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Building decarbonisation transition pathways: initial reflections

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Summary

The problem of decarbonising heating in buildings has been studied for more than 20 years,[1] but there is still no settled consensus on strategy or choice of technology. There *is* consensus that the problem requires analysis of the whole energy system. While there is currently much interest in the conversion of the gas grid to hydrogen as a route to heat decarbonisation, recent literature based on whole system analysis appears to indicate that heat pumps are likely to offer the cheapest decarbonisation option overall. Each new installation would achieve an immediate factor-of-three reduction in emissions, with the promise of close-to-zero emissions by 2030, as a consequence of a process that now appears unstoppable – the decarbonisation of electricity generation.

Although many dwellings would also benefit from additional insulation to increase health and comfort, the overall role of insulation in reducing emissions due to heating in the UK is likely to be secondary. High levels of insulation are not essential to the deployment of heat pumps and are only likely to be cost effective in easy-to-treat properties.

But technology choice is not an either-or question. Combinations of technology, such as hybrid heat pumps, and deployment of large heat pumps in district heating systems, offer obvious advantages. And even though the role of hydrogen as a vector for supplying heat to individual homes appears limited on overall cost grounds, hydrogen or hydrogen-derived fuels are likely to play a strategic role in providing backup for the electricity grid at multiple levels, in particular, for the very long-term energy storage that will be needed from about 2040.

Sifting through the multiple combinations and configurations of technologies that are, and will become available over the coming 30 years will be an on-going activity. In this context, a key recent development is an understanding that technology selection has to involve an appreciation of the overall architecture of the energy system.[2]

1 The broader literature on energy use in buildings goes back even further – see e.g. Leach et al., 1979.

2 We define Energy System Architecture as the spatial, topological and functional organisation of the energy system and its key sub-systems (Lowe et al. 2020).

In addition, there is an ongoing need to evaluate and marshal evidence to establish what works and why, and to enhance learning-by-doing by bridging the gaps between research, innovation and communities of practice.

Importance of early action

Three considerations favour technologies that can be deployed early:

1. **The shape of the transition pathway**. The UK's contribution to climate change will depend on cumulative carbon emissions between now and 2050, which are not tightly constrained by the net zero 2050 target. Emissions under a concave pathway to 2050 can be half those under a convex pathway (Figure 1). Prioritisation for action should therefore be for measures that can be deployed and save CO2 immediately. Measures with carbon payback times of more than a decade may increase, rather than reduce cumulative emissions.

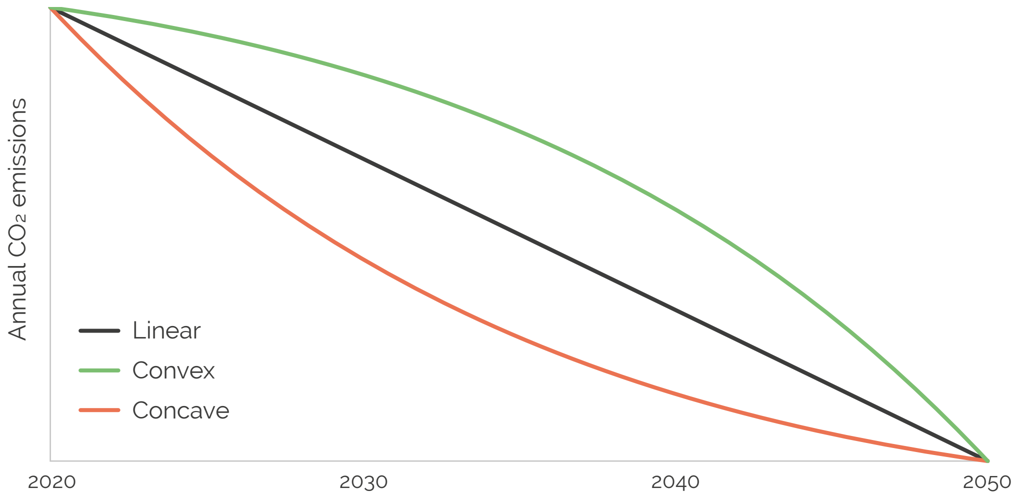

Figure 1. Sketch of concave and convex CO2 emissions trajectories.

2. **Cost reductions arise where technologies can be deployed through natural replacement**. In the UK's stock of c.27 million homes, 1.7 million boilers are replaced, and close to 1 million homes are sold each year; each represents an opportunity to deploy technologies that are already on the market.
3. Deployment through natural replacement also provides for multiple cycles of **learning-by-doing**, which reduces costs and raises performance over the longer term.

Beginning the transition now would likely yield multiple co-benefits. It would provide a powerful signal of the Government's strategic commitment to zero carbon. It would focus industry and consumer attention on the actions that are needed. It would boost the economy, stimulate training, and provide jobs in all parts of the UK. Finally, at the national and global level, it would almost certainly save lives (Watts et al., 2019).

Given the need for early action, what should be prioritised and why? In the context of home heating, four technologies are under consideration. In the following section we briefly review hydrogen and heat pumps in terms of their suitability for deployment, and also touch on heat networks and insulation in relation to the feasibility of mass deployment of heat pumps.

Hydrogen

Hydrogen is not yet ready for deployment, at scale, as a vector for heating UK homes. Compared to its main competitor, heat pumps, it is more expensive, less efficient, does not offer an obvious route to cooling and, because of the impacts of cooling and electric vehicles, may not significantly reduce the need to strengthen the grid. Although parts of the energy system could rapidly accommodate limited amounts of hydrogen from biomass, this would risk becoming a technological dead-end with little strategic value. The beginning of large-scale conversion of the gas grid to 100% hydrogen is at least a decade away. Of the two routes to 100% hydrogen, production from natural gas does not address the problem of upstream fugitive emissions from production and transmission and is therefore, in our view, a high-risk choice given the priority of reducing emissions. The alternative, electrolytic hydrogen, would require almost four times as much electricity as electric heat pumps.[3] Depending on relative deployment rates of renewables and other infrastructure, electrolytic hydrogen may therefore delay decarbonisation and lead to higher cumulative emissions.

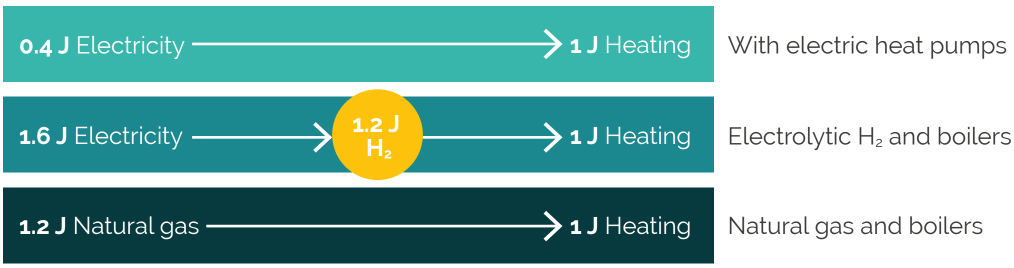

Figure 2. Comparative efficiencies of heat decarbonisation pathways.

Analysis of individual energy conversion pathways, as presented above, does not capture system interactions. This requires, among other analytical tools, the use of whole energy system models such as UKTM or ESTIMO (Scamman et al., 2020).

Analysis using such models tends to show that the strategy with the lowest overall cost for providing domestic heating is not hydrogen but heat pumps, used either individually or in conjunction with heat networks.[4]

3 This factor of four could in principle be reduced to a factor of two if boilers were replaced by fuel cells. But fuel cells do not yet provide the basis for a one-for-one replacement for gas boilers.

4 Heat networks (also known as district heating) supply heat from central sources to consumers, via networks of underground hot water pipes. They can operate at scales ranging from whole cities to small clusters of buildings.

The role of hydrogen in the energy system appears to decline significantly as emissions are reduced from a level equivalent to 20% of current CO2 emissions, down to net zero (Broad et al. 2020 – Figure 3). The same source also indicates that the delivered cost of heat from heat pumps would be significantly less than that from condensing gas boilers fuelled with electrolytic hydrogen.

There is likely to be a case for using hydrogen or, hydrogen-derived fuels to provide the long-term storage that an energy system, based largely or completely on renewables, would need to cope with inter-annual variability in demand and supply. The hydrogen would be produced when there is excess renewable energy and stored for use when there is no renewable generation. But the use of hydrogen as an energy store does not automatically justify its use as a vector to supply heat to dwellings.[5] Moreover, large scale inter-annual energy storage will be one of the final components that will need to be added to the energy system, as the economy moves from c.80% to 100% decarbonisation.

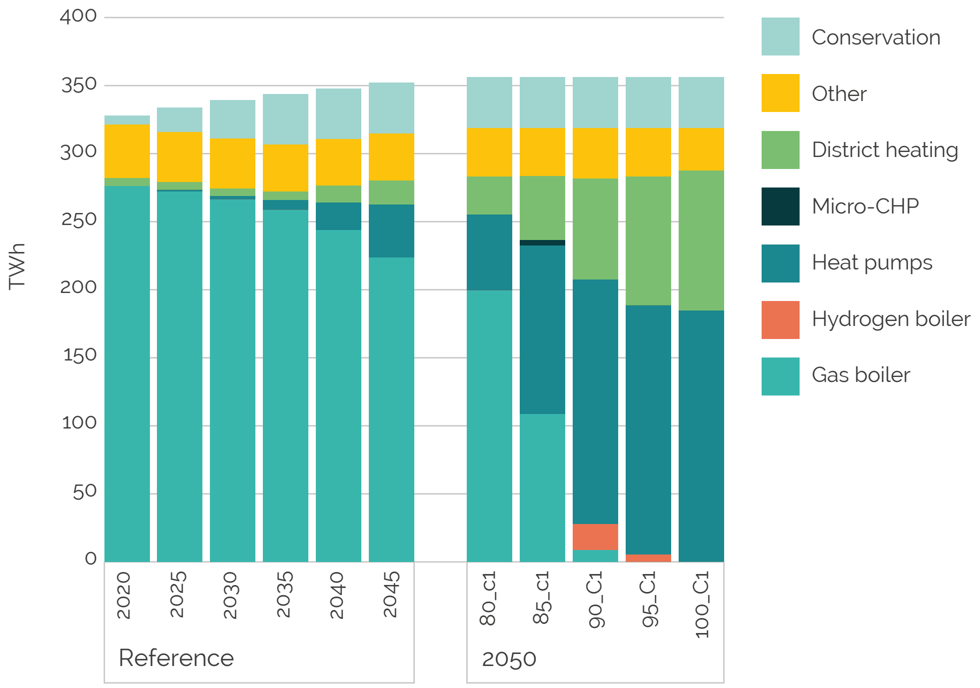

Figure 3. Technology mix for residential heat provision – 80% C1 scenario to 2045 (left); and under five levels of climate ambition for 2050 (right). Broad et al. 2020.

Repurposing the existing gas grid for hydrogen may initially appear both politically and technically attractive, but could, in the end, prove more expensive. One of the strategic advantages advanced for hydrogen for heating, is that it would avoid the need to reinforce the electricity distribution system.

5 Hydrogen is however likely to find multiple roles in the UK economy in addition to long term storage. These include decarbonisation of aviation, shipping, petrochemicals, and the iron & steel industry.

But this may prove illusory in the face of growing electricity demands for electric vehicle (EV) charging, and air conditioning in dwellings and other buildings.[6] The hydrogen transition may also be politically challenging. The simpler transition from town to natural gas in the 60's and 70's caused considerable inconvenience (Falkus, 1988; Hanmer & Abram, 2017). The replacement of electricity mains in streets is not the only way to deal with overloading of the electricity distribution system. A report commissioned recently for the Committee on Climate Change (CCC) observes that capacity can also be added by splitting low voltage circuits and/or increasing the number of sub-stations along overloaded low voltage feeders. The report goes on to predict that by 2035, half of homes could have moved to heat pumps with minimal system costs, a shift that might force reconsideration of the size and role of the gas distribution system (Vivid Economics & Imperial College, 2019).

The UK is not the only country in which mains hydrogen may not be the best or, preferred option for decarbonising heating in buildings. We have not undertaken an exhaustive international review, but the literature suggests that the same is also true of Japan and Germany, both countries in which the role of hydrogen is under active consideration (Kainuma et al., 2015; Hebling et al., 2019).

Heat pumps

Heat Pumps (HP's) are commercially available today. Although they currently make up only 1.6% of central heating boiler installations in the UK, they are more common in Europe with 1.26 million units sold in 2018 (EHPA, 2019).

HPs can be deployed as electricity-only or hybrids, and at building or district level. Although rare in the UK, heat pumps have been used in conjunction with district heating in Sweden since the 1980s (Werner, 2017). The combination of HPs with heat networks offers a number of advantages:

- ability to integrate heat storage at much larger scales than is possible in individual dwellings, and thereby addressing the problem that hot water cylinders have been removed from many UK dwellings;
- ability to integrate multiple means of heat production (boilers, fuel cells, combined heat and power plant (CHP)) and on-site fuel storage allowing hybrid operation, and contributing to system resilience e.g. through the provision of local black-start capability;[7]
- supporting economies of scale for all categories of technology;
- shifting technical complexity from individual dwellings to the district level, thereby allowing scarce engineering capacity to be used more effectively.

6 It has been argued that air conditioning loads could be offset by building-integrated PV, but as climate change disproportionately increases night-time temperatures, this may not be a complete solution.

7 Black start capability is the ability to restart the electricity system following a complete failure.

Replacement of an existing boiler with a HP immediately reduces emissions associated with space heating and hot water by a factor of three,[8] with the almost certain prospect of achieving close to zero emissions by 2030. The government's current consultation on the Future Support for Low Carbon Heat states that "Under all low carbon heat scenarios, we will need to increase deployment of heat pumps significantly in the 2020s to deliver our interim carbon budgets".

Over the coming three decades heat pumps will become cheaper and more efficient. Heat pumps are already available that are capable of providing heat at temperatures up to 80˚C in domestic settings (ICAX, undated), and, in the small fraction of cases where this is needed, up to 110˚C for non-domestic systems (Cooltherm, undated). HPs installed in the coming ten years are likely to be replaced at least once more by 2050, allowing future technical and cost improvements to be captured. In addition, as the climate of the UK becomes milder, the frequency of weather episodes cold enough to impact significantly on heat pump performance will decline. The Paris Agreement would imply roughly an additional 1˚C rise in temperatures compared with the present climate.

Heat pumps – challenges and misconceptions

1. The capital cost of HPs is high compared to natural gas-fired combi-boilers that they would need to replace to achieve a significant reduction in CO_2 emissions. They are however, likely to prove cheaper than hydrogen boilers in the long run.
2. The main internal component of an air source heat pumps (ASHPs) is about the size of a gas boiler, but ASHPs also have external units which generate fan noise at levels between 40-60 dB. Ground source heat pumps are however, typically quieter than the oil and gas-fired boilers that they replace.
3. HPs also require a hot water cylinder. Cylinders have been removed from many homes and the space they occupied is now used for other purposes.
4. The UK industry is currently installing around 30,000 HPs per year, with growth running at around 10% per year. The skills and knowledge required for HP installation is greater than for combi-boilers, but the fundamentals are the same – qualifications in electrics, plumbing and handling of gases. The UK has in place many of the building blocks to help to provide the additional training and to improve practice (for example, the Microgeneration Certification Scheme).
5. The UK lacks a significant manufacturing capacity for heat pumps. But, major boiler manufacturers, such as Bosch, who are active in the UK market also manufacture HPs elsewhere in Europe. Deployment of heat pumps would enable the UK to draw on a global market.
6. The majority of HP's use small quantities of fluorinated hydrocarbons, which are powerful greenhouse gases. These emissions are regulated and alternatives, such as CO_2, which also enable HPs to produce heat at higher output temperatures, are increasingly available.

8 Larger reductions would be achieved in buildings off the gas grid which used more carbon intensive energy carriers.

A common misconception about HPs is that HP performance in existing homes depends on significant upgrades to the building envelope performance and reducing heat loss. This is because HPs tend to operate at lower temperatures than gas boilers (typically 55-60˚C compared to 80˚C), which reduces the output of radiators. In dwellings where this is a problem, it can overcome by improving the level of insulation. In its recent report, Housing – Fit for the Future, the CCC has stated that the average cost of fitting HPs in UK homes would be of the order of £26,000 per dwelling, giving a national cost of around £650 billion(CCC, 2019). We believe that this figure is a factor of between 2 and 3 too high. In part, because the CCC has started with the cost of retrofitting homes to Passive House standard, which is not required for successful heat pump operation, nor applicable across the UK housing stock.

Although we do not know what fraction of the UK housing stock would experience comfort problems as a result of switching to heat pumps, multiple options are available where radiators prove to be undersized. These include fitting larger radiators (at a cost c.£300 per radiator), reducing the dwelling's heat loss by adding insulation or upgrading windows and doors, or simply running the heating system for longer than the boiler it replaced. We do know that on average, HPs are already operated for more hours each day than gas boilers (Love et al., 2017). We also know that the heat loss coefficient for most existing homes is now significantly less than it was when they were built, as a result of improvements that have been undertaken over the years (loft insulation, cavity wall fill, double glazing), and that in many cases, this will already have reduced or, eliminated the need to increase radiator sizes. Improvements to the building envelope of existing homes are very likely to continue into the future, and external temperatures will continue to rise due to climate change, further reducing the mismatch between existing radiator systems and HPs. Finally, as noted above, there are HPs already on the market that are capable of delivering heat at the high temperatures assumed by UK heating system designers.

Next steps

The government is preparing for action on decarbonisation of heat, and many important pieces of the jigsaw are under development, out to consultation, etc. However, what is not in place is an overall strategic vision for the transition to zero carbon. We expect that the BEIS White Paper on Heat, due out towards the end of this year, will be a very significant step forward. There are three other initiatives that are, in our view, needed to support a successful transition.

1. **Energy System Architecture**. Without an overarching analytical and evaluative framework to facilitate the bringing together of multiple sources of expertise and multiple stakeholders, to develop a shared vision for the future of the UK energy system, there is a real risk that outcomes will be disappointing. What is essential is that the way forward be informed not just by energy system modelling, but by application of the principles and tools of System Architecture, (Lowe et al., 2020; Crawley et al., 2015).

2. **Continuing to develop data, tools and concepts to represent the full diversity of the building stock and its supporting infrastructure digitally**. The UK is endowed with multiple sources of data that are already being applied to help plan the energy transition. To give just one example, Energy Performance Certificate (EPC) input data, which has cost millions to collect, could be harnessed and linked to other data, to support the development of a digital twin (Steadman et al., 2020).

3. **Complementing the above with strategic action to bridge the gaps between research, innovation and communities of practice**. This would involve supporting the two-way exchange of information and insight between academia and practice in the field, marshalling data and evidence not just to determine "what works", but why, using research not just to evaluate and select technologies, but to support to learning-by-doing (Lowe & Chiu, 2020). We note with approval a proposal by Prof Jeremy Watson for a "What Works Centre", which, with the right brief, could make a significant contribution..

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