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A Transdisciplinary Engineering and Systems Approach for Decarbonizing UK Home Heating

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Abstract. At present, only around 10% of the heat pumps required to reach our critical 2050 climate goals are being installed in the UK. The government has set ambitious targets to phase out gas boilers by 2035, replacing them with heat pumps. This paper argues that instead of viewing the low carbon heating transition as a simple techno-economic issue, solved by a technology swap, we need a transdisciplinary systems approach to address this complex socio-technical challenge. Drawing on previous research and the literature we identify the current level of heat pump uptake and consider some of the barriers to the low carbon heating transition including technical aspects, installers skill shortages, financial barriers and informational challenges. We find that these barriers are mostly addressed in silos without considering the interrelationship between different aspects. Heat pumps should be considered in the context of a whole house approach to retrofit and barriers need to be overcome to make the technology more attractive to households. In this paper we call for a systemic, transdisciplinary approach to the low carbon heating transition to accelerate uptake: combining an understanding of social, engineering and policy perspectives. Key to this are systems-based methods and transdisciplinary approaches that enable engineering and engineers to be part of the solution. We present the benefits of this approach and suggest some principles for further research.

Keywords. Transdisciplinary engineering, systems approach, decarbonisation, domestic heating, sociotechnical

Introduction

Carbon reduction is vital in our fight against climate change. Globally, countries are taking steps to reduce climate-forcing emissions from home and industrial energy use, transport, and agriculture. While the development of low carbon engineering solutions is an important element, governments also need to ensure that these technologies can be adopted efficiently and without an undue individual financial burden. To achieve this, it important to enable all stakeholders in the system to contribute in a way that suits their own abilities and preferences. This requires an understanding of the barriers and enablers from multiple perspectives, without privileging or neglecting particular stakeholders or concerns. This paper argues that a transdisciplinary, systems approach is required to achieve decarbonisation, focussing on the case of heat pump introduction in the UK

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In the UK, around 18% of emissions come from domestic space heating in winter, and domestic hot water (DHW) throughout the year [1]. Most UK home heating and DHW systems use fossil fuels (see Figure 1) - mainly mains/natural gas (methane) which led to around 51.7MtCO_2e emissions in 2023 [2]. Fossil fuel heating systems are therefore an obvious target for replacements and improvement.

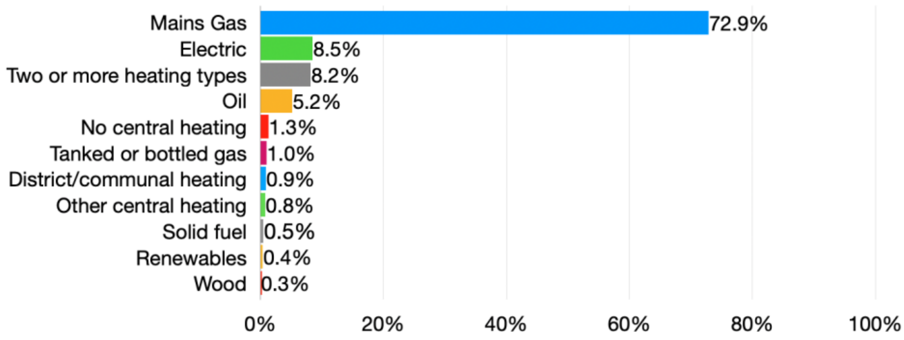

Figure 1. Heating fuel percentages across the UK in 2019 (Scotland) and 2021 (England, Wales, and Northern Ireland) (compiled from [3–5]).

We argue that a systems approach, integrated with principles of transdisciplinary engineering (rooted in Erich Jantch's work [6]) is needed to resolve this complex socio-technical challenge. This approach highlights the importance of listening, not just to academics but to a range of practitioners, and to communities with local knowledge, which will help to identify what is important rather than just what is quantifiable. It also evidences the importance of not seeking to make one aspect (e.g. technical efficiency or economic considerations) dominant at the expense of others. A systemic transdisciplinary approach emphasises the fundamental role of non-linearity and 'feedback loops.' For example, the effect of positive and negative information on heat pump uptake, or the effect of electricity prices on operational costs

In the rest of the paper, we illustrate the importance of seeing decarbonisation as a socio-technical, transdisciplinary engineering problem by drawing on previous research from the authors and from the wider literature (Section 1). We discuss the challenge of low carbon heating uptake in the UK from multiple perspectives, focussing on heat pumps (2 and 3). We then describe an approach and principles that could be used to help overcome these challenges (4) and summarise our conclusions (5).

1. Background to individual perspectives on decarbonisation, culture, practices and technology

There is a tendency in energy policy and related research to explore issues in silos: *either* considering the physical-technical elements of domestic heat decarbonisation, the economic aspects or the social/psychological elements separately. This provides the rationale for considering a transdisciplinary engineering approach.

This can be illustrated by a clear case where there is tension between human socio-cultural perspectives and technical interventions and goals: the challenge of retrofitting older buildings with heritage values. In the UK such homes are estimated to include up to 20% of the housing stock [8] and are often sought after by households for their historic character and material connection with the past. Like *all* existing buildings however, energy demand from these homes must be rapidly reduced and decarbonised via retrofit. These homes are often described as 'hard to treat' because they do not achieve modern building standards and their retrofit can be more expensive and complex. The challenge is often typified in terms of how to fit modern retrofit materials and technologies into these homes, which are compatible with their traditional and often regionally specific construction, while retaining 'significant' heritage values.

We draw on previous research by one of the authors, investigating carbon reduction and heritage retention from residential heritage buildings in the northwest UK. The work involved an online survey of 147 residents of pre-1940 homes [9] and 16 in-depth case studies involving interviews, building visits, technical energy modelling and evaluation [8]. Households' heritage values, energy behaviours and views on acceptable retrofit were explored, the performance of standard energy models were examined and the potential lifecycle carbon of various retrofit measures were explored [10], using multiple methods to create a holistic understanding of households' and their buildings.

1.1. Householder perspectives on standard retrofit approaches

This work found that, even if the building are not officially listed, individuals invest heritage values in their homes, which affect the retrofits they are willing to consider, particularly in terms of standard measures such as solid wall insulation, window replacement and heating system change [9]. This is something often overlooked by policy makers who tend to assume that any retrofits will be suitable for undesignated heritage buildings [9] and often use generalised and expert-led value assumptions [11]. The case study (CS) households often expressed strong feelings about common retrofit measures. For example:

> *'CS1: "External wall [insulation] no! No we wouldn't want to do that, it would destroy the house'" p507 [8]*

Many households also engaged in a range of low energy behaviours such as only heating actively used spaces (69%) and wearing jumpers (88%) [9]. The majority were comfortable in their homes, despite often having lower indoor temperatures than modern standards would suggest [9, 12]. This may be partly because they have a higher comfort tolerance due to the heritage nature of the building, as suggested by the following quotes, and by other research [13]:

> *CS11: 'You can get a bit of warmth from the character in a way' p504 [8].*

> *Survey: 'My house has relatively small windows and is rather dark but I tolerate this because it part of the architecture to be expected in a traditional Cumbrian farmhouse.' p12 [9]*

Together these factors means that standard assessment tools such Energy Performance Certificates (EPCs) poorly reflect energy demand in these homes. Real energy demand was found to be around 40% lower on average than predicted by EPCs [8]. These tools thus fail to support energy retrofit and carbon reduction from heritage buildings, often recommending unacceptable measures which, even if implemented would not lead to the predicted carbon savings [8].

Most households wished to reduce their carbon emissions, provided this could be achieved in ways acceptable to their heritage values and which recognise their individual behaviours and comfort practices. This requires an individualised and holistic approach to identify appropriate and acceptable retrofits and more suitable energy modelling tools to support decision making [8]. The households also noted barriers around identifying information on acceptable measures and finding suitably skilled tradespeople to carry out the work [14]. Financial costs were also a considerable barrier as highlighted by numerous authors for retrofit in general [15] and heritage retrofit in particular [16].

While extreme, heritage buildings, are representative of the decarbonisation challenges faced by UK households, because individual experiences and motivations are shaped by the interaction of personal perspectives and behaviours in specific buildings, especially around something as overarching as low carbon heating (LHC).

2. The challenge of heat pump uptake in UK homes

The principal approach to LCH in the UK is to encourage households to purchase and install heat pumps. To meet the government's legally-binding 2050 decarbonisation goals–5.5 million heat pumps need to be installed in UK homes by 2030, meaning that the annual rate of installations needs to rapidly rise to around 900,000 [17]. in 2021 the UK government set their own target of 600,000 installations a year by 2028 [18].

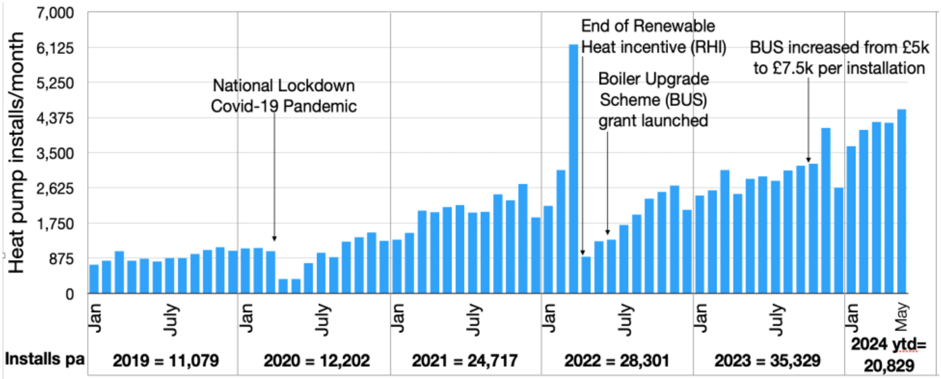

Figure 2. A2W domestic heat pump installations per month January 2019-May2024 compiled from MCS data [19]. Note: Installs pa = annual installations; 2024 ytd = 2024 year to date.

There is no centralized, complete dataset that monitors all UK domestic heat pump installations. Data (or analysis at least) in this area very often conflates different kinds of heat pumps (air-to-air, air-to-water, ground source etc), different stages of the delivery chain (sales versus installations) and different customers (domestic versus business). These data issues are part of a wider problem within this and other related areas of UK policymaking. In UK policy, air-to-water (A2W) heat pumps are predicted to form the vast majority of installations [1]. Other heat pump types are either not currently supported (air-to-air heat pumps) or only form a tiny proportion of installations (ground or water source heat pumps).

The key dataset for UK heat pump installation comes from monthly installations within the Microgeneration Certification Scheme (MCS) – an independent standards organisation which has developed from a previous government initiative (see Figure 2). The Boiler Upgrade Scheme (BUS) currently provides a £7,500 grant for A2W heat pumps in the UK for homes with a modicum of fabric efficiency, as long as the installation is carried out by a MCS certified installer and follows MCS design and reporting standards. Therefore, while not all heat pumps will be registered on this database, the majority will, and it is the most complete dataset currently available.

Meanwhile total heat pumps sold in the UK (all types of heat pumps for all types of buildings and sold rather than necessarily installed) is estimated at around 55,000 in 2022 and around 60,000 in 2023, figures with much greater uncertainty than MCS installations [1]. While the number of installations per year *is* slowly increasing, a *10-18 times* growth in the next four years would be needed to reach the UK's target of 600,000 installations a year.

The UK is acknowledged to be lagging behind many other European countries in rolling out heat pumps [20]. The question is why is the uptake of heat pumps not higher and faster in the UK? We now explore this issue by considering technical, economic, practical, and informational constraints before exploring solutions.

3. Valid explanations for the gap in uptake of heat pumps

The gap in installations can be explained in different equally valid ways. Only a holistic view of all these issues together shows the scale of the challenge the UK faces.

3.1. Technical issues

Ideally heat pumps should be considered as part of whole house retrofit approaches to reducing and decarbonising energy demand [21]. It is important to help households identify the optimal retrofit pathway for their home. A whole house approach supports lower operating costs and improved comfort and wellbeing levels for households [20] but it creates additional technical complexity and financial costs. A whole house approach increases efficient heat pump performance and thus reduces peak demand on the energy grid [22], which will be severely impacted by the electrification of heat.
Currently 80% of UK households also have combi boilers [23] which operate at temperatures >80ºC and do not include hot water storage. Heat pumps work most effectively when the gap between their input temperature (from the external air) and output temperature (to the central heating system) is minimised [24]. While some heat pumps can provide high temperature heat at >70ºC, comparable to that produced by current fossil fuel systems, the majority work most effectively at temperatures of <45ºC, and then use immersion heaters to boost temperatures for DHW applications [24]. This often requires the following expensive and complex adjustments:

- new pipework and heating emitters (i.e. larger radiators or underfloor heating) or improvements to fabric efficiency to reduce energy demand.
- The installation of a water storage system (normally an insulated hot water tank).

3.2. The installer skill gap

While traditional boilers are usually sized simply by the number of bedrooms, heat pumps require detailed sizing calculations for each installation as under-/over-sizing can lead to poor operational performance [20, 25]. This means a much more tailored design process is required for any individual home. While these technical challenges can be overcome they add cost and complexity and require a reskilling of current heating engineers and installers [26]. Challenges are exacerbated by a shortage of trained installers with limited training pathways and low levels of regulation and quality assurance. The installer sector is also very fragmented with limited capacity to upskill due to the high proportion (77% of the total sector workforce) of micro-enterprises with under 7 employees [20, 27].

3.3. Financial barriers

The design complexity and required changes to many central heating systems mean that capital and operational costs are also major barriers to heat pump uptake. An average A2W heat pump costs between £8,000 and £15,000 (including hot water tank and new emitters) compared with gas boiler costs of between £1,500 and £2,500 [20]. The BUS has offered a grant of £7,500 for eligible households but still fails to achieve parity with a gas boiler in many instances.

Electricity is around 4 times more expensive per kWh than gas in the UK. A2W heat pumps generally have coefficients of performance (COPs) of between 2 and 4, meaning they use between half and a quarter of electricity, compared to the gas demand of a comparable system. If they are well designed, they can provide operational cost parity with gas boilers but there is a need for structural changes to reduce electricity prices by shifting certain taxes from electricity to gas [20, 28]. With the BUS grant, less complex heat pump installations are likely to achieve cost parity with gas boilers over their lifetime and are predicted to become more financially attractive in the future [20].

Installation costs reduced by 6% in real terms between 2021 and 2023 but the Government reduction target is an at least 25% between 2021 and 2025 [1], leaving a long way to go in two years. Therefore, at present, A2W heat pumps are not financially attractive to most households, reducing motivations for their installation.

3.4. Practical barriers

Households also face practical barriers. For example households often feel that heat pumps will create space challenges, cause noise pollution and may have negative external visual impact [29]. Disruption is a well-known challenge to retrofit in general [30] and becomes an issue for heat pumps if central heating pipework and emitters need replacing. The shortage of trained installers is also leading to long waiting times which can reduce take up as households become frustrated [20]. The lack of quality guarantees and official training routes can also increase households' perception of risks with a new technology and increase their concerns about system functionality.

3.5. Difficulty accessing comprehensive and impartial information

Households find it challenging to access detailed and specific advice and information on how to reduce energy and carbon from their homes [31, 32]. in particular, finding challenges identifying actionable information on heat pumps and how they interact with associated fabric improvements [33]. This lack of available knowledge leads to misunderstandings on heat pump performance and operation which is an additional barrier to take up. Heat pumps also generally require different operating patterns to gas boilers and better handover processes are required to ensure effective operation and good understanding of controls [24]. Despite a number of advertising campaigns, the National Audit Office have identified that the government lacks an overarching long-term plan for household engagement with the need and methods for LCH in the UK, and there is low public awareness [1]. This has also led in some areas to the spread of disinformation with individual negative experiences being amplified (for example in the media) and therefore discouraging further take up, despite high overall satisfaction amongst households whom have installed heat pumps [24]

4. A Systemic, transdisciplinary view of the problem

Aside from carbon savings, A2W heat pumps offer very few benefits for individuals over the familiar gas combi boiler. To significantly increase uptake, heat pumps have to become cheaper and more accessible to a better-informed public. This requires improvements in the performance of all of the stakeholders involved in across the entire life cycle of heat pumps. However, research and policy approaches have tended to focus on individual elements such as economic barriers or individual technical aspects, without considering the whole system and how different aspects interact with each other.

The first step is to understand the barriers and enablers for each of the stakeholders, so that they each can be supported according to their needs. This integration of perspectives across different communities (policy, installer, manufacturer, engineering design and householder) is central to a transdisciplinary approach.

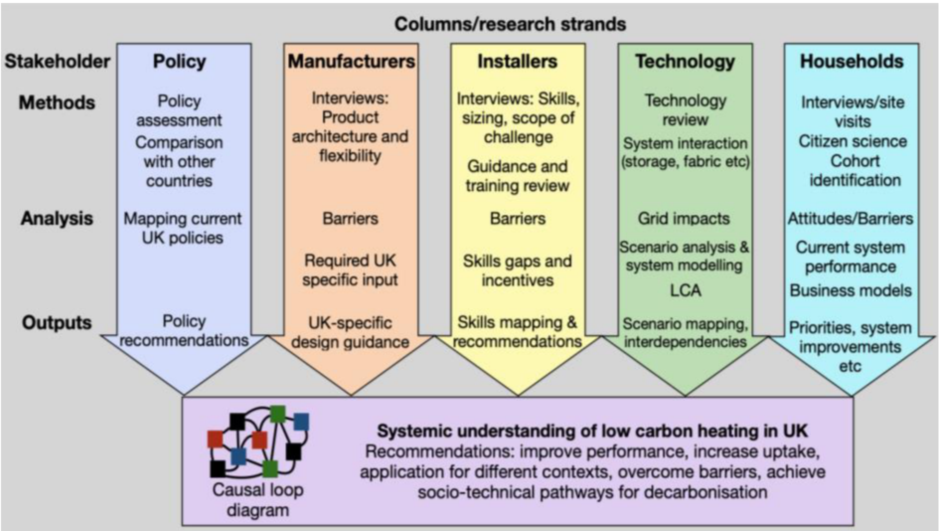

Figure 3. Research strands diagram to integrate different aspects into a systemic, transdisciplinary model.

Figure 3 shows a potential research process, which aims to develop a systems-based understanding of how the various aspects interact both *within* and *between* each stakeholder group. Such a systemic understanding is central to almost all conceptions of transdisciplinarity [e.g. 7]. This understanding could begin to identify leverage points within the complex feedback loops of the LCH ecosystem, on which different actors could apply pressure to accelerate take up. For example, developing new business models relating to heat as a service where the technology is 'rented out' to consumers as part of their contract, or guidelines for information campaigns to enhance household awareness.

Analyzing a complex socio-technical systems such as the LCH transition requires true transdisciplinarity, where no stakeholder or discipline is privileged – but equally none is overlooked. This has not been the case to date in analysis of the UK LCH transition challenges. For example, at present very little research has been carried out on the engineering design, production and customisation of heat pump system from the viewpoint of manufacturers, even though adapting existing heat pump designs to the space constraints of UK house stocking (e.g. no cellar and limited storage) will require considerable investment and have high lead times. Recognising relevant perspectives from engineering is, we argue, key to unlocking options to address these challenges, rather than relying on classic economic interventions alone (e.g. subsidy or regulation). A joined-up ecosystem needs to be generated in which all stakeholders, including households, engineering experts across the spectrum, and policy makers can collaborate.

This transdisciplinarity is a key benefit but at the same time is also a challenge and requires careful management and adherence to principles, to ensure that transdisciplinarity is achieved and that different disciplines work with, not past each other. Given the challenges identified in bringing the social sciences and engineering together [7] it may take significant effort – and not a little humility from all sides, to make rapid progress. In particular, it is important to engage with households, so that heat pumps are not something that is forced on them, but an active choice that they make. We therefore suggest three principles:

- Using systems methods – employing approaches to frame the issue and understand the challenges, using causal loop diagrams or other means to enable an integrated, non-linear understanding of factors underpinning the challenge.
- A co-design approach – working with households to enable and involve them. The imperative of our decarbonisation goals means that change is inevitable, it is therefore important to take people with us on the journey. We must work with people to find suitable solutions for different contexts, practices and values, through a user-centric design approach. This means that we must:
- Respect people’s different views, by understanding their motivations, fears, and expectations to frame and develop the LCH transition in an appropriate manner.

5. Conclusion

While the low carbon heat transition is imperative, the UK is currently well below the level of uptake required to meet its critical heat decarbonisation targets. Drawing on previous research and illustrated by an extreme example of heritage buildings, we show that at present heat pumps offer very few benefits to households besides carbon reduction. Households are asked to replace a reliable and space efficient technology with low initial expenditure with a new technology that requires significant adjustments to most homes. Only by taking a transdisciplinary perspective, which does not privilege one disciplinary interpretation over another, and which gives equal credence to all stakeholders, can we make steps towards overcoming the barriers and developing heat pumps into an attractive technology. A better understanding of how the LCH ecosystem interrelates would support the identification of leverage points to accelerate positive feedback loops, thus increasing take up and gaining momentum for the shift to LCH. However, it is vital that the users are included in this transition and their desires and fears are addressed. While the paper has outlined the benefits of a transdisciplinary approach, future work needs to engage with these different stakeholders and analyse their challenges and concerns in detail to develop solutions. It important to look at the connections between different stakeholders, so they can work together to address each other's problems rather than adding to them. We feel that a transdisciplinary, systems approach is necessary to accelerate the LCH transition in the UK and meet our critical climate goals.

References

[1] National Audit Office, *Decarbonising home heating*. *National Audit Office*, London, 2024.
[2] Department for Energy Security and Net Zero, *2023 UK greenhouse gas emissions, provisional figures*. *National Statistics*, 2024.
[3] Office for National Statistics, *Census 2021 Main statistics for Northern Ireland: Household spaces and accommodation*. *Northern Ireland Statistics and Research Agency*, 2022.
[4] Office for National Statistics, Central heating, https://www.ons.gov.uk/datasets/TS046/editions/2021/versions/4, 2023.
[5] Scottish Government, Chapter 2: A 2045 Pathway for Scotland's Homes and Buildings, http://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings/pages/3/.
[6] E. Jantsch, Inter- and transdisciplinary university: A systems approach to education and innovation, *Higher Education*, Vol. 1, 1972, pp. 7–37.
[7] A.C.G. Cooper, Building physics into the social: Enhancing the policy impact of energy studies and energy social science research, *Energy Research & Social Science*, Vol. 26, 2017, pp. 80–86.
[8] F. Wise, A. Moncaster, and D. Jones, Rethinking retrofit of residential heritage buildings, *Buildings and Cities*, Vol. 2, 2021, p. 495.
[9] F. Wise, D. Jones, and A. Moncaster, Reducing carbon from heritage buildings: the importance of residents' views, values and behaviours, *Journal of Architectural Conservation*, Vol. 27, 2021, pp. 117–146.
[10] F. Wise, A. Moncaster, and D. Jones, Embodied carbon and building retrofit: a heritage example,. In: A. Moncaster and R. Azhari, Eds. *The Routledge Handbook of Embodied Carbon in the Built Environment*. *Routledge* 2023.
[11] K. Fouseki, D. Newton, K.S. Murillo Camacho, S. Nandi, and T. Koukou, Energy Efficiency, Thermal Comfort, and Heritage Conservation in Residential Historic Buildings as Dynamic and Systemic Socio-Cultural Practices, *Atmosphere*, Vol. 11, 2020, p. 604.
[12] F. Wise, A. Moncaster, and D. Jones, Residents' comfort perceptions in domestic heritage buildings, *IOP Conference Series: Earth and Environmental Science*, Vol. 1085, 2022, p. 012024.
[13] C.J. Whitman, O. Prizeman, P. Walker, and J.A. Gwilliam, Heritage retrofit and cultural empathy; a discussion of challenges regarding the energy performance of historic UK timber-framed dwellings, *International Journal of Building Pathology and Adaptation*, Vol. 38, 2019, pp. 386–404.
[14] F. Wise, A. Moncaster, D. Jones, and E. Dewberry, Low carbon heritage: residents' views from Cumbria and the English Lake District World Heritage Site,. In: *EEHB2022 proceedings*. pp. 219–227. *Fraunhofer IRB*, Benediktbeuern Monastery 2022.
[15] J. Albrecht and S. Hamels, The financial barrier for renovation investments towards a carbon neutral building stock – An assessment for the Flemish region in Belgium, *Energy and Buildings*, Vol. 248, 2021, p. 111177.
[16] D. Herrera-Avellanosa, F. Haas, G. Leijonhufvud, et al., Deep renovation of historic buildings: The IEA-SHC Task 59 path towards the lowest possible energy demand and CO2 emissions, *International Journal of Building Pathology and Adaptation*, Vol. 38, 2019, pp. 539–553.
[17] Committee on Climate Change (CCC), *The Sixth Carbon Budget: The UK's path to Net Zero*. *UK Committee on Climate Change*, 2020.

[18] Department for Business, Energy and Industrial Strategy (BEIS), *Heat and Buildings strategy*. *UK Government*, Westminster, 2021.
[19] The MCS Service Company, The MCS Data Dashboard, https://datadashboard.mcscertified.com/InstallationInsights, 2024.
[20] Nesta, *How to reduce the cost of heat pumps*. *Nesta*, London, 2022.
[21] J. Lingard, Residential retrofit in the UK: The optimum retrofit measures necessary for effective heat pump use, *Building Services Engineering Research and Technology*, Vol. 42, 2021, pp. 279–292.
[22] S.D. Watson, J. Crawley, K.J. Lomas, and R.A. Buswell, Predicting future GB heat pump electricity demand, *Energy and Buildings*, Vol. 286, 2023, p. 112917.
[23] B. Gallizzi, UK Boiler Statistics 2023, https://www.uswitch.com/energy/boiler-statistics/.
[24] B. Harris and A. Walker, *Heat Pumps*. *Parlimentary Office of Science and Technology*, London, 2023.
[25] R. Lowe, A. Summerfield, E. Oikonomou, et al., *FINAL REPORT ON ANALYSIS OF HEAT PUMP DATA FROM THE RENEWABLE HEAT PREMIUM PAYMENT (RHPP) SCHEME*. *UCL Energy Institute*, London, 2017.
[26] European Academies Science Advisory Council (EASAC), *Decarbonisation of buildings: for climate, health and jobs*. , Halle, Germany, 2021.
[27] K. Simpson, N. Murtagh, and A. Owen, Domestic retrofit: understanding capabilities of micro-enterprise building practitioners, *Buildings and Cities*, Vol. 2, 2021, pp. 449–466.
[28] J. Barnes and S.M. Bhagavathy, The economics of heat pumps and the (un)intended consequences of government policy, *Energy Policy*, Vol. 138, 2020, p. 111198.
[29] S. Becker, C. Demski, W. Smith, and N. Pidgeon, Public perceptions of heat decarbonization in Great Britain, *Wiley Interdisciplinary Reviews: Energy and Environment*, Vol. 12, 2023, e492.
[30] T. Fawcett and M. Topouzi, Residential retrofit in the climate emergency: the role of metrics, *Buildings and Cities*, Vol. 1, 2020, pp. 475–490.
[31] R.J. Hafner, D. Elmes, and D. Read, Promoting behavioural change to reduce thermal energy demand in households: A review, *Renewable and Sustainable Energy Reviews*, Vol. 102, 2019, pp. 205–214.
[32] F. Wise, A. Gillich, and P. Palmer, Retrofit information challenges and potential solutions: perspectives of households, retrofit professionals and local policy makers in the southwest UK, *Energy Research & Social Science*, Submitted, p.
[33] O. Zanetti, Heat pumps: improving information for householders, https://www.nesta.org.uk/project-updates/heat-pumps-user-journey/.