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The potential for a transdisciplinary systems approach to improve national policy analysis: learning from UK cases of home energy transitions

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The urgent imperative to decarbonise societies requries effective decisions to neogotiate interconnections of people, technology and policies. In this theory paper, we hypothesise that integrating transdisciplinary engineering with systems approaches can provide useful principles and tools to support effective sustainability policymaking. We consider this hypothesis in the context of a historic and current UK energy sector transition: (a) the transition from 'town-gas' to natural gas in the 1960–1970s and (b) the current shift from natural gas to low carbon domestic heating, focussing on heat pump deployment. Through these case-studies, we find that transdisciplinary and systems approaches are apparent in the successful historic transition, while remaining largely absent in the present low carbon heating transition, which is currently stalled. We argue this is caused by policy analysis being siloed and economically focused. We present two systems approach examples to show how they might be applied to begin addressing current UK policy failures for low carbon heating. We identify benefits while recognising some key limitations of this approach, including the resource requirements on officials. The paper concludes with suggestions for further research to continue developing the conceptual and practical basis and therefore lead to improved decision making in national sustainability policymaking.

KEYWORDS
carbon reduction, domestic heating, heat pumps, policy, sociotechnical, systems approach, transdisciplinary engineering

1 Introduction

All aspects of societies must urgently decarbonise if there is to be any chance of limiting global warming to 1.5 °C and avoiding the most devastating impacts of climate change (Intergovernmental panel on climate change (IPCC), 2022; Forster et al., 2025). But how can nations make effective decisions for sustainability when faced with complex and complicated interconnections of people, technology and policy? For many decarbonisation issues, bringing engineering expertise to these choices in national-level analysis is also of considerable importance yet doing so can bring its own problems (Cooper et al., 2021). These issues are central for countries looking to shift the from current fossil-fuel based economies to ones based on sustainable and decarbonised energy. Meanwhile they also have merit for considering other similar shifts in healthcare and environmental protection. In this paper we explore how effective sustainability decisions can be made and how engineering expertise (specifically, the use of systems approaches both as an engineering-rooted method and as means of connecting engineering knowledge to other knowledge) can be bought into national decisions. We focus on the UK and the challenges faced in shifting the landscape of heating technologies, people and society to reduce carbon emissions from a key sector for addressing climate change.

The theoretical foundation for this paper is rooted in previous work by Cooper et al. (2021, 2022, 2023), which centres on the concept of 'engineering policy'. Taking an 'engineering policy' perspective reveals that the importance of engineering is almost entirely invisible to national policy actors, meaning that a dual failure is possible: first, a lack of understanding of the engineering aspects of delivery and second, a failure to make use of engineering-based analytic approaches to diagnose issues and design effective approaches. The simultaneous importance and invisibility of engineering is—according to the engineering policy perspective—central to why effective change can be difficult to achieve (Cooper et al., 2023). Conversely the engineering community also needs to recognise that technical solutions alone are not sufficient and need to be accompanied by, amongst others, better policy rooted in a deeper understanding people and society beyond common economic analysis.

Fundamentally, we argue that both engineers and policy makers lack a sufficiently holistic view to address challenges such as home heat decarbonisation effectively. For this reason, we explore practices that help integrate across engineering and policy worlds, focussing on the key role of transdisciplinary engineering. However, transdisciplinarity introduces challenges for the world of policymaking, which often operates with short deadlines and limited resources. Transdisciplinary working can be complicated, and time consuming as it requires bridging often quite different perspectives and starting points on an issue (Morgan et al., 2025). This suggests that analytic tools are needed to enable transdisciplinarity to have practical value in policy settings. We focus on systems approaches as amongst the most useful family of methods to support this kind of integration of different perspectives (engineering, policy, social). Our hypothesis is therefore that integrating transdisciplinary engineering and a systems approach can enable better, more balanced national policy making.

1.1 Why systems approaches?

The emphasis on systems approaches (see section 2.3 for a brief explanation of what we mean by this term) in an transdisciplinary analysis may seem *ad hoc*, but there are a number of intersecting reasons why it is a reasonable place to start. One reason lies in recent philosophical developments to connect the sustainability-science focused work of the Zurich school of transdisciplinary research (Lang et al., 2012) with systems thinking and practice modelling tools (Morgan et al., 2025). These developments also sit well with recent programmes of work to support more "systems thinking" in the UK government (HM Government, 2023; Royal Academy of Engineering, 2023). However these latter, policy-focused efforts emphasise the systematic aspects paying limited or no attention to the transdisciplinary context into which these approaches potentially gain important impacts. Given the plurality of complex and wide-ranging challenges that UK and other countries currently face, including climate change, international conflicts and a shifting world order, we consider that this study comes at an important moment for the topic and provides a useful synthesis and call to action. At the same time, it is important to consider

> *the null hypothesis: that systems approaches with transdisciplinary engineering are not effective in supporting effective policy decisions.*

In part our goal is to test not the validity of 'transdisciplinary engineering' here, but rather whether the addition of systems approaches are worth considering. Therefore, the key focus for this paper is to justify the systems emphasis, more than the transdisciplinary basis. A key reason why the null hypothesis might be true (that is, that systems approaches are not fundamentally useful in policy analysis) is that systems ideas are ones promoted by engineers (see Royal Academy of Engineering, 2023). It is therefore possible that systems approaches have been promoted by some (typically, systems) engineers simply because it is one of the tools they are familiar with, and not because systems concepts play an important role in understanding national policy planning choices.

One way to assess the robustness of our hypothesis within the confines of this paper is to explore two comparable cases: one a contemporary case in sustainability decision making where policy is failing (and where the absence of systems approaches and transdisciplinarity might therefore be visible) and a documented historical case (from which success or failure can be established) analysed from non-engineering perspectives, that is close enough geographically and by economic sector to enable valid learning for the contemporary case. Given the focus of the special issue, and the core knowledge of the authors, we have settled on comparative UK cases within the energy sector. This links to the sustainability theme as current policy goals in UK energy are strongly focused on carbon reduction in response to the climate crisis.

A key challenge within these efforts is the decarbonisation of UK home heating, where special emphasis has been placed on replacing natural gas boilers with electric-based heat pumps in over 20 million homes. The comparative case is also in the UK, but from 60 years earlier where a similar scale of change was executed in the shift from the incumbent 'town gas' used for heating and cooking to newly-discovered natural gas supply. This historical 'transition' (as the authors of the papers we draw from frame it) has been subject to two separate case study analyses by social science scholars from different traditions, representing a useful and manageable case for exploring if evidence of what is now recognised as transdisciplinary engineering and systems approaches emerge in this case when analysed by non-engineers. Further, this case is useful because there are clear indications of success (completion of the transition). The logic here is that if transdisciplinary and systems approaches do emerge, this provides some validation that such an approach has a wider merit than simply being useful to engineers. If so this can serve as a reasonable basis to further explore the application of this in the contemporary policy setting of accelerating heat pump uptake.

In the rest of this paper, we introduce and discuss engineering policy and theories on transdisciplinary engineering and systems approaches in detail and add to our hypothesis in section 2. Having introduced the theoretical framework, in sections 3 and 4 we then use previous research to explore two case studies of past and current transitions to UK domestic heating and consider the potential of transdisciplinary engineering in these contexts. In section 5 we highlight the lack of transdisciplinary systems approaches in current policies for the shift to low carbon heating. In section 6 we highlight two examples of visualisation tools and provide a summary of how the principles we have been discussing could apply to the low carbon heating transition. Finally in section 7 we discuss our findings and conclude the paper.

2 Engineering policy, transdisciplinary engineering and systems approaches

2.1 Engineering policy

The concept of 'engineering policy' is meant to capture both 'policy for engineering'—the way a nation manages or governs its engineering capacity—and 'engineering for policy'—the use of engineering skills and knowledge to advise policy design and development—in the same way 'science policy' refers to both policy for science and science for policy (Cooper et al., 2023). While both senses are inter-related, we are focused more specifically on engineering for policy here, and in particular aim to explore how engineering (a collection of technical disciplines and practices) can be effectively deployed into policy design spaces that are less technical and more social and political in nature. Previous research by Liote (2022) and Cooper et al. (2021)—which are rare examples of empirical studies on engineering advice to policy in practice—emphasised the importance of effective collaboration between those in government trained as engineers and those not. The studies identified this as a key component of transdisciplinarity and also revealed a wider lack of frameworks for understanding how to best shape these interactions effectively.

While in this paper we focus on transdisciplinary and system approaches, at the same time we recognise that there are other variations which aim to bring engineering into wider areas of action, beyond the typical places of construction, manufacturing, technical design and so on. For instance, the related field of 'transition engineering' offers an alternative and interesting framing. Transition engineering is:

> *an emerging approach for tackling wicked problems and for designing, developing, and delivering real-world steps aimed at downshifting systemic unsustainability [and] …encompasses the workflow, process, and methods for conceptualizing and delivering participatory transformative impact* (Ahrens et al., 2025, p. 3).

Space limitations prevents a more detailed appraisal here but the positioning of transition engineering draws on lessons from safety engineering and therefore may be understood as tackling problems *within* engineering (and the way engineering is carried out) as opposed to understanding how 'engineering thinking' may usefully be applied in policy analysis settings. Indeed, it is highly likely that developments in transition engineering may help a better application of engineering-based methods in policy in the future since any transition engineering methods are likely to fit better into the wider needs of policy analysis. We do, however, return briefly to lessons from transition engineering later in the paper in section 7.

2.2 What is transdisciplinarity?

Transdisciplinarity is an emerging cultural, philosophical and epistemic shift in the contemporary practice of science which builds on interdisciplinarity—the integration of knowledge and methods across disciplines (Barry and Born, 2013). It also connects to the idea of 'co-production of research', where academic and non-academic actors collaborate to shape knowledge production for action (Edelenbos et al., 2011). As developed most recently in the field of sustainability science, transdisciplinarity has been defined as:

> *A reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge.* (Lang et al., 2012, pp. 26–27)

The emphasis throughout Lang et al.'s seminal paper is on integration of knowledge across different disciplines (i.e., interdisciplinarity) and between academia and practice communities, with this definition supported by a recent handbook on transdisciplinarity (Lawrence, 2023). Interestingly, the engineering design community also recognises the need to collaboratively and systematically develop products, their patterns of use and the institutional structures in the which they operate (e.g., Reich and Subrahmanian, 2022) reflecting a natural transdisciplinary orientation within (at least one field of) engineering.

Finally, as noted above in the section on engineering policy—specifically, engineering for policy (engineering advice)—this is the type of setting where a transdisciplinary approach is considered most important. The definition above aligns well with ones offered in the transdisciplinary engineering literature too, for example Wognum defines as transdisciplinary engineering research as:

> *…aimed at solving problems that require a vision beyond the immediate engineering task for their solution… not only technical disciplines need to participate but also disciplines from social sciences. In addition, knowledge is needed from practice and stakeholder communities.* (Wognum et al., 2018, p. 755)

Across all these different definitions, a key concept is central to transdisciplinary practice—it involves the collaboration and/or integration of ideas and practices across different knowledge communities. This typically includes between physical scientists, social scientists and community or policy actors (typical of transdiscplinary research) or between engineering researchers, social scientist and business actors (typical of transdisciplinary engineering). Bringing engineer and engineering approaches into policy settings is one of the relatively unusual elements of our approach here, one that is closely allied to the engineering policy framing set out at the start of this paper.

This makes transdisciplinary engineering particularly suited to applications in policy decision-making for sustainability. However, a practical challenge emerges for those wanting to deploy this in policy settings as noted above—that is, the challenge of integrating a range of different perspectives under pressure of limited time and resources. Given the different orientations of policy and research (explored by Cooper in the energy sector, 2018) this creates a need to explore specific mechanisms to enable transdisciplinary engineering to be effectively applied in policy. Usefully, Morgan et al. (2025) build out a significant amount of philosophical architecture around these issues, and conclude that the use of systems approaches (or "systems thinking" as they and many others term it) can better co-ordinate and integrate different perspectives simply and coherently. We build on their work here—rather than repeat it—with the goal of exploring both the validity of systems approaches and its practical application to a live case. We next consider what we mean by systems approaches.

2.3 Systems approaches

Since general system theory was developed in the second half of the 20th century, it has been applied to numerous fields. 'Hard' system theory, sees systems as interconnected elements which can be controlled, whereas 'soft' systems acknowledge the validity of subjective experience (Zexian and Xuhui, 2010). Collectively this can be called a 'systems approach'—something that has been applied in multiple ways in sustainability and climate change policy arenas, including in the UK (e.g., HM Government, 2023). System approaches can be defined as:

> *a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects* (Arnold and Wade, 2015, p. 675).

A systems approach covers a range of methods that share a core set of concepts (Arnold and Wade, 2015). Our interest in systems approaches at this point is in first characterising them sufficiently to understand whether 'systems' concepts are visible within non-systems analyses of an historic case study. We do this to validate the claim that systems approaches are fundamental to effective sustainability decision-making but also as a basis for understanding how systems approaches can be practically implemented in policy decision-making.

Drawing on a synthesis and review of systems approaches by Arnold and Wade (2015) we briefly present one set of elements for understanding and deploying a systems approach. These seven elements[1] help orient a practitioner, engineer, social scientist or any other relevant stakeholder to the systemic nature of the issue they are confronting.

1 Recognising interconnections
2 Identifying and understanding feedback loops
3 Understanding system structure
4 Differentiating types of stocks, flows and variables
5 Understanding dynamic behaviour
6 Retain but navigate complexity by grouping systems conceptually
7 Understanding systems at different scales

Again, due to space limitations we do not explore this list in depth but rather use it as a typical example in which systems approaches are turned into practical guidance. The point here is to first ask whether we can identify the presence of these elements in non-systems analyses of an historic case relevant to a related contemporary case. If so, this provides evidence that systems approaches, even if not deployed by systems specialists, may in some sense be intrinsic or otherwise foundational features of policy challenges that demand better sustainability decision-making.

1 The original paper by Arnold and Wade set out 8 elements, which included "identifying and understanding non-linear relationships" which they conceded could be grouped under "4. Differentiating types of stocks, flows and variables"—we have taken that advice to reduce the list here for simplicity.

3 Case study one: the 20th century transition from town to natural gas analysed from non-engineering perspectives

This section examines the assessment by two key papers which approach the UK transition from town gas to natural gas using social science theories and non-engineering perspectives. Arapostathis et al. (2019) analyse the importance of strong control and direction as part of a transition management approach and Hanmer and Abram (2017) complements this by taking an actor network perspective to stress the importance of coordination and path-dependency within such a systemically planned, structured and controlled approach.

Over a key 10-year period from 1967 to 1977 over 13 million UK households with around 35 million separate appliances were converted from town gas to natural gas, requiring technical changes to the connections, energy metres and heating, cooking and lighting appliances in these homes and changes to the way the systems worked. Town gas was mainly manufactured from coal carbonisation with local distribution by multiple small companies, although by 1965 these had been merged into a single gas council with 12 area boards. Households were switched to natural gas (methane), from newly discovered gas fields in the North Sea, distributed through a national grid.

3.1 Understanding system structure: strong central control and direction

Arapostathis et al. (2019) take a transitions management approach to analysing the switch to natural gas. Transitions management (Loorbach, 2010) is a political science approach to understanding transitions and focusses on the role of governance and institutions in enabling transitions. For these purposes transitions are defined as:

> *…a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms* (Rotmans et al., 2001, p. 16).

In line with this approach, they highlight that the gas transition took place in a much more centrally managed economy than that of the UK today and began with the dismantling of multiple individual town gas companies and the creation of state-owned British Gas which nationalised and consolidated the industry, providing centralised control of the transition. They note the contrast with today's industry which:

> *Consists of numerous privately-owned national and international companies with much shorter planning and financing horizons, lacking monopolistic or monopsonistic control over their markets, prices and profits* (Arapostathis et al., 2019, p. 136).

Arapostathis et al. also highlight the importance of a 'Fordist' approach to organisation—following the industrial manufacturing approach to standardising products and processes developed by Henry Ford in the early 1900s—to reduce uncertainties, leverage economies of scale and exercise control over the numerous contractors who carried out the installation work. An 8–9-week formal training programme with harmonised technical examination processes was required for all contractors and was administered by 13 new training and examination centres, there were also clear expectations in terms of manner and approach. These requirements were facilitated by a skilled workforce seeking jobs at that time and the transition was supported by substantial resources dedicated to rapidly dealing with any complaints.

This highlights one of the seven elements of systems—understanding system structure. The authors focus on this, and importance they give to it, reinforces the idea that system structure is an important way of understanding how a transition—in their terms—happens.

The transition was compulsory, with town gas being cut off to homes on a given date. Technicians were also given authority to force entry into buildings to switch the technology at the appropriate time for each area if permission was not forthcoming, something that would be close to unthinkable today. Conversion of essential appliances took around 10 h (i.e., was completed in 1 day) and non-essential appliances were converted in the following few days. This command-and-control strategy was also supported by incentives such as the switch being cost free to households, with free conversion—or where necessary replacement (usually if more than 14 years old)—of their own existing appliances to work on the new fuel and with a free call back for up to 8 weeks post switch to deal with any problems, which at the height of the process was needed in around 25% of cases.

3.2 Recognising interconnections: public communications, appliance manufacturers and gas councils

In addition, an aggressive, centrally directed public relations and education campaign was developed for the 'high-speed gas' and new 'modern' appliances, including local public events, leaflets, talks and even film screenings on the benefits of natural gas and its strategic priority for the UK. Another initiative was live cooking demonstrations from 'home economics graduates' comparing the two gas types and showing 'the enhanced safety, convenience and evenness of cooking with natural gas' (Arapostathis et al., 2019, p. 132), while standardised 'bake tests' were also sometimes conducted during call back visits to help support households with learning and to check that appliances were functioning effectively. This included specific guidance to Jewish and Muslim households on ensuring even cooking of Hallal and Kosher food.

Agreement was made with multiple appliance manufacturers and suppliers that they would develop conversion sets for their own appliances and that they would only sell multi-gas type appliances from the 1st of April 1968. Arapostathis et al. also highlight the Gas Councils' generally harmonious and positive relationship with the various governments of the day, both Labour and Conservative, and how they enjoyed mostly steady government support and backing throughout the transition.

It can be seen that this was therefore a purposeful, planned and centrally managed transition with strong and consistent government support in a very different structural context to today's environment. It points to the range of approaches and expertise used in creating functional outcomes for households, which contributed to the rapid progress recorded. This suggests the need to ensure that any co-ordination within the system recognises the role of diverse actors in ensuring two key elements: (i) its resilience to failure and (ii) ability to self-correct, something which is also highlighted in the second paper discussed below. Notably the designers of the approach acknowledged this and put transparent complaint and redress processes in place to handle problems, demonstrating how awareness of distinct roles and benefits of specifically designed functions can support the system effectively. This aspect of their analysis reveals a strong flavour of recognising the importance of interconnections between elements in the system. These interconnections (and the recognition of them) seems to form a key basis for effective action to carry out the transition successfully.

We now look at another angle on this historic case, taken from a paper by Hanmer and Abram (2017).

3.3 Understanding dynamic behaviour: the importance of coordination and the creation of path dependencies

Hanmer and Abram (2017), analyse the same town gas to natural gas case, again framed as a 'socio-technical transition' using Actor Network Theory (ANT)—a social theory first developed by Latour (2007) and others. This is therefore from a quite different social theoretic approach from transition management with a distinct, scholarly community, if albeit still within the broad disciplinary grouping of social sciences.

Hanmer and Abram highlight the importance of the "actor networks" comprising both people (including installers, manufacturers, designers, regulators and so forth—although strangely not households!), and technical system components [such as gas drilling, national distribution pipework, household appliances, etc. (Hanmer and Abram, 2017)]. As with the previous paper they acknowledge the centralised control, management and state sponsoring of the transition and the focus on the communications and technical skills of the installers, whom they identify as vital 'translators' in the transition (thus reinforcing the idea of the importance of interconnections, and possible different types of stocks).

They also identify the planning, overall systems visualisation and research that went into the process prior to the switch, including on the uncertainties and the need for technical changes to existing appliances—because burners required higher airflow rates than town gas. This included the role of 'Watson House'—the Gas Council's national research centre—in field trials, development and approval of technology and communication of technical installation details. As such they argue that Watson House was fulfilling the role of a 'translation hub' which:

> *Characterise[s] a concentration of translation activities in one organisation which aligns with the interests of a constellation of actors and creates stability in the network… in this example aligning the gas industry and appliance supply chain with the requirements of a new fuel.* (Hanmer and Abram, 2017, p. 10)

This notion of translation hubs or indeed individuals, aligns closely with ideas visible in the transdisciplinary research literature. Both refer to individuals or groups who cross knowledge boundaries, including across technical and social knowledge boundaries. The 'translation hubs' concept emphasises the importance of co-ordination activities across different domains and actors and is arguably a form of systems approach. This recognises the importance of dynamic behaviour between elements in the 'actor network' or system, since the coordination happens over time, and by definition is responsive to changes around it as well as changes in the technical installation details which affect the uptake of the new appliances.

3.4 Identifying and understanding feedback: natural gas and central heating

Hanmer and Abram relate how the switch to natural gas also facilitated a much faster shift to central heating, aided by fixed price 'packs' including boilers, radiators and installation, with performance guarantees and with prices standardised on house size, which reduced uncertainty in the minds of households and provided easier pitches for salespeople. The change thus provided households with tangible benefits. This in a sense recognised the role of (positive) feedback loops in the system, since the fixed price pack reduced friction to installation, and likely made it simpler for salespeople to reach more people quickly, especially if the experience of the quick installation supported positive word-of-mouth feedback effects.

Similarly, they highlight how the natural gas transition and its dependent rise in gas central heating for the majority of UK homes has created a high level of 'path dependency'. Homes are effectively locked into existing systems of natural gas boilers with wet radiators, which have become the default choice and create deep structural challenges for any future changes. This links to the next contemporary case we explore below, but in a negative feedback, slowing down the potential for change on account of the path dependency on a fixed type of technology and social systems around it.

3.5 Transdisciplinary and systems approaches and principles visible in the analyses of the historic case study

While coming from different perspectives, both the analyses highlight the importance of planning, collaboration and communication across different stakeholders and perspectives, which is underpinned by a holistic understanding of the system. In particular they show the importance of an integration between technological solutions and policies, as illustrated by ensuring that conversion kits were created for multiple existing appliances and offered free of charge. The planners of the transition programmes thought through all aspects of the transition such as technical standardisation, costs concerns, orchestrated public information campaigns, emphasis on customer service, installer skills development, and so forth; to remove barriers and maintain progress. While the analyses by non-engineers were not framed in those terms they still highlighted the importance of transdisciplinary collaboration.

The exploration of this historic case supports two conclusions. The first is the importance of transdisciplinarity and (plausibly) transdisciplinary engineering in particular, given the emphasis on technical research on devices and installation approaches, as well as taking care of how people interacted and received these, and the governance of the system as a whole. The second is the relevance and validity of a systems approach. Both identified elements that aligned—some more obviously than others—with the key elements of a systems approach as set out by Arnold and Wade (2015). This strongly supports our hypothesis—alongside the other evidence concerning the rise of systems approaches in the UK government—that systems approaches have a general value in these areas.

At the same time, we recognise that a 'systems approach' is not the only useful perspective. For example, it could be seen as design problem, where the processes were designed to meet the needs of different stakeholders and foresaw multiple failure modes. However, the successful transition predates the development of design approaches such as design thinking (e.g., Brown, 2008). This transition problem has characteristics of wicked problems in the sense of Rittel and Webber (1973). Rittel, who was an urban planner, argued that 'nearly all public policy issues' (1973, p. 160), are wicked problems, that are 'ill-defined' and 'malignant'. They cannot be 'solved' but require 'elusive political judgement for resolution…over and over again' (p. 160). However, unlike other wicked problems, in the case of town gas transition, the goal and the end state were clear, even though the details of the implementation required a multitude of flexible judgements.

This fostered a debate on the difference between scientific problems with clear descriptions and unambiguous solutions and complex social issues that need to be addressed by urban planners (see Crowley and Head, 2017). Later researchers drew the important distinction between problems that are wicked by nature and those that are wicked by design, while other argue that all design problems are a priory wicked (e.g., Coyne, 2005). These debates are beyond the scope of this paper, but the interplay of scientific ways and policy ways of thinking permeate into issues of engineering policy design. We suggest design approaches may also merit further consideration in these settings, but we leave that for other scholars or a future paper.

Having provided some validation to our hypothesis that transdisciplinary systems approaches naturally appear in other analyses we will now explore whether they can plausibly add value or insight to a current challenge.

4 Case study two: a current challenge to decarbonise heating

In the UK, following the Climate Change Act in 2008 and subsequent revisions, successive governments have committed to legally binding targets to achieve net zero emissions by 2050 and an interim 68% reduction in carbon emissions from 1990 levels by 2030 (Hutton et al., 2025). Space heating and domestic hot water (DHW) leads to around 60% of emissions from residential buildings as currently 80% of UK dwellings are heated with fossil fuels (73% with gas and 7% with oil), and thus contributes 18% of total UK emissions (National Audit Office, 2024). The transition to low carbon heating technologies (LCH) is widely regarded as missing the target (National Audit Office, 2024)—not quite failing, but far from successful—and the gap between decarbonisation pathways and actual emissions is widening rather than narrowing.

In this section we focus specifically on heat pumps which are widely considered the key technology to replace mains gas in the majority of UK homes (Department for Business, Energy and Industrial Strategy (BEIS), 2021; Watson et al., 2023). To achieve decarbonation of 26 million homes about 1 million homes per year would need to be converted. This was achieved in the previous transition, discussed in case study one, when a single structural system was in place. Now a set of smaller disconnected systems operate across generation, supply, manufacturing and installation of different technologies. There are several consequences of the shift from the previous heavily integrated public-owned energy system to the current disintegrated market-oriented energy system. We will examine throughout the rest of the paper how the consequences of the current approach and environment are contributing to the slow pace of the current shift from fossil heating to low carbon heating, and how the application of a transdisciplinary systems approach could be used to help address these issues.

4.1 Moves towards low carbon heating

Mains gas has been the fuel of choice in most dwellings since the 1980s. These systems principally operate via the national gas grid, supplying gas to an in-home boiler which burns the gas to heat mains water on demand. This water then circulates through pipework and radiators, providing space heating to the home. The majority of these units also provide domestic hot water either on-demand (a 'combi boiler') or via a separate hot water tank in a small number of older systems.

The formal starting point at which the UK government began to take action to incentivise homes to move from fossil-fuels to low carbon heating can be placed with the introduction of the Domestic Renewable Heat Incentive (RHI) in April 2014. This was an operating subsidy over 7 years for specific low carbon heating technologies such as biomass boilers, solar water heating and some heat pumps (Department of Energy Security and Net Zero, 2023). This means that the UK is already over 10 years into the transition. This is therefore a much slower and more gradual transition than the orchestrated shift from town to natural gas discussed in the previous case study.

Comparing UK census data on central heating fuels from the 2011 and 2019/2021 census indicates that the RHI did *not* lead to a substantial step-change in LCH uptake during the period (Figure 1). Gas heating decreased by 2.7% (if tanked or bottled gas is included in 2021 figures) and oil by 0.6%. Electric heating did not change, while two or more heating types, which is likely to include renewables such as solar thermal heating, increased by 4%, suggesting a small but only limited amount of progress.

Government policy shifted in 2021 with the publication of their Heat and Buildings Strategy (Department for Business, Energy and Industrial Strategy (BEIS), 2021), which emphasised the importance of heat pumps and particularly air-to-water heat pumps as a key transition technology for the majority of UK homes. In 2022, the RHI was closed and replaced in England and Wales with the Boiler Upgrade Scheme (BUS)—with a similar scheme in Scotland. This shifted subsidies to installation costs rather operational incentives and prioritised air-to-water and ground-to-water source heat pumps with a current grant of £7,500 towards their installation cost, with lower grants of £5,000 available for biomass boilers (UK Government, 2024).

The advisory Climate Change Committee (CCC) model a 'balanced pathway scenario' of decarbonisation, with mass deployment of air-to-water heat pumps in the UK's 7th Carbon Budget (Climate Change Committee, 2025) and calculate that an annual installation rate of 1.5 million heat pumps per year by 2035 is required. In response to similar modelling in previous carbon budgets the Government set a target of 600,000 heat pump installations per year by 2028 (Department for Business, Energy and Industrial Strategy (BEIS), 2021).

This focus on air-to-water heat pumps and price subsidy interventions without any mandatory phase-out reflects a commitment in UK Government policy analysis to prioritise techno-economic efficiency as the driving priority. This is also visible in the CCC's analysis (2025) and in academic and NGO policy analysis in this area (e.g., Hannon, 2015; Kokoni and Leach, 2021; Lowes et al., 2022). Fundamentally, it is fair to say that the UK approach to decarbonising home heating is dominated by one particular disciplinary perspective—that of economics. This is evident in the focus on financial subsidies for installations and installer training and regulatory changes around planning, recently announced. In a direct sense, this contrasts quite strongly with the systemic and transdisciplinary approach characterised earlier for the successful town gas case. We turn now to see how the difference in approach is affecting policy success.

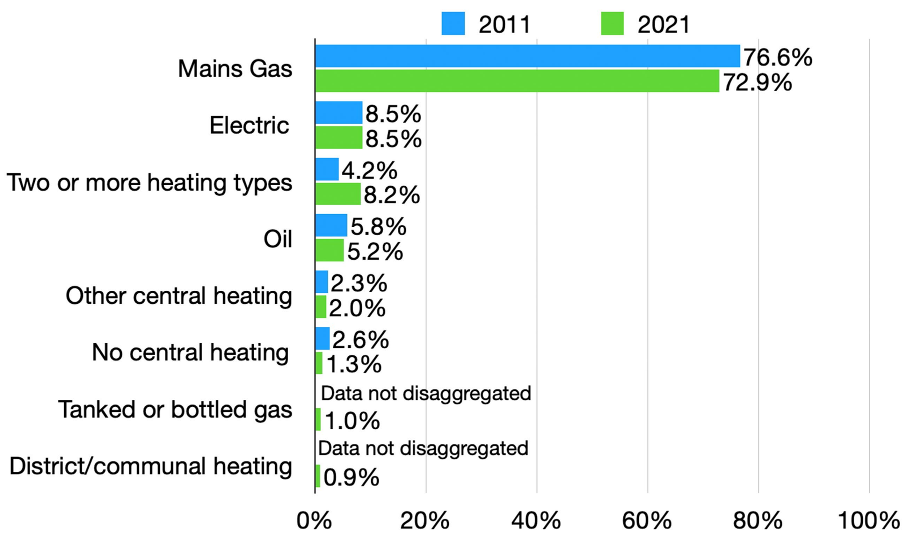

FIGURE 1
Central heating fuel types in the UK in 2011 and in 2019 (Scotland) and 2021 (England, Wales, and Northern Ireland) (compiled from: Office for National Statistics, 2011, 2022, 2023; Scottish Government, 2021).

4.2 Current heat pump uptake

So how is the UK performing in comparison to other European countries and against its own targets? From international investigations, the most recent comparable data covers up to 2021 in terms of heat pump installations as a percentage of population. The UK's progress lags well behind that of 11 other Northern European countries—with a range of similar and different policy and technical contexts—for which data was available (Figure 2). Note that countries in southern Europe have been excluded from the analysis as they have a much higher proportion of air-to-air heat pumps, which are often used for both cooling and heating and which are very rarely used in the UK. The CCC also notes in the latest carbon budget that UK heat pump uptake is lagging behind comparable European Countries (Climate Change Committee, 2025).

National UK data from the Microgeneration Certification Scheme (MCS), the body that ensures installation standards and therefore eligibility for government support (e.g., RHI, BUS), shows that since 2009 255,316 air source heat pumps have been installed across the UK. The monthly and yearly installation numbers for air source heat pumps are shown for 2019 until the end of March 2025 (Figure 3). This is an average of 17,000 heat pumps a year over 15 years although with a slow but steady increase to around 55,000 heat pumps in 2024. This can be compared with the average 1.3million switches per year in the previous gas transition and is well below current targets. So why is uptake so low?

In a sense, the final part of the previous subsection hinted at the diagnosis for why the UK's policy on domestic heat decarbonisation appears to be at best stalling if not outright failing. The clear focus on a mainly economic approach—perhaps underpinned by a technical one (focused on a certain sub-class of heat pumps technology)—is implicated here, in contrast with the successful transition to town gas explored earlier. We now look in more detail at the signs of a lack of transdisciplinarity in the area of UK domestic heat decarbonisation and with it a lack of supporting systems approaches.

5 The absence of transdisciplinary systems approaches in decarbonising domestic heating

This section examines whether analysis around and for effective low carbon heating policy shows signs of a lack of transdisciplinarity. Table 1 shows a comparison between the transition to town gas and the decarbonisation of domestic heating where we classify whether the seven system elements from Wade & Arnold above are fully present, partial (including if the element is only visible in a silo or part of the case) or absent—based on an appraisal of the case material and our understanding of the current domestic heat decarbonisation context. This starkly illustrates the comparative lack of a systems approach in the contemporary case.

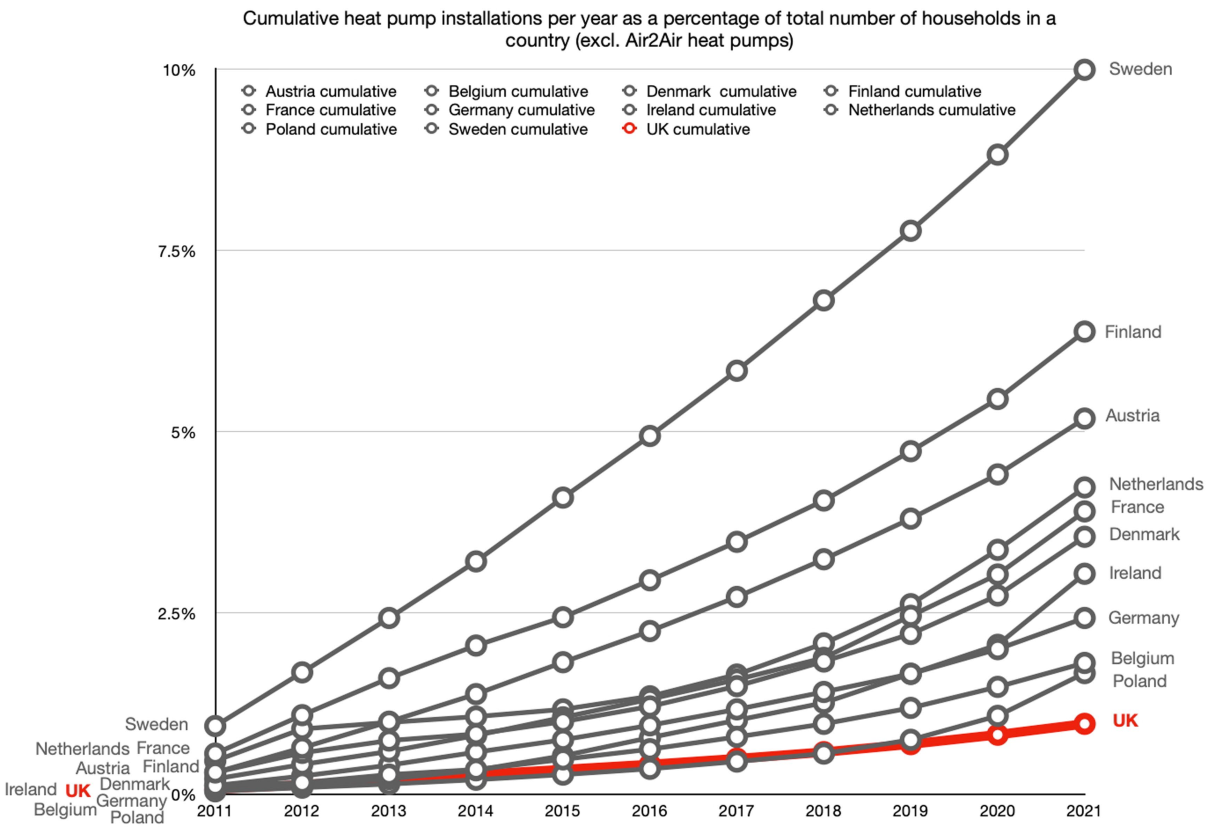

FIGURE 2
Cumulative heat pump installations per year as a percentage of total number of households in a country, excluding air-to-air heat pumps (compiled from: Sarsentis and Orso, 2023).

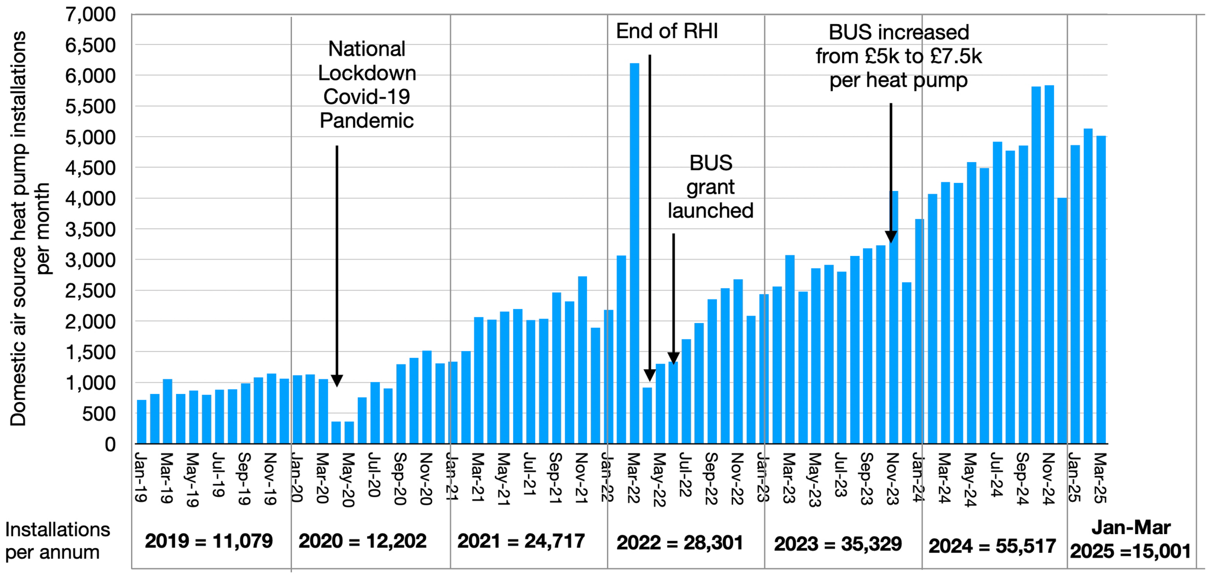

FIGURE 3
Domestic air source heat pump installations per month 2019–end of March 2025 (data from the The MCS Service Company, 2025).

A key indicator of this would be that the published analysis and research in this area is easily divided into the major categories or disciplines that transdisciplinarity is meant to integrate. That includes policy versus academic research, and across disciplinary perspectives. Rather than offering a detailed literature review, we aim to explore whether a range of policy-relevant research and analysis can be readily mapped into different categories. The key categories here are academic versus policy and the disciplinary categories or perspectives of 'social', 'technical' and 'economic', noted by Arapostathis et al. (2019). Our wider stance is that it is problematic to separate these issues too much because of their interdependencies—a point to which we return at the end of this section. Unlike the effective integration of lessons from the more structured organisational system during the town gas to natural gas case, we argue that knowledge today is often dispersed and disconnected. This is in line with Morgan et al.'s (2025) proposal that we need "to embrace interepistemic strategies for working across different knowledge systems" in order to create "the novelty and innovation needed to effectively respond to pressing societal needs." We have summarised policy and research analysis on this topic in Tables 2, 3.

The research organised in Table 2 presents a non-systematic listing of policy research organised into broad disciplinary perspectives of social, technical and economic. Table 3 presents a similar non-systematic listing of academic research organised in the same way. The point here is to illustrate how easy it is to find research that sits within these categories and how little cross-talk there is between them. In some senses the distinctions of social/technical/economic are not a clear cut as the distinction between policy and academic, but the key point remains that the research landscape is characterised by being piecemeal—non-systemic and not transdisciplinary. Some papers potentially lie closer to interdisciplinary boundaries (such as Parrish et al., 2021) and the distinction between social and economic is often blurry—are the barriers manufacturers observe to heat pump adoption an economic or social perspective?—but neither of these undermine the fundamental point of the fragmented landscape.

To further illustrate, a simple search in online indexing database Scopus under title, abstract and keywords for "low carbon heating" returns 233 entries. Adding AND {"systems thinking" OR "systems approaches"} reduces that to 5—one of which is the conference paper that this paper is based on. Three are either purely engineering or economic in nature (so not transdisciplinary: Zhang et al., 2018; Aunedi et al., 2023; Hoseinpoori et al., 2023). The final paper (Nilsson et al., 2020) *does* fit the conceptual perspective argued for here: that transdisciplinary systems approaches are needed for understanding how to effectively navigate the challenge of decarbonising home heating. However, their focus is on integrating across academic perspectives to inform policy using systems approaches rather than exploring the deployment of systems approaches to support policy action in this area.

This section provided evidence that the use of transdisciplinary engineering and systems approaches are likely important—if not vital—to improve sustainability decision making for the low carbon heating transition in the UK and that the landscape shows how fragmented the research and analysis landscape is across two key dimensions—policy vs. academic and across disciplinary perspectives. This is the kind of fragmentation that transdisciplinarity aims to address. In section 6 we thus explore what it might mean for the contemporary case outlined in section 4 to apply transdisciplinary systems approaches and to illustrate the potential benefits they could bring.

6 Towards applying a transdisciplinary systems approach

To illustrate the benefits of the transdisciplinary systems approach we have developed two visualisations to highlight the interconnected nature of different factors which could aid the integration of engineering and social sciences knowledge for policy makers. While neither completely capture low carbon heating transitions both can serve as conceptual and decision making aids (Eckert and Hillerbrand, 2022). These figures are based on an initial, desk-based analysis of domestic heat decarbonisation in the UK and the available evidence supporting the

TABLE 1 Presence/absence of system elements in the historic and contemporary case.

System element present, partial or absent	Transition to town gas	Decarbonising domestic heating
Recognising interconnections	Present Highly connected approach across system elements	Absent Multiple private actors operating in isolation
Identifying and understanding feedback loops	Present Well understood, in particular around complaints procedures	Absent No actor with true system overview
Understanding system structure	Present Great attention to enabling details, e.g., adaptations to tools, cooking classes	Partial Owner is responsible for maintaining many connections, e.g., between heating and insulation
Differentiating types of stocks, flows and variables	Present Different actors and their roles are well understood organisationally	Partial System is highly fragmented
Understanding dynamic behaviour:	Present Understood the importance of transition going well, quality assurance and enforcement of standards	Partial The system is very fragmented, limited quality controls
Retain but navigate complexity by grouping systems conceptually	Partial Holistic planning across multiple levels, centralisation, agreements with manufacturers, training schemes, etc.	Partial Little joined up thinking between the different actors, e.g., training and facilitation of installation disconnected
Understanding systems at different scales	Present Addressed at the level of nation, region, city, household and individual appliance	Partial Little systematic focus on the needs of individual stakeholders

TABLE 2 An illustrative array of policy research and analysis in relation to low carbon domestic heat decarbonisation.

Perspective	Key topics and references
Economic	• Relative installation costs: Heat pump vs gas boiler (Nesta, 2022) • Impact of 'spark gap' (ratio of gas to electricity prices) for operating cost savings and the need to rebalance energy taxation (Climate Change Committee, 2023, 2025; Rosenow et al., 2025; National Audit Office, 2024) • Co-ordinating the regulatory incentives environment (European Academies Science Advisory Council (EASAC), 2021)
Technical	• Technical performance that impacts economic value (Lowe et al., 2017; Nesta, 2022)
Social	• Public perceptions of the heat decarbonisation (National Audit Office, 2024) • Structuring the supply chain for retrofit (Sustainable Development Foundation, 2024)

likely role and impact of each of the elements identified—but can be extensively developed via empirical research to reveal features of the system hidden from even an experienced analyst—and with it, new avenues for effective intervention, and risks to avoid. Systemic diagrams can be drawn from different viewpoints and other interpretations of the same system are equally legitimate. It's also true that the wider toolkit of 'systems approaches' goes far beyond what we cover here. We are simply highlighting the potential of just two approaches—causal loop and life cycle diagrams—as illustrative examples within the systems family in order to prompt wider development and deployment of these approaches in national policy practice. Drawing on established analytical tools such as the causal loop diagrams can be a powerful aid to thinking through systematic connections in a transdisciplinary way.

6.1 Causal loop diagram analysis

A transdisciplinary systems approach emphasises the fundamental role of non-linearity, 'feedback loops', and the identification of different 'levers' to influence the system. The potential of this approach is illustrated by Figure 4, which shows a causal loop diagram (CLD). The elements of this CLD are coded into the three disciplinary areas used to sub-classify academic and non-academic research in this area. This illustrates how the different viewpoints can begin to be integrated. The point here is to illustrate how transdisciplinarity and systems approaches can manifest practically, in a way that is implementable in a policy setting. Of course, more detailed work is needed in validating first, the nature of the elements of this diagram—they are broadly in line with the elements identified in Tables 2, 3 but also contain insights from the authors, such as 'technical complexity'. The use of CLDs also forces the user to think in terms of directionality as well as the nature of relationships between elements. This applies a discipline to the approach but is potentially constraining in an artificial sense, which is where a broader awareness of different methods—such as rich pictures—can be beneficial (Checkland and Poulter, 2020).

The CLD in Figure 4 has two reinforcing loops—key features of causal loop diagrams that help explain outcomes of system behaviour:

- The risk of poor installations arises out of the technical complexity of the systems to be installed, coupled with the supply of trained

TABLE 3 An illustrative array of academic research and analysis in relation to low carbon domestic heat decarbonisation.

Perspective	Key topics and references
Economic	• Impact of 'spark gap' (ratio of gas to electricity prices) for operating cost savings (Barnes and Bhagavathy, 2020) • Experience rates of low carbon technologies (Renaldi et al., 2021) • Manufacturers identification of barriers to adoption (Stieß and Friedrich, 2022) • Relative installation costs: Heat pump vs gas boiler (Zwickl-Bernhard et al., 2022) • Retrofit capabilities of installers (Simpson et al., 2021; Nesta, 2022)
Technical	• Technical performance of heat pumps and other technology (Rashidi et al., 2020; Lingard, 2021; Gaur et al., 2021; Aunedi et al., 2023). • Effects on electricity grid infrastructure of electrification of heat (Watson et al., 2023). • Negative impact on Energy Performance Certificate (EPC) ratings: gas boiler vs heat pump (Wise, 2022) • Reliance on fabric measures/house efficiency for positive heat pump impacts (Zanetti, 2021; Harris and Walker, 2023)
Social	• Household perspectives on changing domestic heating systems (Calver et al., 2022; Becker et al., 2023) • Installer perspectives (Wade, 2020; Murtagh et al., 2023) • Public perceptions of the goal of policy (Becker et al., 2023) • Impartial and partial advice sources (Wade et al., 2017; de Wil and Spaargaren, 2019; Hafner et al., 2019; Bobrova et al., 2021; Wise et al., 2022, 2025) • Householder interactions with technology (Parrish et al., 2021)

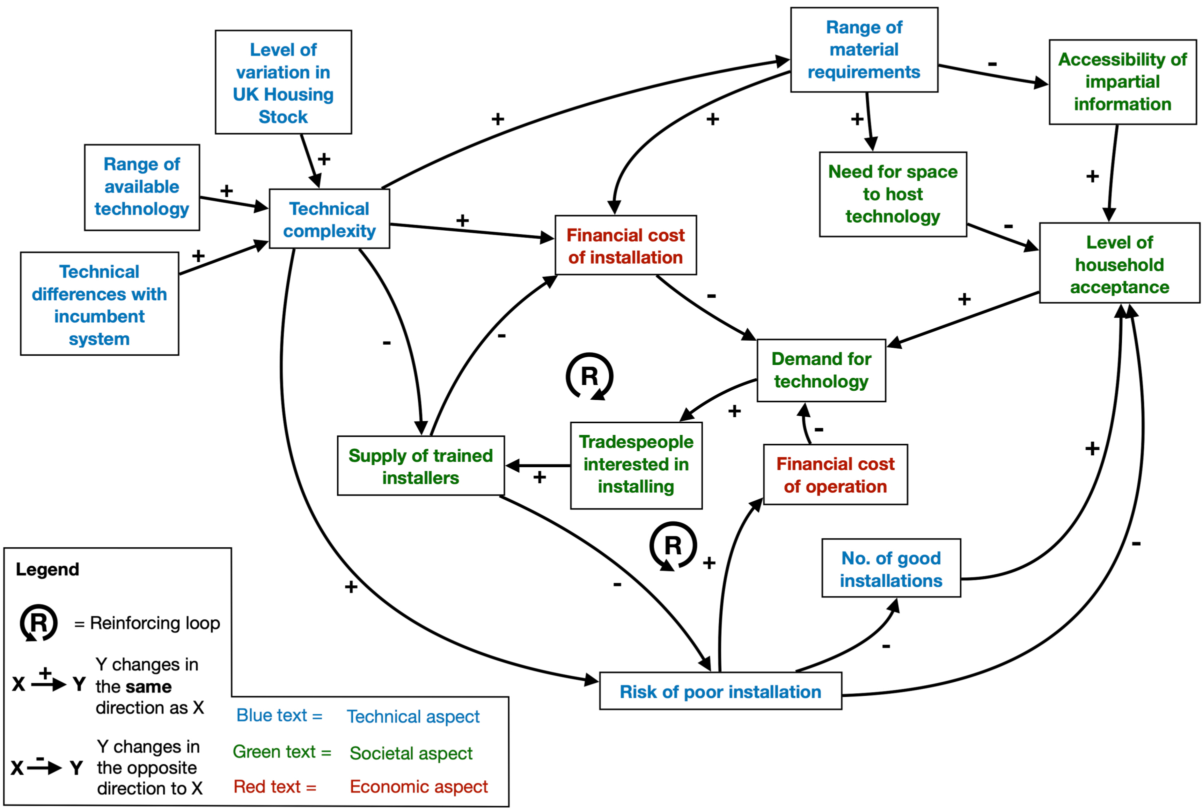

FIGURE 4
Causal loop system diagram aimed at explaining patterns of UK domestic space heating installations.

installers. As the risk of poor installation goes down, the financial cost of operation goes down (as better installed technology performs more cost-efficiently). This increases the demand for that technology, which increases the number of potential installers interested in training to be an installer, which increases the supply of trained installers, reducing the risk of poor installation. As soon as this loop is reversed, due to, e.g., the lack of tradespeople interested in installing, the whole system goes into reverse. This may be one reason why installations are not increasing rapidly.

- The financial cost of installation has been the central focus of policy intervention in the UK with the £7,500 BUS subsidy. If this cost goes down, so the demand for the technology goes up, this then leads to more tradespeople being interested installing, and the supply of trained installers goes up. When this goes up, the cost of installation goes down. However, this seems not to have happened in a consistent way, with the general pattern being rising installation costs, and a limited supply of installers (Nesta, 2022). One explanation becomes visible in the diagram—the role of the technical complexity of the system—as this goes up, so does the installation cost.

What both these reinforcing loops have in common is, on the one hand a relationship with the technical complexity of the technology, and on the other, an interaction of factors that cuts across social, economic and technical domains. A focus on the technical complexity of heating systems might give rise to wider strategies of decarbonisation in the UK that rely less on one specific type of heat pump and more on a wider array of technologies. This could include air-to-air heat pumps, various forms of heat and energy storage, local generation, district heating and direct electric where useful. The capacity for a nation to generate a wider array of diverse technical approaches can be understood as part of the engineering policy of a nation. This is something that has recently been raised as an important blind spot in policy communities (Cooper et al., 2023) and is generally overlooked in debates because air-to-water heat pumps have been identified as the most economically efficient heating decarbonisation strategy for the majority of UK homes (Climate Change Committee, 2025). However, this does not mean that it is the only or best option in all cases.

6.2 Lifecycle systems

Looking at the technology ecosystem is also important for a transdisciplinary systems approach and by examining the lifecycle of a heat pump a different perspective on the process and its systemic interactions can be gained (see Figure 5). Current policy focusses on the installation stage of heat pumps and neglects the other lifecycle stages such as in-situ performance, interaction with other building systems, maintenance and user experience. However heat pumps and other low carbon heating systems can only make substantial contributions to carbon reduction if they perform effectively in the buildings in which they are installed and if they are well maintained. The lifecycle diagram therefore highlights a need for an increased focus on in-use performance through monitoring and guarantees, more engagement with households in using new systems and better awareness of maintenance needs and their effect on other parts of the system. This in turn could reduce the cost of ownership for homeowners.

Lifecycle approaches more broadly can also help identify key intervention points such as the importance of manufacturers, which are often overlooked in policy. They also show how causal loop diagrams (such as in Figure 4) might fit into or touch upon different systems across its life cycle, for example the effectiveness of heat pumps is greatly improved by other decarbonisation methods, which could also be insentivised by policy. This approach can allow decisions makers to navigate—and potentially organise pathways through—complexity in a system, without reducing it in ways that lead to suboptimal policy outcomes, such as the UK is currently experiencing—thus allowing them, in the framework of systems approaches set out above, to 'retain but navigate complexity'.

While these two systems examples are only illustrative in nature—not expressly rooted in specific empiric research—the potential of adopting a systems approach in each of these areas is immediately apparent. As emphasised earlier, part of the insight from the systems approach proposed here rests on the transdisciplinary nature. Systems approaches and methods naturally allow for transdisciplinarity, but equally they can be applied in non-transdisciplinary ways (National Engineering Policy Centre, 2020) and doing so will limit the quality and range of insights.

We summarise our analysis by showing how key principles, introduced in section 2.3, of integrating transdisciplinary with a system approach could apply in the context of low carbon heating. These principles can help policy makers to predict the behaviour of the systems they are engaging in and thus recruit the relevant expertise.

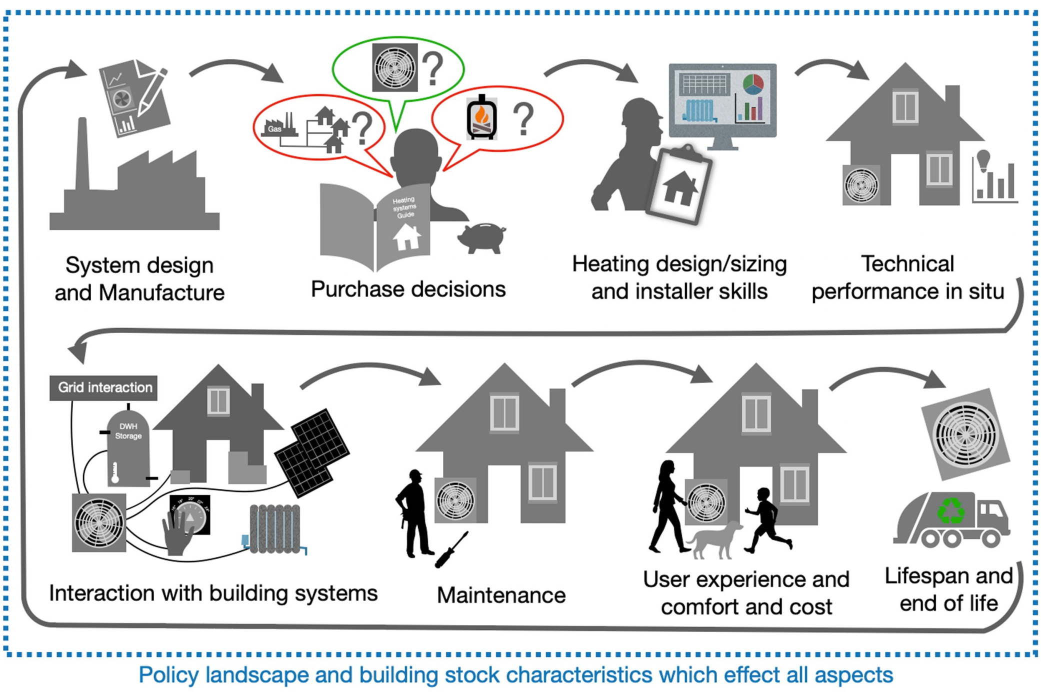

FIGURE 5
Lifecycle system diagram of a LCH installation.

6.2.1 Recognising interconnections

Analysts of policy need to understand the interaction of global and national factors with specific local variations and implementations—this means going beyond small scale interconnections such as the heating system installer and home owner, or product and manufacturer and looking at longer range interconnections.

6.2.2 Identifying and understanding feedback loops

Policymakers needs to be able see how either virtuous or vicious circles are caused by policy and either hold back progress or present opportunities to accelerate. Actively seeking to identify feedback loops when a policy is 'stuck' or otherwise progressing in ways that mean it will not meet its goals should trigger this kind of reflection.

6.2.3 Understanding system structure

A structured variety of experts and actors, such as policy officials, the general public, engineers, and manufacturers, as well as academics across disciplines must be acknowledged. This helps reveal different elements of a system and where many actors and experts intersect, showing core parts of the system structure, rather than emphasising detail from a single element. In addition, each of these perspectives may highlight different structures (such as trade bodies, standards bodies etc.) as important structural features, as well as the institutional structures of installers, manufacturers and so on.

6.2.4 Differentiating types of stocks, flows and variables

Understanding stocks (how much of X there is) and flows (how much X changes over time). Combined with point 3, these stocks can be physical, social or economic concepts and it can help to think of the stocks of 'low carbon heating systems' as well as flows—across the life cycle to get a richer understanding of how a policy might progress. This is also a useful principle under which to think of the availability of installers.

6.2.5 Understanding dynamic behaviour

A key reminder to policy is that these systems are dynamic and understanding that dynamism is important in revealing otherwise hidden effects. Numerical system dynamic or agent-based modelling tools can help to identify the emergent dynamic behaviour of a system. They also allow analysis of whether certain assumptions are as central as first thought or if other parameters have a more significant role. For low carbon heating, this might include interactions with wider gas prices due to international conflict and their effects on progress.

6.2.6 Retain but navigate complexity by grouping systems conceptually

A system can be understood in a range of ways—all of which might be considered 'complex' and which can lead to a desire to simplify in order to make progress in policy—however, such simplification is fraught. Instead, grouping partial systems conceptually allows for a retention of the complexity which is key to ensuring error-inducing simplifications are avoided, while also enabling valid, transparent and constructive decision-making. This might be looking at the household or the supply chain interactions and so on, for LCH policy. In particular heat pump installation at present is not well linked to other forms of decarbonisation of domestic buildings.

6.2.7 Understanding the system at different scales

This is a variant of 6 but emphasising scale as a means of identifying how the complexity is managed at individual, supply chain, national or international scales. Problems in systems can arise on different scales and affect each other, e.g., shortage of components can delay installation and thus funding targets. One outcome of this kind of scalar or component thinking is that it might have implications for team organisation in policy bodies that oversee understanding of these groups rather than via the more traditional sector or technology focus.

7 Discussion and conclusion

In this paper we developed a hypothesis that: integrating transdisciplinary engineering and a systems approach can enable better, more balanced decision making in national policymaking. We explored theories relating to transdisciplinary engineering and systems concepts and then tested our hypothesis by drawing on previous research to consider two cases relating to UK energy 'transitions'. Using the first case of the transition from town to natural gas in the 1960–1970s as analysed using different social science theories (Hanmer and Abram, 2017; Arapostathis et al., 2019) we found evidence that system approaches were strongly implied in understanding how and why this wide-ranging, complicated socio-technical programme was successful, even when analysed from different social science perspectives. This supported the initial claim that systems approaches are likely to be important for addressing contemporary cases, at least in similar settings.

In the second contemporary case we considered the stalled efforts to shift to low carbon heating in the UK mainly through the replacement of gas boilers with heat pumps. We identified how current policy approaches tend to have an overdependence on simple economic levers and market mechanisms that fail to engage with, and overcome, the full range of socio-technical, informational and wider economic barriers identified. We suggest that research and policy efforts to address these barriers are often siloed and fragmented and therefore do not achieve the level of change required. Because of this narrow economic focus, we suggested that current low carbon heating policy misses important aspects of the wider system that would help to overcome barriers and increase uptake.

The second case study provided further support to our hypothesis that transdisciplinary systems approaches could be beneficial in addressing policy issues such as the low carbon heat transition which involves complex and complicated interconnections of people, technology and policy across multiple scales and landscapes. In section 6 we then considered two examples of visualisations that could support the application of a transdisciplinary system approach, namely Causal Loop Diagrams (CLDs) and lifecycle system mapping. However we acknowledge that these are just two examples in a wide range of tools which could be used. Finally we summarise our analysis by showing how transdisciplinary systems approaches could be applied to improve policy responses to the need to transition to low carbon heating.

Using systems approaches is important for policy to see past the simple short run logic of economic analysis that results in subsidy policy rooted in a belief that if a consumer is not buying a technology which provides a wider set of benefits to society (i.e., it has positive externalities), then reducing the capital prices (subsidising) should fix this market failure—something that is clearly not working as planned in the UK. Systems approaches open up the problem in a way that allows for other kinds of issues and solutions or options to play a role in the analysis (e.g., they are technically challenging to fit etc.). However, systems approaches on their own are likely to fall foul of a similar kind of issue as current policy analysis—too narrow a perspective on the issue. This is because it is possible to create economic, social or technical systems analysis for any policy topic—hence the need to pair it with transdisciplinary working (and expressly transdisciplinary engineering, in particular) to avoid this.

We acknowledge that a systems approach on its own—even a transdisciplinary one—is no panacea. There are no ready menus or recipes for how to divide up a complex system into sub-systems to better navigate the complexity. Indeed, the inevitable simplifications that accompany systems diagrams such as CLDs or lifecycle diagrams are themselves potential traps—leading to the conviction that the complexity has been captured or at least tamed, when in fact it has just been mis-represented in some way. As such, the hard work of understanding how best to intervene in a system to generate effective and positive outcomes is only partially achieved with the application of a systems approach. The authors' wider experience and work in this area points to the need for an engagement in research and practice spaces—guided by systems approaches—that shape both novel data collection and new research into ways of reshaping practice. In this, it is vital that different accounts and perspectives are seen as equally valid and no single narrative on how to increase the uptake of low carbon heating is privileged. Only if all the elements in the system align and work together can transformative improvements be made.

We argue that the integration of these analytic tools into policy practice—combined with a deeper understanding of the engineering involved in these systems—will lead to improved policy outcomes. We acknowledge that a transition within policy might be needed for this to happen, and that in so doing this may present hidden hurdles to adoption, which we do not go into here. However, we think the general case for investigating how to adopt these approaches is strong.

As noted earlier, there may be an important role here for novel or emerging approaches that enable engineering to play a deeper role at the community level. The notion of 'transition engineering' (Krumdieck, 2020; Ahrens et al., 2025) potentially provides a framework for this level of action complementing the national policy level focused here. Transition engineering projects provide a novel kind of workflow and skillset for engineers to work with organisations or communities (which by definition, enables transdisciplinary working), in a way that systems approaches provides a platform for transdisciplinary working in national policy. This is clearly an area future work could develop to see how alignments between approaches developed in transition engineering and the systems approach in transdisciplinary engineering explored here can be effectively integrated into both community and policy spaces simultaneously, for possibly even better outcomes. For instance, a recent study by Oikonomou et al. (2022) used causal loop diagrams to understand domestic heat decarbonisation in the UK, enabling them to combined technical features with psychological features to understand how technical design interacts with consumer behaviour. However, the paper itself is limited to occupants and their heat pump system—a level of detail which, while useful, is not directly relevant to national policy systems understanding. In some senses, however, the transdisciplinary systems approach does enable a 'system of systems' mentality in policy, especially when combined with the lifecycle approach noted above.

While the paper has outlined the potential benefits of a transdisciplinary systems approach, future work needs to strengthen key aspects of this approach, including documenting the specific challenges and opportunities from a simultaneous and conscious use of transdisciplinarity and systems approaches in the same project. This is particularly true for transdisciplinary engineering which is commonly applied to business or industry rather than public policy settings (Cooper, 2023). In addition it will be important to explore other systems approaches than those covered here, such as 'participatory systems mapping' (e.g., Pomeroy–Stevens et al., 2022). This can provide a related systems method to support the exchange of knowledge across diverse stakeholder groups, while building towards methods (CLD, life cycle).

The historic case highlighted the important role of 'translation hubs' as a mechanism for transdisciplinary practice. Therefore further research could also delve into what a contemporary translation hub might look like, which organisation/institution might fit this role and how it could work in the current much more globalised and privatised market of today. The MCS for example might be well placed to act as a translation hub as they already have a role in installer quality assurance standards required to receive funding and consumer outreach such as their 'find an installer' service. However at present they are not fulfilling this role convincingly with limited reach, enforcement abilities and influence as a private company and further investigation would be needed to examine this potential more fully and consider how their role could be usefully developed. For example by having a stronger relationship and role in managing the heat pump supply, strengthening standards and working more closely with other installer training bodies.

Finally, the business case for investing resources to develop the skills of officials and to spend time undertaking this kind of analysis is likely necessary. For instance, it is clear that systems approaches can add value to decision-makers use of information to make decisions, though evidence suggests this needs to be in conjunction with standard written document formats as well (Veldhuis et al., 2025) but we do not know how much better decisions are and whether the time invested to get there makes it overall more efficient or effective.

This paper has formulated and commenced initial testing of a hypothesis that transdisciplinary engineering and systems approaches can help to improve the effectiveness of policy decision making for sustainability. We conclude that this approach could be a promising way to bring engineering expertise into policy and improve policy outcomes. It could also help to identify the most effective way to utilise strained state resources to achieve desired policy outcomes Further research could expand and develop this concept with empirical work and consider whether it can be extended to other national policy challenges.

Author's note

This paper has been developed from, and expands upon, ideas originally presented in a conference paper at the 31st ISTE International Conference on Transdisciplinary Engineering, London, 9–11 of July 2024 (Wise et al., 2024).

Data availability statement

Publicly available datasets were analysed in this study. This data can be found at: https://mcscertified.com/low-carbon-landscapes/mcs-data-dashboard/.

Author contributions

FW: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. AC: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Validation. CE: Conceptualization, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Ahrens, F., Nettlenbusch, L.-M., Krumdieck, S., and Hasse, A. (2025). Sustainable healthcare plastic products: application of the transition engineering design approach yields a novel concept for circularity and sustainability. *Sustainability* 17:4672. doi: 10.3390/su17104672

Arapostathis, S., Laczay, S., and Pearson, P. J. G. (2019). Steering the 'C-day': insights from the rapid, planned transition of the UK's natural gas conversion programme. *Environ. Innov. Soc. Transitions* 32, 122–139. doi: 10.1016/j.eist.2019.03.004

Arnold, R. D., and Wade, J. P. (2015). A definition of systems thinking: a systems approach. *Procedia Comput. Sci.* 44, 669–678. doi: 10.1016/j.procs.2015.03.050

Aunedi, M., Olympios, A. V., Pantaleo, A. M., Markides, C. N., and Strbac, G. (2023). System-driven design and integration of low-carbon domestic heating technologies. *Renew. Sust. Energ. Rev.* 187:113695. doi: 10.1016/j.rser.2023.113695

Barnes, J., and Bhagavathy, S. M. (2020). The economics of heat pumps and the (un) intended consequences of government policy. *Energy Policy* 138:111198. doi: 10.1016/j.enpol.2019.111198

A. Barry and G. Born (Eds.) (2013). *Interdisciplinarity: reconfigurations of the social and natural sciences*. London; New York, NY: Routledge.

Becker, S., Demski, C., Smith, W., and Pidgeon, N. (2023). Public perceptions of heat decarbonization in Great Britain. *WIREs Energy Environ.* 12, 1–22. doi: 10.1002/wene.492

Bobrova, Y., Papachristos, G., and Chiu, L. F. (2021). Homeowner low carbon retrofits: implications for future UK policy. *Energy Policy* 155:112344. doi: 10.1016/j.enpol.2021.112344

Brown, T. (2008). Design thinking. *Harv. Bus. Rev.* 86:84

Calver, P., Mander, S., and Abi Ghanem, D. (2022). Low carbon system innovation through an energy justice lens: exploring domestic heat pump adoption with direct load control in the United Kingdom. *Energy Res. Soc. Sci.* 83:102299. doi: 10.1016/j.erss.2021.102299

Checkland, P., and Poulter, J. (2020). "Soft systems methodology" in *Systems approaches to making change: a practical guide*. eds. M. Reynolds and S. Holwell (London: Springer), 201–253. (Accessed April 4, 2025).

Climate Change Committee (2023). Annex: reform of domestic EPC rating metrics to support delivery of net zero. Available online at: https://www.theccc.org.uk/wp-content/uploads/2023/02/Annex-Reform-of-domestic-EPC-rating-metrics-to-support-delivery-of-Net-Zero.pdf (Accessed April 4, 2025).

Climate Change Committee (2025). *The seventh carbon budget*. UK: Climate Change Commitee.

Cooper, A. C. G. (2018). Evaluating energy efficiency policy: understanding the 'energy policy epistemology' may explain the lack of demand for randomised controlled trials. *Energ. Effic.* 11, 997–1008. doi: 10.1007/s12053-018-9618-8

Cooper, A. (2023). "Transdisciplinary engineering versus transdisciplinary research: differences, similarities, lessons and opportunities" in *Leveraging transdisciplinary engineering in a changing and connected world*. (Amsterdam: IOS Press), 911–922.

Cooper, A. C. G., Lioté, L., and Colomer, C. (2023). We need to talk about engineering policy. *Technol. Soc.* 72:102196. doi: 10.1016/j.techsoc.2023.102196

Cooper, A. C. G., Marvulli, L., Black, K., Holmes, J., and Mehta, H. (2021). Engineering advice in policy making: a new domain of inquiry in evidence and policy. *Evid. Policy* 17, 487–505. doi: 10.1332/174426420X15852883943798

Cooper, A., Vingre, A., Bryan, B., Shah, M., McHugh, S., and Cimatti, R. (2022). "Understanding transdisciplinary engineering in public policy: a survey of policy actors' perceptions of engineering expertise" in Transdisciplinarity and the future of engineering, Amsterdam: IOS Press 727–738.

Coyne, R. (2005). Wicked problems revisited. *Des. Stud.* 26, 5–17. doi: 10.1016/j.destud.2004.06.005

Crowley, K., and Head, B. W. (2017). The enduring challenge of "wicked problems": revisiting Rittel and Webber. *Policy. Sci.* 50, 539–547. doi: 10.1007/s11077-017-9302-4

de Wil, M., and Spaargaren, G. (2019). Designing trust: how strategic intermediaries choreograph homeowners' low-carbon retrofit experience. *Build. Res. Inf.* 47, 362–374. doi: 10.1080/09613218.2018.1443256

Department for Business, Energy and Industrial Strategy (BEIS) (2021). *Heat and buildings strategy*. Westminster: UK Government.

Department of Energy Security and Net Zero (2023). Evaluation of the reformed RHI: synthesis of findings from the evaluation of domestic RHI. Department for Energy Security and Net Zero. Available online at: https://assets.publishing.service.gov.uk/media/64a5aad74dd8b3000c7fa52d/rhi-domestic-synthesis-report.pdf (Accessed March 26, 2024).

Eckert, C., and Hillerbrand, R. (2022). Models in engineering design as decision-making aids. *Eng. Stud.* 14, 134–157. doi: 10.1080/19378629.2022.2129061

Edelenbos, J., van Buuren, A., and Schie, N. (2011). Co-producing knowledge: joint knowledge production between experts, bureaucrats and stakeholders in Dutch water management projects. *Environ. Sci. Pol.* 14, 675–684. doi: 10.1016/j.envsci.2011.04.004

European Academies Science Advisory Council (EASAC) (2021). Decarbonisation of buildings: for climate, health and jobs. Halle, Germany. Available online at: www.easac.eu (Accessed July 2, 2021).

Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Cassou, C., et al. (2025). Indicators of global climate change 2024: annual update of key indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* 17, 2641–2680. doi: 10.5194/essd-17-2641-2025

Gaur, A. S., Fitiwi, D. Z., and Curtis, J. (2021). Heat pumps and our low-carbon future: a comprehensive review. *Energy Res. Soc. Sci.* 71:101764. doi: 10.1016/j.erss.2020.101764

Hafner, R. J., Elmes, D., and Read, D. (2019). Promoting behavioural change to reduce thermal energy demand in households: a review. *Renew. Sust. Energ. Rev.* 102, 205–214. doi: 10.1016/j.rser.2018.12.004

Hanmer, C., and Abram, S. (2017). Actors, networks, and translation hubs: gas central heating as a rapid socio-technical transition in the United Kingdom. *Energy Res. Soc. Sci.* 34, 176–183. doi: 10.1016/j.erss.2017.03.017

Hannon, M. J. (2015). Raising the temperature of the UK heat pump market: learning lessons from Finland. *Energy Policy* 85, 369–375. doi: 10.1016/j.enpol.2015.06.016

Harris, B., and Walker, A. (2023). *Heat pumps*. London: Parlimentary Office of Science and Technology.

HM Government (2023). Systems thinking for civil servants. GOV.UK. Available online at: https://www.gov.uk/government/publications/systems-thinking-for-civil-servants (Accessed April 7, 2025).

Hoseinpoori, P., Hanna, R., Woods, J., Markides, C. N., and Shah, N. (2023). Comparing alternative pathways for the future role of the gas grid in a low-carbon heating system. *Energ. Strat. Rev.* 49:101142. doi: 10.1016/j.esr.2023.101142

Hutton, G., Stewart, I., Burnett, N., Tyers, R., Hinson, S., and Malik, X. (2025). The UK'S plans and progress to reach net zero by 2050. UK Parliament. Available online at: https://commonslibrary.parliament.uk/research-briefings/cbp-9888/ (Accessed March 19, 2025).

Intergovernmental panel on climate change (IPCC) (2022). The evidence is clear: the time for action is now. We can halve emissions by 2030. — IPCC. IPCC press release. Available online at: https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/ (Accessed April 24, 2022).

Kokoni, S., and Leach, M. (2021). Policy mechanisms to support heat pump deployment: a UK case study based on techno-economic modelling. *Renew. Sustain. Energy Transit.* 1:100009. doi: 10.1016/j.rset.2021.100009

Krumdieck, S. (2020). *Transition engineering: building a sustainable future*. Boca Ratan: Taylor & Francis.

Lang, D. J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., et al. (2012). Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustain. Sci.* 7, 25–43. doi: 10.1007/s11625-011-0149-x

Latour, B. (2007). *Reassembling the social: an introduction to actor-network-theory*. Oxford, New York: Oxford University Press.

R. J. Lawrence (Ed.) (2023). *Handbook of transdisciplinarity: global perspectives*. First Edn. Northampton: Edward Elgar Publishing.

Lingard, J. (2021). Residential retrofit in the UK: the optimum retrofit measures necessary for effective heat pump use. *Build. Serv. Eng. Res. Technol.* 42, 279–292. doi: 10.1177/0143624420975707

Liote, L. (2022). "Modelling for the UK's utility-scale solar regulation change: lessons for transdisciplinary engineering in policy practice" in Transdisciplinarity and the future of engineering, Amsterdam: IOS Press 187–196.

Loorbach, D. (2010). Transition management for sustainable development: a prescriptive, complexity-based governance framework. *Governance* 23, 161–183. doi: 10.1111/j.1468-0491.2009.01471.x

Lowe, R., Summerfield, A., Oikonomou, E., Love, J., Biddulph, P., Gleeson, C., et al. (2017). *Final report on analysis of heat pump data from the renewable heat premium payment (RHPP) scheme*. London: UCL Energy Institute.

Lowes, R., Gibb, D., Rosenow, J., Thomas, S., Malinowski, M., Ross, A., et al. (2022). A policy toolkit for global mass heat pump deployment. Regulatory Assistance Project (RAP). Available online at: https://www.raponline.org/knowledge-center/policy-toolkit-global-mass-heat-pump-deployment/ (Accessed August 22, 2024).

Morgan, M., Lin, Y. C., Walsh-Dilley, M., Webster, A. J., Stone, A. B., Chief, K., et al. (2025). Convergence, transdisciplinarity, and team science: an interepistemic approach. *Ecol. Soc.* 30. doi: 10.5751/ES-15492-300103

Murtagh, N., Owen, A. M., and Simpson, K. (2023). Engaging UK repair–maintain–improve practitioners in improved building performance. *Int. J. Build. Pathol. Adapt.* 41, 11–24. doi: 10.1108/IJBPA-03-2021-0042

National Audit Office (2024). *Decarbonising home heating*. London: National Audit Office.

National Engineering Policy Centre (2020). *Net zero: a systems perspective on the climate challenge*: Royal Academy of Engineering.

Nesta (2022). *How to reduce the cost of heat pumps*. London: Nesta.

Nilsson, M., Dzebo, A., Savvidou, G., and Axelsson, K. (2020). A bridging framework for studying transition pathways – from systems models to local action in the Swedish heating domain. *Technol. Forecast. Soc. Change* 151:119260. doi: 10.1016/j.techfore.2018.04.003

Office for National Statistics (2011). QS415UK - central heating. Data viewer - Nomis - official census and labour market statistics. Available online at: https://www.nomisweb.co.uk/census/2011/QS415UK/view/2092957698?cols=measures (Accessed March 20, 2025).

Office for National Statistics (2022). *Census 2021 main statistics for Northern Ireland: household spaces and accommodation*. Belfast: Northern Ireland Statistics and Research Agency.

Office for National Statistics (2023). Central heating. Available online at: https://www.ons.gov.uk/datasets/TS046/editions/2021/versions/4 (Accessed July 14, 2023).

Oikonomou, E., Zimmermann, N., Davies, M., and Oreszczyn, T. (2022). Behavioural change as a domestic heat pump performance driver: insights on the influence of feedback systems from multiple case studies in the UK. *Sustainability* 14:16799. doi: 10.3390/su142416799

Parrish, B., Hielscher, S., and Foxon, T. J. (2021). Consumers or users? The impact of user learning about smart hybrid heat pumps on policy trajectories for heat decarbonisation. *Energy Policy* 148:112006. doi: 10.1016/j.enpol.2020.112006

Pomeroy–Stevens, A., Goldman, B., and Grattan, K. (2022). Participatory systems mapping for municipal prioritization and planning. *J. Urban Health* 99, 738–748. doi: 10.1007/s11524-022-00654-2

Rashidi, S., Shamsabadi, H., Esfahani, J. A., and Harmand, S. (2020). A review on potentials of coupling PCM storage modules to heat pipes and heat pumps. *J. Therm. Anal. Calorim.* 140, 1655–1713. doi: 10.1007/s10973-019-08930-1

Reich, Y., and Subrahmanian, E. (2022). The PSI framework and theory of design. *IEEE Trans. Eng. Manag.* 69, 1037–1049. doi: 10.1109/TEM.2020.2973238

Renaldi, R., Hall, R., Jamasb, T., and Roskilly, A. P. (2021). Experience rates of low-carbon domestic heating technologies in the United Kingdom. *Energy Policy* 156. doi: 10.1016/j.enpol.2021.112387

Rittel, H. W. J., and Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy. Sci.* 4, 155–169. doi: 10.1007/BF01405730

Rosenow, J., Barnes, J., Galvin, R., O'Mara, S., and Lowes, R. (2025). Total cost of ownership of heat pumps and policy choice: the case of Great Britain. *iScience* 28:111784. doi: 10.1016/j.isci.2025.111784

Rotmans, J., Kemp, R., and Van Asselt, M. (2001). More evolution than revolution: transition management in public policy. *Foresight* 3, 15–31. doi: 10.1108/14636680110803003

Royal Academy of Engineering (2023). Academy supports valuable new resources for systems approaches to policy development in government. Available online at: https://raeng.org.uk/news/academy-supports-valuable-new-resources-for-systems-approaches-to-policy-development-in-government (Accessed April 7, 2025).

Sarsentis, D., and Orso, L. (2023). How the UK compares to the rest of Europe on heat pump uptake. NESTA. Available online at: https://www.nesta.org.uk/report/how-the-uk-compares-to-the-rest-of-europe-on-heat-pump-uptake/ (Accessed February 7, 2024).

Scottish Government (2021). Chapter 2: A 2045 pathway for Scotland's homes and buildings. Heat in buildings strategy- achieving net zero emissions in Scotland's buildings. Available online at: http://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings/pages/3/ (Accessed September 13, 2023).

Simpson, K., Murtagh, N., and Owen, A. (2021). Domestic retrofit: understanding capabilities of micro-enterprise building practitioners. *Build. Cities* 2, 449–466. doi: 10.5334/bc.106

Stieß, I., and Friedrich, T. (2022). Accelerating market uptake of heat pump systems: challenges, visions and steps for change - results from a stakeholder process in four European countries, Hyeres: ECEEE Summer Study 1263–1271.

Sustainable Development Foundation (2024). Retrofit at scale – how many, houw deep, what cost: upgrading our homes to meet UK CLimate targets: A call to action to industry and policy makers. Available online at: https://sdfoundation.org.uk/news/retrofit-at-scale (Accessed August 13, 2024).

The MCS Service Company (2025). The MCS data dashboard. Available online at: https://datadashboard.mcscertified.com/InstallationInsights (Accessed June 14, 2024).

UK Government (2024). Boiler upgrade scheme. GOV.UK. Available online at: https://www.gov.uk/apply-boiler-upgrade-scheme (Accessed March 20, 2025).

Veldhuis, G. A., Smits-Clijsen, E. M., van Waas, R. P. M., Hof, T., Maccatrozzo, V., Rouwette, E. A. J. A., et al. (2025). The influence of causal loop diagrams on systems thinking and information utilization in complex problem-solving. *Comput. Hum. Behav. Rep.* 17:100613. doi: 10.1016/j.chbr.2025.100613

Wade, F. (2020). Routinised heating system installation: the immutability of home heating. *Energ. Effic.* 13, 971–989. doi: 10.1007/s12053-020-09867-3

Wade, F., Shipworth, M., and Hitchings, R. (2017). How installers select and explain domestic heating controls. *Build. Res. Inf.* 45, 371–383. doi: 10.1080/09613218.2016.1159484

Watson, S. D., Crawley, J., Lomas, K. J., and Buswell, R. A. (2023). Predicting future GB heat pump electricity demand. *Energ. Buildings* 286:112917. doi: 10.1016/j.enbuild.2023.112917

Wise, F. (2022). *Reducing carbon while retaining heritage: Retrofitting approaches for vernacular buildings and their residents*. Milton Keynes: The Open University.

Wise, F., Cooper, A., and Eckert, C. (2024). "A transdisciplinary engineering and systems approach for decarbonizing UK home heating" in *Engineering for social change*. (Amsterdam: IOS Press), 359–368.

Wise, F., Gillich, A., and Palmer, P. (2025). Retrofit information challenges and potential solutions: perspectives of households, retrofit professionals and local policy makers in the United Kingdom. *Energy Res. Soc. Sci.* 119:103866. doi: 10.1016/j.erss.2024.103866

Wise, F., Moncaster, A., Jones, D., and Dewberry, E. (2022). "Low carbon heritage: residents' views from Cumbria and the English Lake District world heritage site" in *EEHB2022 proceedings* (Benediktbeuern Monastery: Fraunhofer IRB), 219–227.

Wognum, N., Bil, C., Elgh, F., Peruzzini, M., Stjepandić, J., and Verhagen, W. (2018). Transdisciplinary engineering research challenges. Transdisciplinary engineering methods for social innovation of industry 4.0, Amsterdam: IOS Press 753–762.

Zanetti, O. (2021). Heat pumps: improving information for householders. NESTA. Available online at: https://www.nesta.org.uk/project-updates/heat-pumps-user-journey/ (Accessed September 19, 2023).

Zexian, Y., and Xuhui, Y. (2010). A revolution in the field of systems thinking—a review of Checkland's system thinking. *Syst. Res. Behav. Sci.* 27, 140–155. doi: 10.1002/sres.1021

Zhang, X., Strbac, G., Teng, F., and Djapic, P. (2018). Economic assessment of alternative heat decarbonisation strategies through coordinated operation with electricity system – UK case study. *Appl. Energy* 222, 79–91. doi: 10.1016/j.apenergy.2018.03.140

Zwickl-Bernhard, S., Auer, H., and Golab, A. (2022). Equitable decarbonization of heat supply in residential multi-apartment rental buildings: optimal subsidy allocation between the property owner and tenants. *Energ. Buildings* 262:112013. doi: 10.1016/j.enbuild.2022.112013