainable Homes. This has led to many new homes being built only to minimum standards for energy efficiency; for example, just 1% of new homes in 2018 were Energy Performance Certificate band A (CCC, 2019c). Also, the ‘as-built’ performance of homes must be better monitored and enforced to close the energy use performance gap in new homes (the difference between how they are designed and how they actually perform) (CCC, 2019c). The CCC have called for the Future Homes Standard to be fully defined now, legislated before 2024 and its introduction brought forward if possible, in order to build industry confidence and upskill the workforce (CCC, 2020).

4.5 Building fabric retrofit

Around 80-85% of the homes of 2050 have already been built (IET & NTU, 2020). Over 70% of homes currently fall short of the EPC band C standard the UK Government has set as a target for all dwellings by 2035. Retrofitting the 27 million existing homes has, therefore, a much greater potential than new-builds for cutting emissions, driving commercialisation of products and improving comfort and wellbeing.

As with new-builds, the UK’s current policy approach to retrofitting is too vague and lacks the required ambition to tackle the scale of the challenge (Green Alliance, 2019). The House of Commons Business Energy and Industrial Strategy Committee reports that the £5 million Green Home Finance Innovation Fund is “woefully inadequate to stimulate demand for energy efficiency within the ‘able to pay’ sector [...and provide] sufficient incentives for the market to grow” (House of Commons Business Energy and Industrial Strategy Committee, 2019 ; p.3-4).

Improving the thermal performance of existing UK housing could be achieved principally by increasing insulation levels (e.g., double/

4. Building Thermal Efficiency for Reduction and Load-shifting

triple glazing and solid wall insulation) and by improving building airtightness (e.g., draughtproofing and mechanical ventilation with heat recovery (MVHR)). Adding thermal mass can also help with passive solar gain and with avoiding peak-time electricity demand for heat pumps but can also lead to over-heating in summer. The CCC have stressed the importance of considering fabric efficiency, overheating and ventilation jointly when retrofitting or building new homes, to reduce the high risk that poor ventilation and air-tightness will lead to overheating and poor indoor air quality (CCC, 2020).

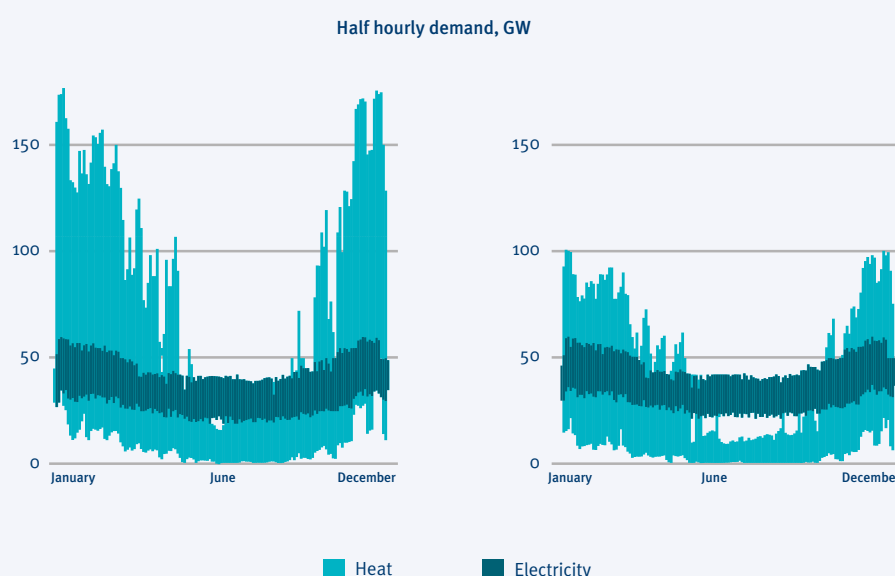
4.6 Barriers and solutions for retrofit

As the figures for EPC ratings attest, uptake of retrofit measures to improve the energy efficiency of UK housing is low. Reasons for this include the inconvenience of building work and consumers' unfamiliarity with technology and installers. While costs are paid upfront, the benefits are not wholly clear and savings accrue over a longer timeframe.

Most home improvements are carried out for improved amenity and comfort rather than energy efficiency (Wilson, Chryssochoidis, & Pettifor, 2013). It makes sense to piggyback on these works to install energy-saving building improvements at the same time; these should be aligned to 'trigger points' points of contact with service providers (Ibid).

New approaches and business models are also needed to drive better engagement by mitigating householders' concerns about trust and transparency and address the key difficulty of how to finance building fabric improvements which inevitably have long payback periods. The Energiesprong ('energy leap') approach, for example, uses off-site construction and delivery at scale to cut the cost of whole-house retrofits that reduce energy demand to net zero at no net cost to the occupiers (Regen, 2020). This is typically achieved by installing: a new thermally efficient façade; a heat pump; solar PV roof panels and optional batteries. These retrofits are funded with a whole-life financing model, where the cost is covered by lower bills and home maintenance costs (Green Alliance, 2019).

FIGURE 12: ENERGIESPRONG BUILDING RETROFIT COULD LOWER PEAK DEMAND BY 41%
SOURCE: (GREEN ALLIANCE, 2019)



In terms of government policy, support could be increased for retrofit of all energy efficiency improvements to building fabric to replace the UK's current major domestic retrofit programme (Energy Company Obligation). Options include: Variable Council Tax and Green Mortgages (EeMAP, 2017; Miu, Wisniewska, Mazur, Hardy, & Hawkes, 2018) and access to low interest loans, as advocated by a number of organisations including IPPR, ACE, SEA and the CCC (BEIS, 2017a). The size of loans available should be compatible with an integrated 'whole house' approach to heating and insulation (a feature which was lacking from the Green Deal). It is worth noting that 64 per cent of the UK public "support more investment by government in combatting climate change, including investment in renewables and insulating homes, with only 9 per cent opposed" (Meadway, 2019; p.3).

Government support for a mass programme of building retrofits also holds an opportunity for green recovery and job creation, especially timely in the context of the economic impacts of COVID-19. An extensive survey of experts, policy cataloguing and review of policy literature highlighted building efficiency retrofits as one of five recommendations for achieving economic and climate goals (Hepburn, Callaghan, Stern & Zenghelis, 2020). Garrett-Peltier (2017) finds that almost three times as many jobs are created in energy efficiency as in fossil fuel industries per \$1 million of spending.

Making UK housing more energy efficient could also unlock further economic activity by reducing barriers to households adopting low-carbon heating systems and the storage technologies discussed in the following chapter.

4. Building Thermal Efficiency for Reduction and Load-shifting

5. Smart Thermal Energy Storage

As an alternative, or in addition to, preheating the living space, load-shifting can also be achieved using dedicated storage technologies. Around 3.5 million UK households use reduced-rate electricity overnight to store heat in night storage heaters and domestic hot water (DHW) tanks. These storage heaters and ‘legacy TOU’ tariffs, such as Economy7 and Economy10, were introduced to use spare night-time capacity from nuclear power and today storage heaters are the primary method of heating for around 1.7 million UK households (NEA, 2019).

The transition to variable renewables and the need for flexibility now presents a very different context. The choice of both storage technologies and electricity tariffs has also moved on. Traditional night storage heaters (containing thermal mass in the form of ceramic/bricks) release the stored heat gradually over the following day. Limited controllability means that occupants find they are too hot in the morning and by evening the heat has dissipated so they have to resort to expensive on-peak supplementary heating to provide adequate thermal comfort. A number of better storage options exist now which provide better controllability, integration with low-carbon heating systems and greater opportunities for reduced heating costs.

5.1 Types of smart thermal energy storage (TES)

Smart thermal energy storage (TES) devices can overcome the limitations of legacy night storage heaters by being able to retain more heat over longer periods, release it with greater control, and respond automatically to changes in electricity rates. New materials also offer more compact energy storage. The major types of TES are discussed below.

Water

There are approximately 11 million UK homes with domestic hot water (DHW) tank-based storage systems, largely heated overnight using electricity on Economy7 tariffs. Smart hot water tanks are now available: for example, Mixergy’s smart hot water tanks use stratification and intelligent control that allow users to selectively heat a smaller portion of the tank and have Internet connectivity enabling integration with dynamic time-of-use tariffs.

Modelling of water storage by the Energy Technologies Institute finds that, “reducing or entirely eliminating power draw from the heat pump during the evening peak demand period is possible with technically feasible quantities of storage” (Energy Technologies Institute, 2018; p.109). The storage required for a typical UK home in the North East of England, with a comprehensive insulation retrofit, would be around 20kWh – about twice that of a standard DHW tank. The lower temperature of the stored water means the tank would need to be around 2.5 times the size of a typical DHW storage tank (Ibid). Dwellings will differ in the amount of suitable space available for a thermal store. A cost-optimum sizing of tank would still require some use of the heat pump during peak hours on coldest days and this may require some network reinforcement.

Some other options exist for maintaining thermal comfort on the coldest days, including preheating rooms, further improving building efficiency, or having gas boilers provide back-up heat (this would align with the hybrid heat pump scenario outlined in Chapter 3). If storage costs fall, as technology learning curves would predict, the cost-optimal sizing for storage would increase. Similarly, if heat electrification and the penetration of renewable generation increase

substantially, as anticipated, greater rewards for flexibility and arbitrage would also increase the cost-optimal sizing of storage that can make greater use of surplus renewable generation.

TABLE 1: ADVANTAGES AND DISADVANTAGES OF WATER FOR THERMAL ENERGY STORAGE

Water TES	
Advantages	Disadvantages
Can have multiple inputs, both thermal and electric	Three times less energy dense than Phase Change Materials and nine times less than electrochemical batteries
Heat sources need not be high temperature (e.g., compatible with solar thermal)	If used for heating they would be likely to require greater space per kWh stored than existing DHW cylinders, due to a lower temperature of stored water.
Can release stored heat at a faster rate than electro-chemical batteries powering a heat pump	
Longer lifespan than electrochemical batteries	
Smart storage tanks can use stratification to avoid needing to heat whole store to desired temperature	
No shortage or uncertainty over availability of raw materials	

Phase change material (PCM) heat batteries

Phase change materials (PCM) operate by storing and releasing latent heat as the materials change between solid and liquid. PCM heat storage systems have 75-90% efficiency and can be used with both conventional and renewable high temperature heat sources (BEIS, 2016b). SunAmp produces heat batteries which can receive input from photovoltaics (PV) or grid electricity. PCM Products produces a range of phase change thermal storage including modules for underfloor applications with 27°C (81°F) phase change material that can increase the thermal mass of a building by as much as 10-15 times, capture excess heating during the day and maintain that heat into the night.

TABLE 2: ADVANTAGES AND DISADVANTAGES OF PCM-BASED THERMAL ENERGY STORAGE

Phase-change material PCM TES	
Advantages	Disadvantages
Three times more energy dense (compact) than water	Three times less energy dense than electrochemical batteries
Can have multiple thermal inputs, conventional and renewable (e.g., PV)	May require high temperature heat source/inputs, thus solar thermal currently little used
Can release large quantities of stored heat at a faster rate than electro-chemical batteries discharging to power a heat pump	
Longer lifespan than electrochemical batteries	

Electrochemical battery storage

A number of companies now offer home battery storage including Tesla, Powervault and Moxia. Used batteries from electric vehicles can also be given a ‘second life’ as home storage batteries when their performance drops.

Power from these batteries can be used in direct electric heating systems (e.g., dry UFH or thermal skirting) but greater efficiency is achievable if used to power a heat pump. Using a battery storage to generate heat in this way “would shift the storage of energy from the output side to the input side of the heat pump. This would reduce the quantity of energy storage required by a factor equal to the heat pump’s CoP (coefficient of performance)” (ETI, 2018; p.111). Whereas an electrical resistance heater has a CoP of 1.0, the CoP of air source heat pumps range from 3.2 to 4.5 and ground source heat pumps between 4.2 and 5.2 (depending on outdoor air/ground temperatures and required temperature of output). A home battery that stored 10kWh² worth of power would, therefore, provide 10kWh of heat if passed through direct electric heating but if used to run a heat pump with a CoP of 3.0 would yield 30kWh of heat.

In addition, a heat pump drawing from stored electricity could run when heat is needed without drawing power from the grid during peak hours. More of the heat pump’s operation would therefore avoid overnight operation (to charge a thermal store) when outdoor temperatures are lower. This results in higher CoPs and reduced night-time noise (ETI, 2018).

Innovation in electro-chemical battery storage could considerably reduce future costs, although there is considerable uncertainty (Schmidt, Hawkes, Gambhir & Staffell, 2017).

5. Smart Thermal Energy Storage

² Powervault 3 is a single unit, available in four different capacities: 4.1kWh, 8.2kWh, 12.3kWh and 16.4kWh. Tesla’s Powerwall holds 13.5kWh.

TABLE 3: ADVANTAGES AND DISADVANTAGES OF ELECTRO-CHEMICAL THERMAL ENERGY STORAGE

Electro-chemical storage	
Advantages	Disadvantages
Around 80% to more than 90% efficient for newer lithium ion devices	Lithium batteries have shorter lifespans (performance degrade more quickly)
Much more energy dense than water TES (x9) or PCM (x3). If used to power a heat pump the CoP makes storage even more compact	Maximum heat output of the system is limited by the heat pump capacity (ETI, 2018)
Can also supply other household appliances during periods of high electricity price and also participate in grid-balancing services	Greater embodied energy in manufacture
Can allow heat pump to run during periods of warmer outside temperature rather than running HP overnight to charge a thermal store	Only compatible with electrical input not thermal inputs

Thermo-chemical (TCS) storage

Thermochemical heat storage systems use reversible thermo-chemical reactions. They are not market-ready yet but in the future could offer very compact storage without heat loss or the need for insulation.

5.2 Barriers to adoption and solutions

Various combinations of heat source and storage device are possible. Smart storage devices have a significant role to play in cost-effectively delivering flexible low-carbon electric heating, but more modelling and analysis is needed to further understand which combination of technologies best suit which applications and households in the most cost-effective manner (ETI, 2018). Consumer engagement and adoption of these TES technologies and accompanying services will be a key issue. Some of the barriers to household engagement and recommendations for accelerating adoption are discussed below.

For some homes, restriction on available space may be a barrier for many TES technologies. Where even compact TES may be unfeasible or not cost-effective, shared communal or community-based energy storage (CES) may become a viable solution. Grid-scale energy storage has also recently emerged.

Thermal or electrical storage devices offer an alternative to, or can complement, preheating the living space. Their installation is likely to be less disruptive, and for many properties cheaper, than improvements to the building fabric and so may present fewer barriers to widespread adoption.

5. Smart Thermal Energy Storage

Cost-effectiveness and affordability are still barriers for consumers.

“For a cost-efficient decarbonised system, consumers should be directly incentivised for intelligent and efficient energy and network use. This can only be achieved if customers are rewarded for shifting demand away from peak times and providing flexibility to the networks to help manage system stability and constraints. Alongside smoothing generation peaks and troughs, flexible asset technologies can provide other valuable grid services like frequency response. [...] By removing barriers to demand flexibility and introducing more efficient market dynamics, the uptake of flexible technologies will accelerate.” (Powervault, 2020)

Policy changes that reduce the costs of, or increase the rewards for, behind-the-meter storage devices enabling load-shifting could improve adoption. Specific new support for TES could include zero VAT rating of all home energy storage (electrical or thermal), as is the case in new build housing, but legislation is currently moving towards increasing rather than lowering VAT on storage.

Another specific area of regulation affecting the cost-effectiveness of investment in and operation of storage is Ofgem’s Significant Code Reviews.

“The largest uncertainty for electricity storage assets is the two Ofgem Significant Code Reviews currently underway, the Targeted Charging Review (TCR) and the Electricity Network Access and Forward-Looking Charging Review. Analysis by Aurora suggests this will reduce the business case for electricity storage by imposing new charges and reducing sources of value. At this stage it is unclear whether the second of the reviews might improve the business case for batteries. Many stakeholders are asking for the timelines of the two reviews to be better aligned to reduce uncertainties.” p.28 (Morris, Hardy, Elmes, Hannon, & Hepburn, 2018; p.28)

Ofgem has confirmed controversial plans for the TCR that will see all businesses and households pay for the use of the electricity network via a fixed charge. The fixed transmission charges will be introduced in 2021 and distribution charges in 2022. The REA also consider that the TCR decision will negatively impact homes and businesses who have taken steps to install low-carbon technologies on-site and is likely to undermine the business case for batteries and other forms of storage until the Access and Forward Looking Charges review currently scheduled to be implemented in 2023 (REA, 2020).

6. Conclusions

The decarbonisation of heating will require a coordinated approach across buildings, heating systems, the power sector and infrastructure. This will take time, so progress is urgently needed (Rosenow & Lowes, 2020a). Despite some uncertainties about the pathways to decarbonising UK domestic heating, the electrification of heat through heat pumps is anticipated to play a major role. The electrification of UK transport and at least a large portion of heating poses two key challenges: having enough low-carbon generation capacity and balancing supply and demand.

The increase in electricity demand for heating would raise a typical UK household's annual electricity consumption from around 3 MWh (Ofgem, 2020) to 8 MWh (ETI, 2019). Charging for electric vehicles will typically add a further 3 MWh (Ibid). Whilst this is a dramatic increase, it is, in principle, feasible to supply these new loads with low-carbon power if sufficient commitment is shown to expanding offshore wind and other renewables.

The Government has shown commitment to decarbonising power through variable renewables. But if the grid is to be operated in a secure and cost-effective manner the new electricity loads for heat and transport will need to have a degree of flexibility to remain within the constraints of supply and the distribution network. This, too, is feasible. Fortunately, both heat and EV-charging have considerable scope for load-shifting, especially when facilitated by smart controls and pricing incentives for flexibility. Greatly improving building thermal efficiency could reduce overall demand for heat and allow living spaces to be preheated during off-peak periods, so that heating loads could be shifted to off-peak times. Energy storage devices also hold great potential for further enabling flexibility in power demand for heat.

Both air-source and ground-source heat pump technologies are proven, reliable and remarkably efficient: thermal output from heat pumps is several times the electricity input, as long as they are installed correctly. The greatest efficiency is achieved when heat pumps are run continuously at lower temperatures and paired with emitters with large surface areas such as underfloor heating (UFH) or over-sized radiators. Modestly-sized heat pumps have also been shown to be able to maintain thermal comfort without changing radiator sizing when operating as a hybrid system in tandem with an existing boiler and smart control system (Freedom Project, 2018). While these smart hybrid heat pump (HHP) systems are able to reduce carbon emissions from heating by displacing 80% of gas usage, financial savings are currently only seen in homes off the gas grid that use more expensive LPG or oil. However, these HHP trials did not include storage or building fabric interventions, all of which could improve the financial case for heat pumps.

This briefing paper has discussed four key elements for enabling smart, flexible and cost-effective electric heating in UK homes:

- (i) low-carbon heating systems to replace fossil fuel use;
- (ii) cost-reflective electricity pricing to incentivise load-shifting;
- (iii) thermally efficient buildings to reduce consumption and enable pre-heating;
- (iv) smart storage devices to enable load-shifting.

The planned Future Homes Standard should assure an end to fossil-fuel heating systems in all new houses from 2025. A greater impact and challenge, by far, will be switching the 27 million existing UK homes to low-carbon heat. The successful decarbonisation of heat through

electrification will hinge on households adopting new end-user technologies within their home: heat pumps, storage devices, deep retrofits for building fabric improvements, and accompanying time-of-use tariffs and other demand response (DR) offerings.

There are a number of barriers to mass adoption of these technologies and services. These challenges, and some options for overcoming them, are summarised in Figure 13 and discussed below in terms of more supportive policy and other interventions to enable informed adoption.

6.1 Policy and regulation for smart electric heat

Up-front costs are a significant barrier to upgrading heating systems and building efficiency improvements. 80% of consumers surveyed report they ‘would not or could not afford’ the relatively straightforward case of a hybrid heat pump installation (Clarke, 2018). Even for able-to-pay households, possible savings from energy storage systems which could be enjoyed over the longer term usually count for less in household decision-making than the immediate up-front costs (this cognitive bias towards near-term costs and gains is known as ‘temporal discounting’).

For these reasons, it is a positive step that the tariff-based payments under the Domestic Renewable Heat Incentive (dRHI) will be replaced in April 2022 by a Clean Heat Grant of £4,000 towards the cost of heat pumps, albeit with quarterly grant windows and a cap on spending (BEIS, 2020a). Smart controls are key to enabling intelligent and cost-effective flexibility, but air source heat pumps are not generally ready for smart digital control. Setting standards for smart appliances and stipulating smart controls on all heat pumps as a requirement for grant eligibility would, therefore, be a valuable step. Other measures to reduce up-front costs might include reducing VAT to zero on all installations of smart heat pumps including smart controls.

Reducing heat pump running costs could impact not only on householders’ purchase decisions but also on customer satisfaction and affect the offerings that suppliers and third parties would consider economically viable. One way to make the running of heat pumps more economical is by enabling greater tariff arbitrage: using electricity during cheaper periods and avoiding peak-rate electricity.

The biggest challenge to the adoption of smart electric heat and home energy storage technologies is the lack of a route to market and revenue streams for residential flexibility (OVO Energy and Imperial College London, 2018). Introducing a ‘flexibility first’ approach to new regulation that improves access to the full market value of flexibility in household electricity demand could make investment in heat pumps, storage and building fabric more cost-effective (Ibid). Such changes could also incentivise suppliers to offer new cost-saving demand response services including the bundling of hardware, such as heat pumps and storage, along with smart tariffs or heat-as-a-service (HaaS) models to offer households an integrated solution. Regulation that facilitates the stacking of revenue streams from an asset such as a battery (Morris *et al.*, 2019) for example, could make such technologies more cost-effective and attractive. Burke, Byrnes, & Fankhauser (2019), Gisse *et al.* (2019) and Hirst (2020) all argue that carbon pricing (Carbon Price Support) successfully pushed coal off the grid and that a stronger carbon pricing mechanism could further decarbonise power and support flexibility linked to variable renewables.

In some cases, the regulations intended to encourage commercialisation and adoption of low-carbon heating technologies may be acting to restrain uptake. The EPC system uses out of date carbon factors for electricity that will be updated; the new carbon factor should dynamically reflect ongoing decarbonisation of power (Rosenow, 2019). Ideally, improvements to EPC methodology would also reflect both the lower carbon intensity and lower costs associated with flexible consumption.

6.2 ICT for informed adoption of smart electric heat

From a Diffusion of Innovation perspective, innovative technologies and services are adopted more rapidly when they are seen as having: high *relative advantage*, *trialability* and *observability* and *low complexity* (Rogers, 2003). In terms of ‘relative advantage’ (the perceived superiority and attractiveness compared to existing products), consumers will need to be offered low-carbon heating propositions that are at least as attractive as the gas boilers to which they have grown accustomed for over a generation.

Cost will be a central part of comparisons and decisions about adopting new technologies and we have outlined some policies above which could improve the affordability and cost-effectiveness of smart electric heat solutions and building improvements. But consumers’ decisions also involve a new level of *complexity* which is a further barrier to uptake. A wide range of heating technologies, tariffs and other supplier offerings presents a ‘choice overload’. This is compounded by the ‘cognitive overload’ of trying to calculate and compare future costs and savings for unfamiliar technology and smart tariffs. Consumers tend to defer and procrastinate when faced with information and choice overload (Strong, 2014). Heat-as-a-service models and other third-party services may take away some of this complexity, and indeed risk, for consumers but choosing between them and other options still falls on the consumer. There is an important opportunity for price comparison websites (PCWs) to support informed consumer adoption of smart flexible heat solutions by including smart energy services and bundled offerings in their market comparisons (Carmichael, 2019; Carmichael, Gross and Rhodes 2018; He, Azevedo, & Meeus, 2013); work, funded by BEIS, is ongoing to develop such smarter digital comparison tools (<https://www.gov.uk/government/publications/smart-meter-enabled-tariffs-comparison-project-smarter-tariffs-smarter-comparisons>).

The trialability of innovations is also associated with more rapid adoption (Rogers, 2003). However, ‘try-before-you-buy’ is not possible for heat and building technologies in the same way that an electric vehicle can be trialled via a test drive, car club or rental. Digital tools, or information and communications technology (ICT), offer some possibilities for mitigating this low trialability. Tailored *ex-ante* cost projections provided by PCWs offer one way by which digital tools could reduce uncertainty.

A second opportunity for ICT to support adoption is by leveraging *ex-post* evaluations of how smart electric heating solutions actually perform in the households that have adopted them (Carmichael, 2019). This could be achieved by new regulation that requires (and supports) installers to provide independently verified *ex-post* evaluations of the real-world performance of smart heating technology. Further, making these *ex-post* assessments *publicly accessible on an online database* could be extremely effective in lowering barriers for potential adopters. Being able to see the real-world performance, running costs, pay-back periods, and customer satisfaction with low-carbon heating systems and associated storage, insulation, smart controls and energy service offerings could help potential adopters navigate through the complexities of unfamiliar technologies (reducing cognitive and choice overload). Such a database would make adoption more visible to others (*observability* is associated with more rapid diffusion of a new technology), support take-up through ‘social proof’ (the tendency for consumers to be influenced by others when faced with complex and unfamiliar choices) (Kahneman, 2003) and through normalising and increasing trust in these unfamiliar technologies and installers (Carmichael, 2019).

The CCC has highlighted the potential for greater use of real-world performance data and a ‘whole-house’ approach for informing policy frameworks (CCC, 2019b); such a database of verified *ex-post* assessments and consumer satisfaction data would also create a useful growing dataset for policymakers:

6. Conclusions

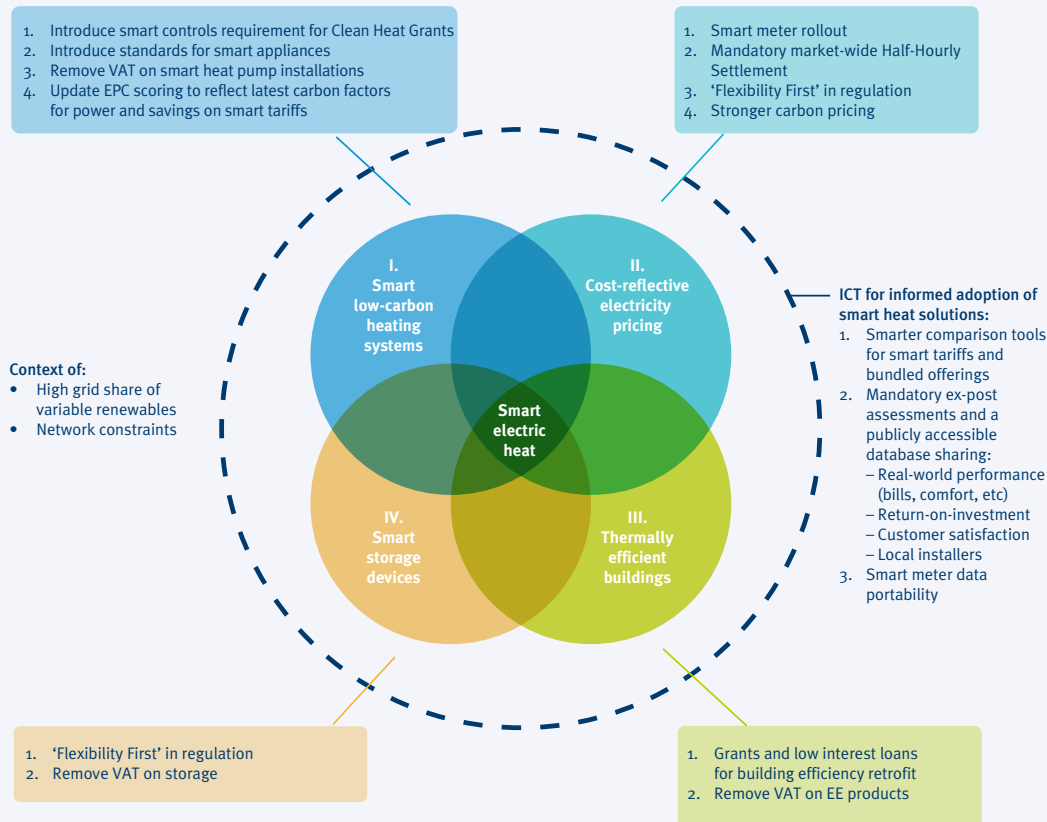
“Learning how different low-carbon heating technologies perform in different types of buildings, occupied by different occupants, is critical for making informed policy decisions in the future” p.10 (Rosenow & Lowes, 2020a)

“Further development of “comfort metrics” that can be modelled and, crucially, measured in real houses, would help identification of pathways that are attractive to consumers and may help stimulate the market for such improvements. [...] Monitoring to compare with the predicted performance would need to be combined with recording of the householders’ reactions to the changes to identify quantitative measures that relate to their experience of thermal comfort.” p.113 (Energy Technologies Institute, 2018)

Both smarter price comparison tools and a database of *ex-post* assessments could also help to drive public engagement with the UK smart meter rollout by adding value to smart meter data and by stimulating interest in smart heat solutions that require households to have a smart meter.

However, if these ICT tools are to operate effectively, better arrangements are required to enable consumers to share their smart meter data, as needed, with third parties offering *ex-ante* comparisons and *ex-post* assessments. In the future, the basic in-home displays that accompany smart meters may be replaced by consumer access devices (CADs) with advanced functionality potentially allowing highly granular consumption data to be sent from the smart meter directly to the cloud and shared (Ferk, 2019). In the short-term, another option for data portability is for third parties to become registered users of the Data Communications Company (DCC) secure network for accessing smart meter data, but this is complex and costly (Ibid), suggesting the need for an intermediary to facilitate this. The authors are involved in work exploring how both these ICT tools could be delivered.

FIGURE 13: FOUR ELEMENTS FOR SMART FLEXIBLE ELECTRIC HEAT WITH SUGGESTED POLICY AND ICT INTERVENTIONS



6. Conclusions

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