TYPE Original Research
PUBLISHED 08 July 2025
DOI 10.3389/fsuep.2025.1514717

OPEN ACCESS

EDITED BY
Giuseppe Pellegrini-Masini,
Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Italy

REVIEWED BY
Suyash Jolly,
University of Ostrava, Czechia
Iraklis Argyriou,
Queen's University Belfast, United Kingdom

*CORRESPONDENCE
Richard A. Oduro
r.a.oduro@leeds.ac.uk

RECEIVED 21 October 2024
ACCEPTED 12 May 2025
PUBLISHED 08 July 2025
CORRECTED 10 July 2025

CITATION
Oduro RA and Taylor PG (2025) GB energy networks: experts' views on future pathways and multi-vector energy networks approach. *Front. Sustain. Energy Policy* 4:1514717.
doi: 10.3389/fsuep.2025.1514717

GB energy networks: experts' views on future pathways and multi-vector energy networks approach

Richard A. Oduro[1,2]* and Peter G. Taylor[1,2,3]

[1]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, United Kingdom, [2]Energy Transition and Net-Zero Research Group, School of Chemical and Process Engineering, University of Leeds, Leeds, United Kingdom, [3]Sustainable Low Carbon Futures Group, School of Chemical and Process Engineering, University of Leeds, Leeds, United Kingdom

The decarbonization of energy systems poses significant challenges to energy networks due to the introduction of new energy vectors and changes in the pattern of energy demand. However, this is currently an under-researched area. This paper addresses a gap in the literature by drawing on the socio-technological transitions and multi-system interactions literature to explore the views of experts from industry, academia and other sectors about the challenges facing UK energy networks and the possible solutions, including taking a more wholistic approach to the planning and operation of different networks. Using these frameworks, we have demonstrated that systems can be deliberately integrated to interact and solve particular system challenges, and have identified the nature of these interactions. The empirical results identify areas of consensus and disagreement about the future development of network infrastructure and regulation. They also highlight how government policy responds to the challenges and opportunities presented by the UK climate targets. The findings show widespread agreement that the UK energy system will become more electrified and decentralized as it incorporates more renewable energy. However, the role of gaseous fuels in the energy system is more uncertain, with some experts seeing a move from natural gas to hydrogen as being key to maintaining the security of supply, while others see little or no role for hydrogen. There is also widespread agreement that the regulatory structure should change to address the challenges facing energy networks with much less agreement on whether this could happen quickly enough. Recent developments indicate the UK Government recognizes the need for regulatory change, but it is premature to foresee their success in helping networks be a driver of, rather than a barrier to, a net-zero energy system.

KEYWORDS

multi-vector energy networks, electricity networks, gas networks, hydrogen, multi-energy systems, multi-systems interactions, socio-technological transitions

Highlights

- Energy networks are enablers of the UK's energy transition but are facing multiple challenges.
- Experts anticipate the need for significant changes in UK network architecture, policies and regulation.

- There is both consensus and disagreement regarding how energy networks should evolve.
- Experts are conversant with MVEN approaches but differ in views on their usefulness.
- UK policy is starting to address some of the challenges identified by the experts.
- Further work on the MVEN approach is needed to inform policy.

1 Introduction

Energy is at the core of a number of policy challenges—energy security, affordability and sustainability—often described as the energy trilemma. These goals can come into conflict, for instance, with the need to invest in aging infrastructure and replace carbon-intensive generation with cleaner technologies, placing pressure on energy bills. At the same time, the energy system is changing in response to the climate emergency and the UK's target for net-zero greenhouse gas emissions by 2050. The growth in renewable generation brings challenges of intermittency and reliability (Martinot, 2016). The decarbonization of heat and transport is changing the scale of electricity demand, and increasing digitalization creates new ways for all parts of the energy value chain to interact. The future is uncertain, but all scenarios of the future forecast substantial changes from our current energy systems (Whinskel et al., 2019). There are challenges and opportunities because of these changes, and these must be met if the UK is to be successful at achieving its 2050 climate change targets.

Much attention has been focused on the changes taking place in supply and demand, but energy networks play an essential role in the future energy transition of the UK and in meeting the energy trilemma. Unlike generation and supply, electricity and gas networks have not been opened up to competition and have been run and regulated as national or regional monopolies since the liberalization of the energy sector in the late 1980s. For most of the last 30 years, this regulation has prioritized short-term cost saving over longer-term development, leaving them poorly positioned to meet the commercial and technological challenges arising from deep decarbonization of the energy sector (Ofgem, 2018). This is starting to change because of new regulatory attempts to stimulate innovation and transformation, but there are question marks about whether this goes far enough and what more is needed.

While existing networks need to adapt, new networks are also being promoted and developed. The need to decarbonize heat poses a key challenge to meeting the 2050 carbon targets, and there is currently no clear plan about how this will be done. There is general agreement that natural gas use must be reduced, but differing views on whether hydrogen might be suitable as a widespread replacement. This creates considerable uncertainty about the future of gas network infrastructure, which is currently a vital backbone of the UK energy system (Broad et al., 2020; Chaudry et al., 2015). District heating networks present another opportunity to decarbonize heat, particularly in urban areas, and provide future flexibility for heat sources to be changed as lower-carbon alternatives become available (Competition and Markets Authority, 2018).

Central to the energy transition is the appropriate network infrastructure, planning and operations to transport these energy vectors from where they are produced to where they are in demand. Energy networks have always provided these transport services through transmission and distribution. But the challenge now is that some of the energy resources to be transported are chemically and physically different, requiring new operational and managerial approaches. These changes pose many challenges to stakeholders and thus require suitable regulations and policies to protect consumer and investor interests. Network operators, regulators and policymakers know of such changes and are searching for the best ways to tackle these challenges while guaranteeing accessibility, affordability, and security.

Over the years, energy networks have shown greater interdependencies and interactions, and these have the potential to solve grid integration and flexibility challenges. The multi-vector energy networks (MVEN) approach is one of the forms of multi-energy systems that exploit the optimality of the interdependencies and interactions between two or more networks to provide flexibility and grid integration solutions with the support of other energy conversion technologies (Hosseini et al., 2020; Mancarella et al., 2016; Oduro and Taylor, 2023; Taylor et al., 2021).

The benefits and challenges of multi-energy system approaches have been studied across various multi-energy configurations and concepts, such as integrated energy systems and energy hubs (Hosseini et al., 2020; Mancarella, 2014; Oduro and Taylor, 2023; Taylor et al., 2021; Wang and Shao, 2019; Yan et al., 2018). However, the views of experts and policymakers regarding their potential benefits and challenges have not been explored. The essence of experts' views is not to justify the validity of solutions, but experts' opinions provide grounds to probe alternative solutions to solve problems (Fischer et al., 2014; Karlsen and Karlsen, 2007). Using experts' views, it is thus imperative to investigate how MVEN can solve some of the network challenges, where they can be more beneficial, and what policy and regulatory arrangements could support the MVEN system.

To understand how experts see these different elements unfolding and interacting, we draw on the socio-technological transition literature. Since energy networks connect multiple systems, considering the sustainable socio-technological and multi-systems interactions theories or frameworks can help expose the transition dynamics and system interactions. Using a socio-technological transition lens to understand and characterize the energy networks' transition pathways can clarify how expectations of the transition can shape decision-making and policies. Reflecting on multi-system interactions perspectives and the systems interaction and interdependency attributes of energy networks and in particular multi-energy systems is also critical to understanding the current and future views of the energy system. Such reflections can provide insights on the

---

Abbreviations: CCUS, Carbon Capture Utilization and Storage; DH, District Heating; DHC, District Heating and Cooling; DNO, Distribution Network Operator; DSO, Distribution System Operator; EV, Electric Vehicle; IES, Integrated Energy Systems; MES, Multi-Energy Systems; MLP, Multi-Level Perspective; MVEN, Multi-Vector Energy Networks; P2G, Power-to-Gas; P2H, Power-to-Hydrogen; RESP, Regional Energy Strategic Plan; RE, Renewable Energy; SSEP, Strategic Spatial Energy Plan; TO, Transmission Owner; TSO, Transmission System Operator; VRE, Variable Renewable Energy.

possible collaborations, tensions and policy and institutional/actor alignment and cascading effects of system changes. Multi-energy systems therefore describe an energy landscape in which there are multiple linked systems that interact with one another, while multi-system interactions perspectives attempt to theorize and frame the dynamics and effect of interactions in these multiple systems.

Thus, this research aims to understand experts' views on the UK energy transition pathways, the energy networks' role in accelerating decarbonization, and their viewpoints on the MVEN approach in dealing with energy network challenges. The specific research questions we address are as follows:

> **Q1.** What are energy networks' key opportunities and challenges over the next 30 years?
> **Q2.** What are the discourses and areas of agreement and disagreement relating to likely future pathways for UK energy networks in response to these opportunities and challenges?
> **Q3.** How do experts understand the MVEN approach, and do they believe that the approach can help energy networks drive forward the energy transition?
> **Q4.** To what extent is the policy environment changing to support the different future pathways for energy networks identified and to promote an MVEN approach?

The article discusses socio-technological transition pathways and multi-system interaction in section 2, materials and methods in section 3, and the case of UK energy networks and multi-energy systems in section 4. Results and discussions are presented in sections 5 and 6, respectively, and then section 7 concludes.

2 Theoretical framework

Sustainable socio-technological transition frameworks have been used to analyze and understand dynamics and interactions among multiple socio-technological systems, regimes and niches. These frameworks aim to enhance our understanding of the actors' processes and interactions that help manage and govern a transition from an old (or existing) regime to a new (future) regime. Socio-technical systems provide social functions (e.g., energy, transport and food). Regimes are the combinations of dominant materials (technologies and infrastructure) and social (rules and actor networks) conformations that define systems to ensure stable patterns of production and use (Rosenbloom, 2020). Sociotechnical systems are dominant regimes that incrementally innovate and are disrupted by innovative niches that rapidly respond to landscape pressures to alter established patterns (Kemp et al., 1998). Therefore, sociotechnical system transitions are a multi-actor process in which actors with different viewpoints, interests, and capabilities constantly respond to and interact with each other to face critical challenges posed by landscape pressures or agendas (e.g., the low-carbon energy transition). Thus, studying sociotechnical systems or regimes, niche concepts, and theories is central to understanding niche development and evolution and their responses to transition landscape pressures.

The literature on socio-technical transitions and niche theories is extensive, and the associated frameworks/pathways have been used to support and enhance our understanding of the constantly evolving and interactive transition landscapes. These frameworks include the coevolution transition framework (Foxon, 2011), multi-level perspective (Geels, 2002), regime transformation (Van De Poel, 2003), systems innovation (Elzen et al., 2004) and transition management (Rotmans et al., 2001). Geels's multi-level perspective (MLP) defines the typology of sociotechnical transition pathways at different levels (micro, meso and macro), including technological niches, socio-technical regimes, and the sociotechnical landscape (Geels and Schot, 2007). Foxon's coevolutionary framework for analyzing transition pathways uses the coevolution of ecosystems, technologies, institutions, business strategies and user practices to explore and explain existing and possible future regime processes. Several authors have applied socio-technical transition frameworks to analyze the frontiers of the energy transition at various levels, and these include Zhang and Andrews-Speed (2020), Winskel and Kattirtzi (2020), Baker and Phillips (2019), Kucharski and Unesaki (2018), Simpson (2017), Child and Breyer (2017), Ruggiero et al. (2015), Nepal and Jamasb (2015), Foxon (2013), Smith and Raven (2012) and Kahrl et al. (2011). Others, including Ewijk (2014) and Smith and Raven (2012) have applied niche theory to explain niches, innovation and supporting technologies.

So far, we have identified the value of analyzing sociotechnical systems transitions using these various frameworks and have discussed some of their applications. Although it is agreed that actors interact, the dynamics and nature of such interactions across multiple technologies and multiple systems and regimes are not fully captured in most traditional socio-technical transition literature, such as the MLP (Andersen and Markard, 2020). Yet, there is significant evidence that the boundaries of sociotechnical systems are not immutable and that system boundaries change as they interact and respond to landscape pressures, regime change or innovation, and disruptive niche innovations. Multi-systems interactions and perspectives form a strand of research that investigates these interactions in more detail beyond the usual niche-regime levels. A particular benefit of these approaches is that they can help to reveal possible system alignments and tensions that could be levers for political and regulatory interventions (Rosenbloom, 2019). Multi-system interactions and perspectives can also help analyze the consequences of system cascading effects of transition changes (Rosenbloom, 2019). Andersen and Markard (2020) analyzed multi-technology interactions in socio-technical transitions using recent dynamics in HVDC technology and highlighted how these inform transition theories. Rosenbloom (2019) applied transition and disruption insights to analyze interactions between multiple socio-technical systems in Ontario's key energy transition pathways (electricity, heating and transport) and their actors. The study uncovered emerging patterns of interactions in terms of competition or symbiosis while identifying alignments and tensions with policy implications. Others have argued that in analyzing future pathways of network utilities, it is essential to evaluate multi-level perspectives for production, consumption and governance but highlight the need to unravel the interactions and interdependence of multi-regime dynamics (Konrad et al., 2008).

3 Materials and methods

3.1 Research design

In this study, we adopt a sustainability sociotechnical transition framework (Figure 1), based on Foxon's co-evolution transition framework and the MLP to design our data collection and analysis methods. The framework's function and capability to leverage whole systems thinking across sectors and institutions make it valuable for analyzing the UK's future pathways for energy networks. Specifically, the framework helped to shape the categories of experts to interview and the topics for discussion. Compared with other frameworks, it gives an overarching perspective of what is needed to transition from one regime to another across various sectors, including the existing physical and institutional architectures and their outlook under the new regime. Specifically, we collected evidence on probable future archetypes of the physical network infrastructure while investigating whether the transition would require changes in regulation, policy, actors or institutions. The framework thus guided us in exploring the potential of innovative options (for example, MVEN and hydrogen) to solve network challenges.

In addition, energy networks span and connect parts of the energy system across supply and use. Understanding the possible pathways for the UK's energy networks transition and the potential for a multi-vector energy networks (MVEN) approach highlights the required collaborations between niche and incumbent technologies/actors that are constantly challenging, interacting and eventually influencing the direction of socio-technical transitions. MVEN and other energy transition pathways depend on supporting several innovative technologies, including Power-to-Gas (P2G), Power-to-Hydrogen (P2H), electrolytic technologies, thermal storage technologies, new information and communication technologies, and innovative data management practices. Thus, reflecting on multi-systems interactions and perspectives broadens the scope of the research to understand the sites of interactions and to identify enabling and limiting alignment within and outside the systems of focus. In this study, we use multi-system interaction insights to help us visualize and understand the consequences of the interactions and interdependencies within and outside the energy network systems. The insights produced are used to question and validate experts' views of energy networks operations and management.

The research focused on analyzing experts' views on future pathways for energy networks as the UK pursues a net-zero transition. The main areas investigated include energy network challenges, responses and opportunities, network architecture, multi-vector energy networks approach, network impact on consumers, policy and regulation. Expert views are crucial in exploring various facets of an issue of interest, as they are experienced and knowledgeable in their fields of expertise. In addition, for exploratory studies, the expert views method can be more efficient than other methods, including observations, systematic reviews and extensive surveys. This is because the researcher is more assured of identifying and interviewing individuals with expertise in the research themes (Döringer, 2021; Kaiser, 2014; Meuser and Nagel, 2009). However, relying on experts' views could also impact the quality of research outputs if researchers cannot validate or distill the biases of the experts during the analysis process (Bogner et al., 2009). With these limitations in mind and following the recommendations in Von Soest (2023), we designed the research to enable discussion of controversial discourses by various experts with different backgrounds and interests. We were particularly keen to moderate any biases during the interviews, so we presented counterarguments from literature or other interviewees to enable the experts to justify their views.

Regarding the data collection, we selected and interviewed participants who are experts in one or more aspect(s) of energy network(s). A snowballing approach was used to identify experts. We identified the first batch of experts based on recommendations from participants in the Supergen Energy Networks Hub (an academic-industry research collaboration in the UK), and the other sets of experts were recommended by the experts we had already interviewed. We gathered both tacit and explicit knowledge about specific aspects of the research domain. We assessed these insights during the interviews by posing logically connected questions to elicit further information and clarification by suggesting counter perspectives.

We considered, but rejected, possible alternative approaches such as E-labs (Karlsen and Karlsen, 2007) and Delphi methods (Kattirtzi and Winskel, 2020; PwC et al., 2016; Winskel and Kattirtzi, 2020). These have been used with expert groups to solicit views for energy futures and foresight studies. Discussing experts' views and building consensus on discourses around pathways can be facilitated by such techniques. However, such approaches also have limitations. First, mistrust between participants or competitors could impact the quality of the evidence collected (Karlsen and Karlsen, 2007). For example, a party may be reluctant to acknowledge that evidence because it may be linked to business secrets (Kuusi, 1999). The other limitation is the difficulty of assembling policy and industry partners in one place. Thus, we interviewed experts individually because it was considered a robust and pragmatic approach.

3.2 Experts interviewed

From 23 January 2020 to 10 June 2022, we interviewed fifteen (15) experts from energy companies (electricity distribution network operators, gas distribution network operators, and transmission system operators), energy consultants, regulators, policymakers, consumer groups, and academic researchers (Table 1).

See Figures 2, 3 for distributions of experts based on their current organizations and their vector experience.

Most experts had experience in more than one vector, except two with experience in either gas or electricity. Many experts had experience in two vectors, the most common cross-vector experience related to electricity and gas.

3.3 Conducting and analyzing interviews

Ethical approval for the research was given by the University of Leeds Business, Environment and Social

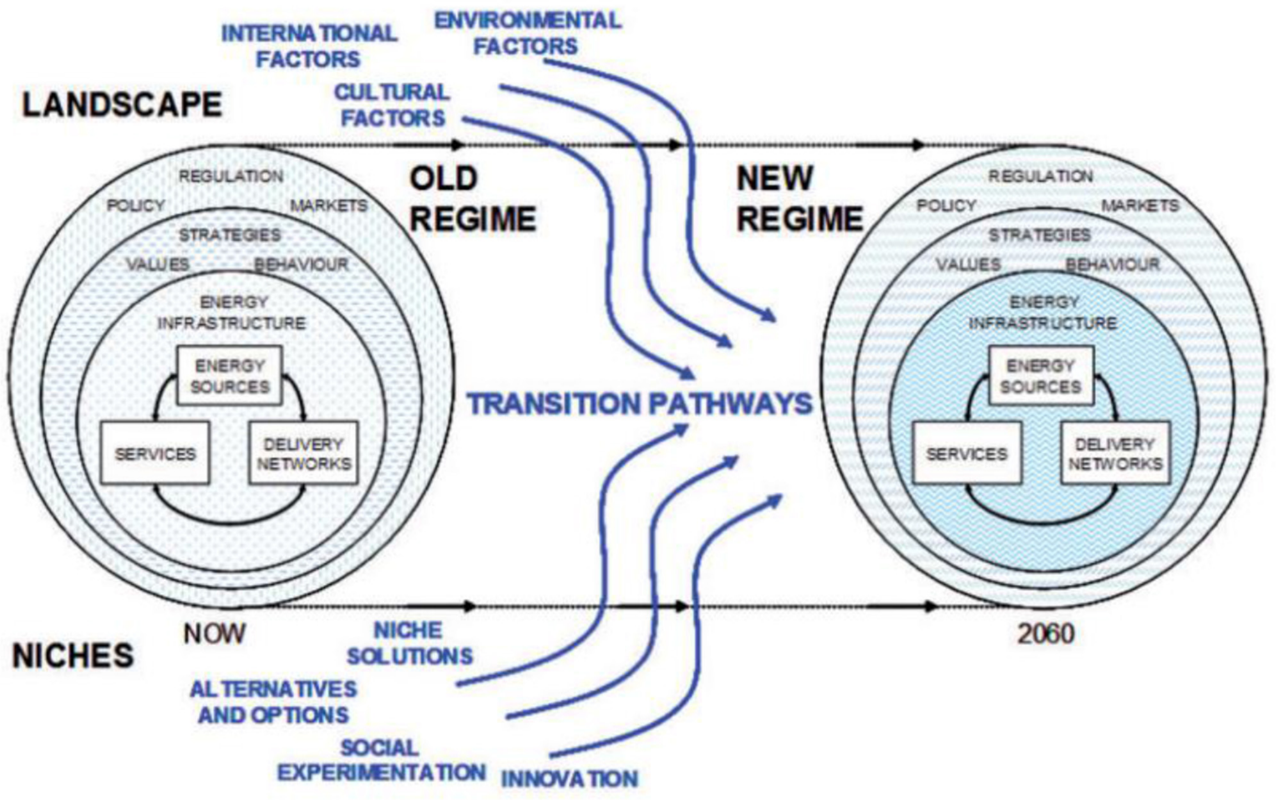

FIGURE 1
A sustainable socio-technological framework - possible transition pathways and factors that influence them. Source: Foxon et al. (2010).

Sciences Faculties Research Ethics Committee (approval reference LTSEE-101). We identified any ethical concerns, informed participants of the research and its methods, sought participants' informed consent, anonymised their responses and assured them of data confidentiality before conducting the interviews.

A semi-structured script (Appendix A) was used to guide the interviews and to ensure all aspects were covered. Even though the expectation was for interviewees to answer questions according to the main themes, it was permissible for some questions to be answered under different themes. Each interview lasted between 30 and 50 min and was conducted in person, over the telephone or on Teams/Zoom. The interviews were recorded, transcribed and organized into the main and sub-themes.

We used content analysis to create themes and sub-themes and assigned experts' statements accordingly. Given the relatively low number of interviews and the transcript length, it was plausible to code the transcripts manually. The research questions predefined the main themes, and during the coding process, sub-themes were created, deleted and sometimes recreated through an iterative inductive process. Additionally, we identified, grouped and counted the frequency of similar views. The tallying exercise was to help reveal areas of greater or lesser consensus and to identify relationships between participant types and their opinions.

4 Empirical case study: GB energy networks and multi-energy systems

The sections below explain the critical roles of energy networks in the UK and then introduce the individual network's capacity and current challenges relating to industry technology, regulation and policies. We then discuss multi-energy systems approaches and how they could be used to solve some of the network challenges.

4.1 Developments in GB energy consumption

The most extensive energy networks in the UK are for electricity and gas. Heat networks are far less developed, although they are expanding in some city areas and could increase their share of energy transport as the UK transitions to net zero. Figure 4 shows how final energy consumption in the UK has evolved over the last 50 years. Two important points stand out. The first is that, in contrast to most countries, total final energy consumption has fallen over time, with a particularly significant downward trend since 2004. The second is the change in the contribution of the energy carriers to meeting the final demand. There has been the almost complete elimination of coal from final energy consumption, but a significant increase in the use of natural gas.

TABLE 1 Experts, their roles and backgrounds.

Expert ID	Energy vector(s) of expertise	Roles and background
E1	Electricity	Academic researcher in energy policy and regulation
E2	Gas/Electricity/ Hydrogen/DH	Academic researcher in energy policy and innovation
E3	Gas/Electricity	Engineer/Network regulation
E4	Gas	Manager/Knowledge transfer and professional network
E5	Gas/Electricity/DH	Engineer/System operator
E6	Electricity/Gas	Engineer/Network operator
E7	Electricity/Gas	Consultant and expert in energy regulation and policy
E8	Electricity/gas	Consultant for low carbon energy
E9	Electricity/Gas/DH	Academic researcher in energy system modeling
E10	Electricity/Gas	Energy Policy Officer/Civil society organization
E11	Electricity/Gas	Academic researcher in energy policy and innovation
E12	Electricity/Gas	DNO Operator/Policy/Regulation
E13	Electricity/Gas	TSO/Engineer, technology and innovation expert
E14	Electricity/Gas	Academic researcher in electricity system modeling
E15	Electricity/Gas	Academic researcher in energy planning and policy

Oil consumption has also fallen slightly, while electricity use has increased over the whole period but with a decline since 2005. Other energy carriers, such as heat, have grown but still represent a small share of total final energy consumption.

4.2 GB energy networks[1]

Electricity, gas, and heat are produced and transported to final consumers via pipes and wires that make up the UK's energy networks. In contrast, while there are oil pipelines, most oil products are delivered to consumers in road tankers.

4.2.1 Ownership structure and operation

4.2.1.1 Electricity

The UK has an extensive electricity distribution and transmission system with over 800,000 km of wires and a sophisticated market and regulatory regime. The transmission network transmits high voltage (HV) power from generators and interconnectors into the distribution networks. A System Operator manages the system—currently National Grid Electricity System Operator (NGESO)—and it is largely owned and maintained by three Transmission Owners—one (National Grid) in England and Wales, and two (Scottish & Southern Electricity Network and SP Energy Networks) in Scotland (National Electricity System Operator, 2024).

All parties must ensure the system remains in balance in real time, with the ESO taking the role of the residual balancer and ensuring it has contracts in place so that supply can be ramped up or down quickly as required. The TOs also have a security of supply obligation and must ensure sufficient capacity (NESO, 2024).

Distribution Networks (DNs) are the parts of the network that carry power from the high voltage transmission grid to over 29 million homes and businesses across Great Britain. The distribution network is separated into eight license areas in mainland GB, which are currently run by 6 distribution network operators (DNOs) (Ofgem, 2023). They also have a role to play in balancing supply and demand on their networks (NGESO, 2021).

4.2.1.2 Gas

The UK gas network infrastructure is also extensive, summing up to about 300,000 km of pipes and connecting over 22 million homes and businesses. Gas enters the energy system from three sources: UK production, pipeline imports from Europe, and imports of Liquefied Natural Gas (LNG) that are shipped from other parts of the world. National Grid Gas (NGG) plc acts as both the System Operator (SO) and the Transmission Owner (TO) for the National Transmission System (NTS) (National Gas, 2024). As the SO, their role is to ensure a broad balance between inputs and outputs of the NTS over the gas day. As the TO, they have to ensure there is enough network capacity to maintain the security of supply (National Gas, 2024).

The gas distribution networks (GDNs) transport gas from the high-pressure NTS to homes and businesses. There are 8 regional networks, which are managed by 4 companies. There are also a few Independent Gas Transporters (IGTs), who own and manage smaller grids within the regions (Ofgem, 2024).

4.2.1.3 Heat

Heat networks work by carrying hot water from local heat sources to homes and businesses, using insulated pipes and enabling the use of efficient CHP plants, waste heat, large-scale renewables and low-carbon heat sources (ADE, 2018). They are powered by a variety of energy sources depending on the network, and these sources can be changed later as lower carbon alternatives become available or more commercially viable (ETI, 2018).

Heat networks are still poorly developed in the UK, providing only 2% of heat demand and supplying 1% of households, although they have a much higher uptake in large institutional estates, where they currently provide up to 50% of heat demand (ETI, 2018). However, there is increasing interest in the role of DH in UK cities and large towns where it is seen as a solution that can tackle both climate change and fuel poverty (Bolton and Foxon, 2015; Crisp et al., 2017).

1 There is an integrated system in GB. Northern Ireland is separate.

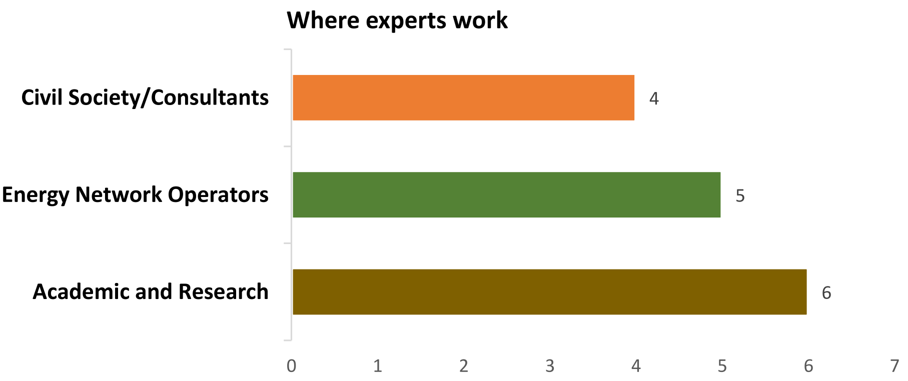

FIGURE 2
Experts' places of work.

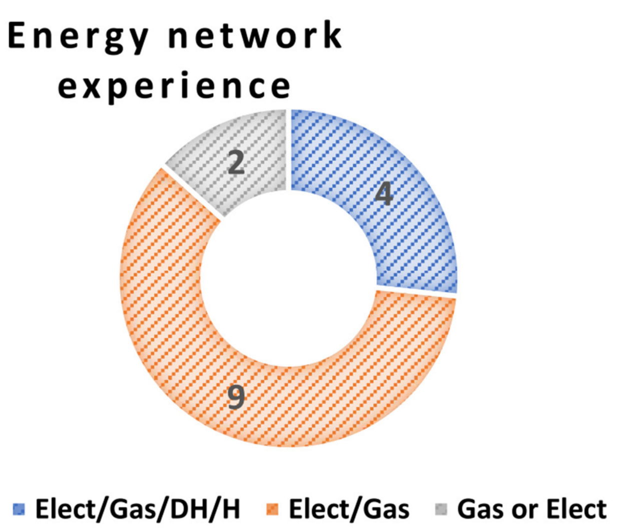

FIGURE 3
Experts' experience of different energy vectors.

4.3 Regulatory framework

4.3.1 Gas and electricity

The gas and electricity networks are natural monopolies and are, therefore, regulated to ensure that they deliver an acceptable quality of service. Both gas and electricity networks are governed and regulated by the Office of Gas and Electricity Markets (Ofgem) and the Department of Energy Security and Net Zero (DESNZ). The key regulatory tool is a price control framework, which has gone through several iterations over the last 30 years, with a trend toward increasing complexity as new challenges and obligations have emerged. Previously, the regulator's focus was narrow—protecting customer interests by promoting competition – and networks were regulated under an RPI-X framework; simple structures that focused primarily on driving cost reductions through efficiencies (Helm, 2017).

However, the external policy environment has changed since the inception of RPI-X, and Ofgem's remit has expanded to address growing concerns about energy security and climate change (Bolton and Foxon, 2011). Additionally, key challenges have emerged, such as aging infrastructure and the spread of distributed generation. There has also been increasing awareness that having separate incentive schemes for operating and capital expenses encouraged network companies to solve network issues through capital investment rather than considering smarter solutions (Lockwood, 2016).

The sector is now regulated under the "Revenue = Incentives + Innovation + Outputs" (RIIO) framework, which was implemented after an Ofgem consultation in 2010. This covers transmission and distribution companies for both electricity and gas. It was implemented for transmission and gas distribution in April 2013 and electricity distribution in April 2015. It aims to "promote smarter gas and electricity networks for a low carbon future" (Ofgem, 2010).

The RIIO framework represents some key changes from previous regulatory approaches. It is output-focused, with companies challenged to deliver on customer satisfaction, reliability and availability, safe network services, connection terms, environmental impact and social obligations. There have also been changes to how network companies' cost allowances are set, notably the switch from a traditional Opex/Capex[2] split to a Totex allowance, designed to encourage companies to take a flexible approach to delivering outputs. In addition, the price control period has been lengthened from 5 to 8 years to provide more security and stability for investors and encourage longer-term planning.

4.3.2 Heat networks

Unlike electricity and gas networks, heat networks are not currently centrally regulated, and the resulting perceived lack of consumer protection has been identified as one of the barriers to deployment (DECC, 2013). An independent customer protection scheme, The Heat Trust, and a voluntary Code of Practice

2 Operating expenditure is expenditure on operating and maintaining the network (inspection and maintenance, fault repair, engineering and business administation costs).
Capital expenditure is expenditure on investment in long-lived network assets (cables, overhead electricity lines and substations).

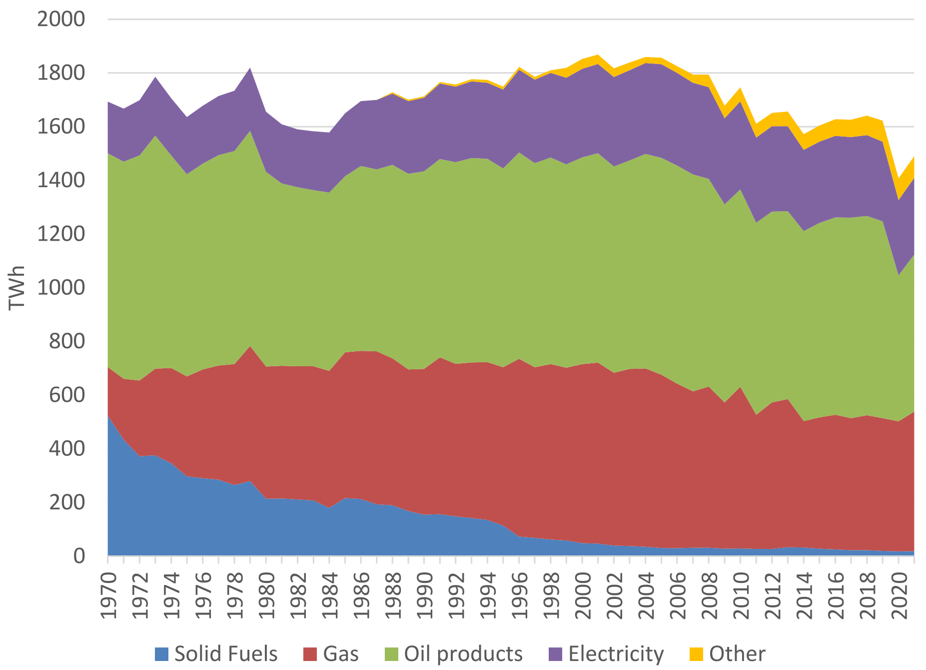

FIGURE 4
Final energy consumption by energy carrier (Source: based on data from DUKES).

have been created, and any projects applying for Heat Network Investment Programme (HNIP) funding must comply with these standards (BEIS, 2021). However, the regulation of heat networks in GB is planned to begin during 2024-25 (DESNZ and Ofgem, 2024).

4.4 Multi-energy systems

Energy systems are moving away from operating in silos to systems where various vectors interact and are interdependent to increase benefits to the whole system. The field of multi-energy systems (MES) is vast, with concepts spanning from energy hubs to integrated energy systems to energy system integration, multi-generation systems, whole systems approach and multi-vector energy networks concept. Energy network operations and planning have been described as smart (mostly the electricity grid) and have birthed typologies, including smart energy grids and smart integrated energy systems. Concepts of multi-vector or multi-energy, their optimisation and their assessment are discussed in (Hosseini et al., 2020; Mancarella, 2014; Oduro and Taylor, 2023; Taylor et al., 2021). Mancarella explains the concept of MES as a whole-system approach that optimizes and evaluates specific cases or levels (building or country level) that expand beyond the boundaries of a particular sector or vector of interest. General benefits of the system include increasing conversion efficiency and utilization of primary energy sources; enhancing market interactions because of the optimal deployment of both centralized and decentralized resources; and increasing system flexibility to respond and increase integration of variable renewable energy (wind and solar) (Mancarella, 2014; Taylor et al., 2021). Different authors have attempted categorizing MES to reveal and make simpler the various perspectives and complexity that characterize the concept. The spatial perspective relates to the MES applications at various levels or aggregation -from buildings (with multiple energy-generating technologies interacting with one another) in districts, regions and even countries. A multi-service perspective is the optimal integration of different energy vectors at the supply level to deliver multiple services. There is also the multi-fuel perspective, where the focus is on how the classical fuels (NG, Biomass, RE) can be integrated to supply MES services optimally.

The last perspective is the Networks Perspective, and this study aims to investigate its potential in the future of UK energy network operation, planning and investments. The focus of this perspective is on how energy networks (DH, DHC, Electricity, Natural Gas, and Hydrogen) interact and are interdependent on one another and enable the optimal integration of, and interaction with, multi-energy generating and conversion technologies to supply multi-services at the demand side in an MES. Figure 5 is an MVEN illustration taken from Taylor et al. (2021). The horizontal lines are the network infrastructure for various energy vectors, while the vertical lines are energy supply vectors interacting with energy networks and delivering services at the demand side. Conversion and storage technologies, including fuel cells, steam reformers, heat pumps, power to gas, adsorption and electric chillers interact with, and interdepend on, the various energy network operations.

5 Results

This section presents the thematized views of experts on various discourses. Several discourses birthed agreements and

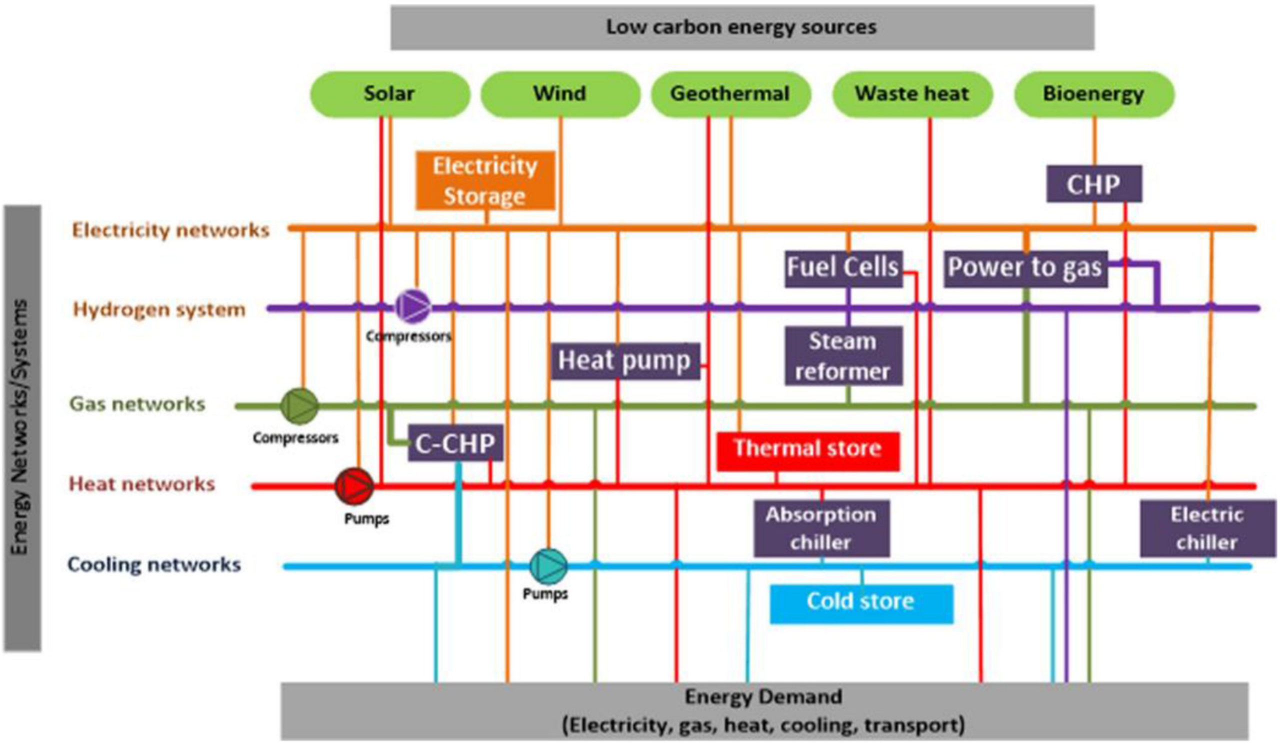

FIGURE 5
Multi-vector energy networks illustration. Source: Taylor et al. (2021).

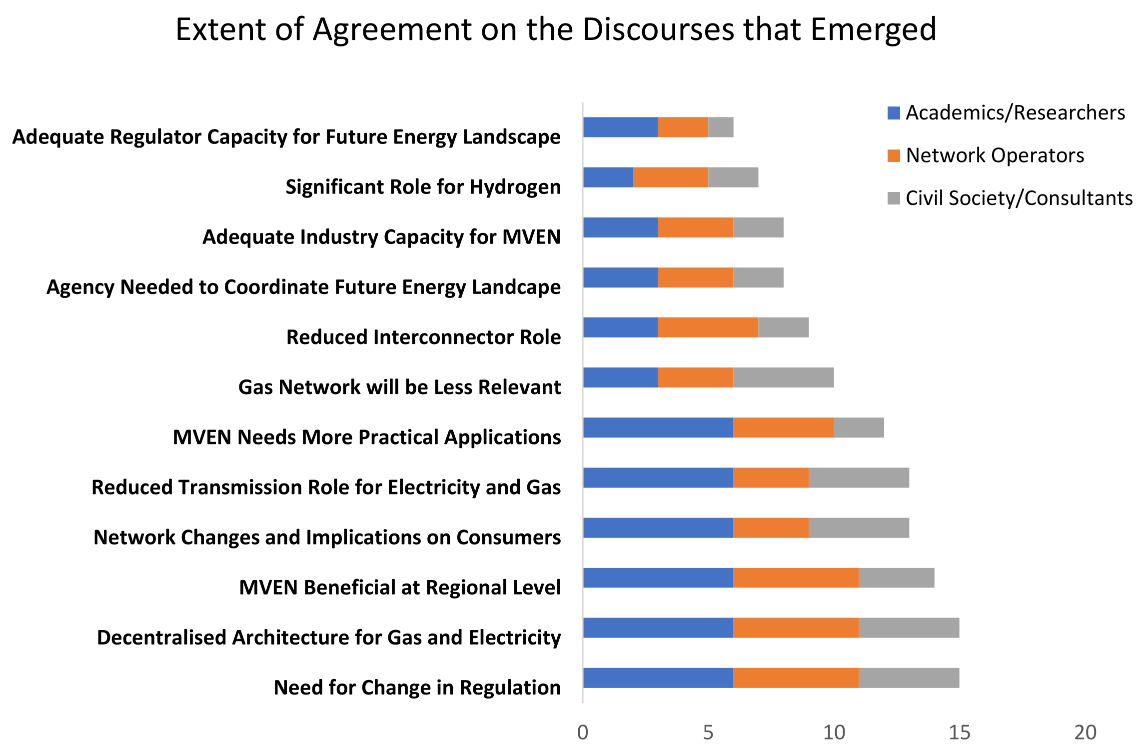

FIGURE 6
Number of experts supporting different discourses of the future pathways of energy networks.

disagreements on the challenges of energy networks, future pathways and network architecture, multi-vector energy networks' potential, and consumer impact.

5.1 Challenges of energy networks

This section explores experts' views on the UK's energy network challenges and opportunities as the country pursues its energy transition. We categorized their views into five themes with related key statements in Appendix B. The first theme is planning and operational challenges resulting from the increasing electricity demand met by a growing share of VRE generation resources. All experts indicated that TSOs and DNOs must deal with grid integration, flexibility and congestion issues as more VRE comes on stream. Most of the experts also agreed that a combination of technological and market solutions could address these challenges. They mentioned market solutions (flexibility market options and locational pricing), battery storage, grid reinforcement and extension, and conversion and coupling technologies, including P2G, P2H, and V2G. Generally, the experts agreed that the real challenge is operationalizing these interventions to decarbonize heat and transport at a reasonable cost.

> *"The electricity networks need to expand or reinforce to supply more electrical heat and … when you think about where that electricity is going to come from [and] their decisions to [deal with] generation as well. So, I think that's at the center of the problem. … for flexibility to be a real success, you need the distribution level and its active management to be much more developed than it is at the moment."* **[E6]**

> *"[How to] purchase hardware required to connect the 50GW of offshore and wind and the increase of bulk solar… e.g. the amount of cables required is more than the total global cable market in the last 5 years."* **[E13]**

> *"If we take electricity, I think the biggest challenge is to be able to have the capacity available at transmission and distribution at the same pace as the zero-carbon transition has received. And that's a big challenge at the moment because the network is quite full right now."* **[E15]**

The second theme relates to the uncertain role of gas networks in a future UK energy system. All experts suggested that the gas network is at a crossroads, but with a range of views around the likely path ahead. The uncertainty was supported by pointing to UK transition plans with different future scenarios for gas demand, from long-term decline to a significant role for hydrogen as a replacement for natural gas [for example, the three net zero scenarios in the UK's Net Zero Strategy in (HM Government, 2021b)]. They highlighted that this uncertainty has implications for future operation, long-term planning and investment in the gas network, with a significant risk of stranded assets. The two quotes below exemplify the need for GDNs to deal with the uncertain role of gas and the challenge of recouping asset investments in scenarios with little gas use. In contrast, the third quote represents a view of the future with a significant role for gas in the UK.

> *"So, there is a kind of scenario of [gas] decline and managing decline and how do you pay for a declining network? I think the gas networks have a... much tougher, and much more uncertain future."* **[E2]**

> *"An interesting conundrum is the role of gas in this future world and the role of the gas networks particularly… The main challenge is [with] gas …it is the recognition that they [gas networks] are either going to be managing a declining system or a declining service."* **[E7]**

> *"There are no credible future scenarios where there isn't a significant use of gases or vectors whether it's hydrogen or green gas… You [the UK] need a secure backup … when it's not windy."* **[E3]**

Third, a few experts emphasized that the rapid pace of decarbonization requires energy networks to innovate and invest "ahead of need," anticipating increased demand from both recharging significant numbers of EVs and high levels of electrification of heating. However, such an approach is not without risks, given the uncertainty regarding both the timing and extent of these developments. The regulatory framework guiding network investment and operation has historically discouraged such an approach because the regulator has been keen to protect current consumers from unnecessary costs associated with what could be speculative investments. Yet, without some anticipatory investment, network developments will likely lag what is needed to meet increased demand. This is a shared challenge for energy networks and the regulator (Ofgem), compelling the latter to adapt the regulatory framework to the speed of the transition. Key statements from **E3** and **E5** illustrate some of the issues.

> *"But if you're going to relax the attitude to risk, I think you need to then think about, how do you change the way the regulator adjusts if something goes wrong?"* **[E3]**

> *"Investment ahead of need not quite allowed by Ofgem **u**ntil recently because they are always more interested in protecting consumers now than consumers of the future."* **[E5]**

The fourth challenge is the lack of clarity in the UK energy policy direction. Industry experts, in particular, highlighted the lack of clarity in policy direction for decarbonizing certain sectors, including heating. This lack of clarity increases operational and investment risks for the network operators and can have knock-on implications for energy prices. Below are quotations from two experts:

> *"Lack of clarity on how we are going to decarbonise the energy system is preventing any significant steps forward."* **[E3]**

> *"So, I think the thing we are missing is the political will and political signaling of what the heat strategy is. So, once it's clearer about what the heat strategy is supposed to be, and where and what different pathways [there] are, the more certainty there will be, and the best job the regulator can do."* **[E6]**

The final network challenge deals with reducing consumer costs and understanding consumer behavior as the UK transitions. All experts agree there are at least short to medium-term cost implications for consumers as networks respond to sustain their businesses. Understanding consumer behavior could drive innovation to reduce network operation costs but experts suggest the energy industry seems inadequate in this domain.

> *"…who's going to pick up the tab? Who's going to pay for all these changes? That's a massively important question because quite a lot of the infrastructure changes will come at a significant cost. And at the moment, the way that we socialize costs means they can be distributed in a number of different ways."* **[E6]**
>
> *"… as a network, we need to transform into what society and our customers want us to become, but currently we are not allowed to due to regulatory constraints."* **[E13]**

5.2 Future pathways and architecture of UK energy networks

Experts discussed different ways the energy network architecture could develop, including centralized, regionalized and localized approaches. Appendix C shows experts' key statements and inferred perspectives on potential future architectures. Most experts were concerned about the security implications of an electricity-centric future, while two experts were optimistic about an all-electrified pathway with an insignificant role for natural gas between 2030 and 2050. These two experts were also skeptical about a future in which hydrogen played a significant role.

> *"About whether power for hydrogen will ever really happen because of the efficiency losses and because of the requirement for high rate [of permeability] … I'm slightly skeptical that you will be taking renewable electricity and turning it into hydrogen for a few hours a year or a few days in a year."* **[E7]**

Most experts foresee a dominant role for the electricity network but emphasize that the energy system will still require gas (e.g. hydrogen, a blend of hydrogen and natural gas, and bio methane or ammonia) to play a significant role in the transition.

> *"There are no credible future scenarios where there isn't a significant use of gas as a vector, whether it's hydrogen or green gas"* **[E3]**

Experts also discussed the role of the transmission network for both gas and electricity. Disagreement on this matter was not pronounced. The dominant view is that a continued role for the electricity transmission network is inevitable. However, they perceive that it will play more of a balancing role than be used for the bulk transmission of power. This insight is built on a conceived scenario of an energy system with more locally generated renewable energy. For example, we infer from views of E1, E2, and E5 that the electricity transmission network is inevitable, but it will play a lesser role in transmission than in storage and system balancing because they believe the electricity generation will become more local. In the quote below, E7 expresses a skeptical view on the role of the transmission network.

> *"I think there probably would be elements of both. You know, we're already involved in a project with [name removed] for doing peer-to-peer trading in Cornwall, and I think there is value to that and that if you know can balance the local area network but at the same time you've got to also balance the transmission system as well, yeah. So, I think it's probably both, but in terms of the interaction between those two… I'm not sure I'm afraid."* **[E7]**

Some of the experts were unsure of the future of the gas network but some perceived gas would operate in the sub-national and regional setting. For example, it was inferred from E2, E5, and E7 that the future of the gas network (hydrogen, blended or repurposed) is more certain to be at the regional and sub-regional levels.

Two experts envisioned an architecture in which interconnectors play an important role. However, another highlighted an imminent decrease in interconnector utilization capacity, which could reduce its prominence in the UK. Low seasonal and daily demand variability between the UK and Europe, the significant increase in local energy supply and balancing capacities are the factors that the experts highlighted could lead to a reduced interconnector role.

> *"Interconnectors are great, but to some extent, and there are cost implications, and the economics are not good. Utilization, given the location of the UK, will even get lower and lower, as it [the energy system] becomes more regional."* **[E5]**

The structural archetypes below represent the foresight views of **E1, E6,** and **E14,** respectively:

a. All electric, with a reduced role for electricity transmission, significant decentralized generation and little or no gas.
b. Highly electric but with a significant role for gas, very decentralized with both transmission lines and interconnectors.
c. A shared gas and electricity future with a highly decentralized system but with transmission lines and interconnectors.

5.3 MVEN- benefits and challenges

An MVEN approach is considered a possible pathway to solve some of the VRE-imposed challenges by coordinating and optimizing operations, planning and investments of two or more energy networks together. Almost all the experts were conversant with the MVEN concept and could distinguish it from other related ideas, such as MES. Two experts were familiar with MES but were unaware of the MVEN approach. Perhaps not surprisingly, experts from the gas industry were more aware of and generally supported and advocated for the MVEN approach. Conversely, we noticed that experts who were skeptical about the role of MVEN were also unsure about the future role of gas.

We also gathered views on the benefits and challenges of MVEN, and how the approach could benefit the UK. Key statements on the benefits and challenges of MVEN are captured in Appendix D.

Most experts were positive about MVEN's role in the UK, although two were skeptical about its benefits/role. Their view centered on how hydrogen would be central to an MVEN approach consistent with the UK's net-zero ambitions and that there were too many obstacles to its rapid and widespread deployment.

> *"I don't know how it will work in a decentralized system. Hydrogen is more theory at the moment than it is proven, and there is a short timescale for us to reach net zero, thus, we cannot take a risk on that. [A] fair amount of balancing can be done anyway given by the distributed energy resources."* **[E1]**

Those experts with a fair idea of MVEN highlighted that the approach could help deal with grid integration and curtailment challenges as VRE increases. They emphasized that the interdependencies between electricity and gas will become more apparent in the UK. Some experts highlighted what they saw as the operational and regulatory challenges of MVEN but indicated that these are resolvable.

> *"So, if you've got one (network) that was constrained in every way, and the other network isn't, then it makes sense that you look at solutions that involve using the one with a spare capacity." Solving constraint issues between gas and electricity networks is where planning networks can be revealed. But it's almost down to the market, to realize and to bring forward a solution."* **[E3]**

E2, E4, and E5 also envisaged that an MVEN approach would be most feasible at the regional and sub-regional levels. They believe that gas networks will be less dominant at the transmission level. The reason is that the distribution of green gas production (hydrogen and biomethane) and the use of gas in electricity peaking plants are likely to be highly non-uniform across the UK. As such, it will be more valuable for hydrogen and biomethane to be produced and used for peaking plants at particular geographical locations.

> *"At the local level, there is more potential for MVEN, but there are current challenges based on the existing framework. (It is) quite early days, but companies at the local level can integrate two networks and benefit from saving investments and cost."* **[E2]**
>
> *"There is a long way to go because this concept [MVEN] is applicable at the regional level, and even with existing electricity and gas systems, regionalization is still a challenge."* **[E4]**
>
> *"[MVEN] is being driven by the fact that you know, electrification will prove to be just so hard. … there is use of hydrogen for example, in certain areas [e.g.] industrial heartland of the north of the country, South Wales, and North Wales. [These] places could be probably desperate for hydrogen, and other places and maybe a more multi-vector approach to the sector."* **[E5]**

Experts highlighted some of the specific benefits and challenges of the MVEN approach. First, almost all interviewees suggested that it increases efficiency by optimizing networks and investments. Most explained the storage capability of MVEN to demonstrate how the approach could conserve currently wasted or curtailed energy. A few experts mentioned that line-packs could offer more balancing/flexibility capacity for the electricity grid if the networks were planned and optimized together. Cost efficiency and environmental gains were also noted as benefits of MVEN, except that two experts were skeptical about what scale, type, and quantity of hydrogen (blue or green) could make such benefits realizable.

Regarding challenges, experts noted the practical difficulties of implementing MVEN at the required pace to meet the UK's net zero target. The experts doubted the extent of the current collaboration between the electricity and gas networks. Thus, the ambition of co-planning investments and operations between networks could be too great in the short term if the required collaboration does not currently exist.

> *"Solving constraint issues between gas and electricity network is where [the benefits of] planning networks can be revealed. But it's almost down to the market to realize it [the need for co-planning] and to bring forward a solution."* **[E3]**

Several experts, however, were more positive and highlighted that energy networks must collaborate more than ever before and that MVEN will emerge organically even in an electricity-dominated future.

> *"MVEN will emerge organically and may require active policy and regulatory action for it to happen. It has an advantage even in an all-electrified UK, and in that situation, it will be relevant in a downgraded gas industry where it can help with grid integration problems with VRE."* **[E7]**

Some experts saw MVEN's data exchange requirements and related complex models as problematic. For the data challenge, the argument was that even gathering and managing critical data to make the electricity network smarter has faced challenges at the local and regional levels. One expert referred to a case where only two utilities had completed the data collection phase of a smart grid project, suggesting that convincing stakeholders regarding the data challenge could be difficult. Thus, collecting, sharing and managing data across two or more networks could be more challenging. Nonetheless, two other experts suggested that the energy domain has highly skilled individuals who can overcome data and modeling complexities. Thus, identifying coordination roles and resourcing competent staff would be a logical step to take with the data and modeling issues.

> *"It is not widespread, but there are still lots of people who understand this stuff and...there are some very clever people in the energy industry, and they are starting to work on this stuff. So positive that they start falling (creating) big solutions."* **[E5]**

Other experts keenly highlighted the regulatory authorities' role in supporting MVEN approaches. Their views regarding the regulatory framework suggest it would need to change significantly for MVEN to function. They believed that the regulator's capacity is inadequate to deal with the MVEN approach, given that the networks have historically been regulated separately. Two experts agreed that a specific policy package is needed to bring forward the required regulatory changes that will drive the MVEN application.

> *"[The challenge is] whether there are enough incentives on planning to accelerate planning in terms of MVEN or not, the system designer to do so, or they [the networks] have to do it themselves."* **[E6]**
>
> *"MVEN … requires active policy and regulatory action for it to happen [in the UK]"* **[E7]**
>
> *"I think we need to open up policy [for MVEN to happen]"* **[E13]**

5.4 Potential impact on consumers

This section discusses experts' perspectives on how different future pathways for energy networks may impact consumers. Key statements made by the experts are in Appendix E. First, some of the experts believed that, even though energy networks are engaging stakeholders in their plans, general consumer awareness about the role of networks in the energy transition is incredibly low. These experts highlight the danger of not taking consumers along on the journey since the energy transition will directly impact them. Second, almost all experts envisaged cost implications for consumers relating to the transition, and those from academia and civil society groups appeared particularly concerned about an increase in costs. Three questions emerged from this theme: who is likely to bear the additional cost, what would be an equitable distribution of such costs, and which mechanisms (policy, market and regulation) could ensure such a fair distribution and so protect vulnerable groups? Experts agree that minimizing cost implications for all consumers is critical, but vulnerable consumers deserve extra support. Two participants highlighted the need to balance the responsibilities and burden across generations and the costs across different consumers and adopters of new low-carbon technologies and infrastructure. For example, ensuring equity between EV and non-EV users (who may have low incomes) when recovering public investments in EV infrastructure is complex and controversial.

> *… so, when you are thinking about [energy] network changes, or how to decarbonise heating, particular attention to people on lower incomes is really important, otherwise, the risk is that the politics will not work."* **[E2]**

Four perspectives emerged concerning equity and protecting vulnerable consumers: socializing the transition cost, providing fiscal reliefs and incentives to specific groups, using regulation to increase efficiency and reduce cost and providing flexible financing options. Below is a statement from E3 regarding how to deal with the transition cost.

> *You have a mixture of consumer funding and taxation paying for the transition. And then once you've got all the new energy arrangements in place, you can then switch the market arrangements back on."* **[E3]**

5.5 Implications for policy and regulation

Experts' key statements on future network implications for policy and regulation are captured in Appendix F. Possible changes in the energy sector drive the need to reassess the flexibility and robustness of existing policies and regulations. The potential changes to network architecture and institutions, changes in residential, industrial and transport energy demand and the potential introduction of new vectors (hydrogen, blended natural gas and hydrogen, ammonia, etc.) will require policy and regulation to adapt. For example, introducing new vectors and increasing decentralization require new policies and regulations. Some experts thought that a complete change to the regulatory system was needed to meet these challenges.

> *"The market system [must] change dramatically for this to work. Because of the regulations, …, and the market rules, everything has been set up for a centralized system. … everything is being tweaked within that [centralized system] too. Trying to enable more decentralization and you tweaking a framework, which is no longer viable. You are trying to just piecemeal alter a centralized set of rules and industry codes and all the rest of it rather than deciding that yes, if we want a decentralized system, we need to start again with the rules and what have you. "* **[E1]**

Given that decarbonization may entail reconfiguring the existing regulatory framework, most of the experts agreed that the regulator (Ofgem) would need additional capacity to deal with the requirements of the transition, including coordinating new technological developments and decentralization. While some experts advocated for a new institution/agency to coordinate the decarbonization agenda, two experts were uncertain about the need for this. See views from **E2** and **E6**:

> *"I'm a bit more cautious on this, but there has been some debate about … Do we need to create another New agency, an Energy Agency or? Well, so I suppose there's a debate at the moment about that, and that's broader than what should Ofgem do. It's kind of is Ofgem the right body to do this?"* **[E2]**
>
> *"The decision has to be made on whether we want a centralized system with a system operator or a regional system operator that works [on a] small local basis and is coordinated by some kind of central body for a security of supply."* **[E6]**

Managing risks regarding "investing ahead of need" and protecting consumers is crucial for net zero given the urgency of the required innovation. However, some experts expressed that this approach would need a change of attitude from the regulator. Others expressed skepticism that the regulator could match the industry's planned speed of innovation, citing the regulator's pro-consumer and incremental change culture as inhibiting factors.

Ultimately, protecting consumers is the regulator's prime objective. Thus, it is challenging to implement frameworks that could unfairly distribute costs and benefits between different consumers: current and future consumers and consumers and network investors. One expert highlighted the complexities in designing a regulatory framework that is flexible enough to accommodate a least regrets approach while investing ahead of need.

6 Discussion

In this section, we discuss the experts' views on the thematic areas presented in the results and contextualize them by considering developments since the interviews were held. The section is structured to directly address the four research questions in the introduction, and then we conclude by reflecting on the findings in the light of the literature on socio-technical transitions and multi-systems interactions perspectives.

6.1 Energy networks challenges and opportunities

Our results highlight that experts see integrating massive amounts of renewable energy as among the biggest challenges facing the electricity network, while decarbonizing heat poses challenges of different kinds for both electricity and gas networks. The pathway for transport decarbonization seems clearer on the use of electric vehicles replacing fossil-fuelled passenger cars and vans than the approach to decarbonizing heat, which is still contested. However, since the interviews were conducted, the arguments for electrifying heating by using air-source heat pumps seem to have gained ground relative to those who see the widespread use of hydrogen for domestic heating (Rosenow, 2022). Linked to the future of heating is the uncertain future role of the gas network. The Heat and Buildings Strategy (BEIS, 2021) outlined Government plans to develop an evidence base to inform strategy in 2026 about the future role of hydrogen in home heating. Then, in October 2023, the government clarified that heat pumps and heat networks would be the primary low-carbon technology for decarbonizing home heating over the next decade and will play a key role in all pathways to 2050 (National Audit Office, 2024). However, the longer-term future of gas beyond 2035 remains unclear.

The Russian invasion of Ukraine in February 2022 has had a major impact on the energy policy discourse in the UK, with issues of affordability and security becoming much more prominent. In response, the Government has committed to reducing dependence on fossil fuel imports through further exploitation of domestic oil and gas in the North Sea, as well as plans for new nuclear power stations and the development of CCUS and both blue and green hydrogen production (HM Government, 2021a). These developments are underpinned by a commitment to accelerate the development of energy network infrastructure to both anticipate need because planning minimizes cost and public disruption, and deliver increased flexibility in matching supply and demand so that minimal energy is wasted. The Government estimates that this more efficient, locally responsive system could reduce costs by up to £10 billion a year by 2050 (HM Government, 2021a).

6.2 Agreements and disagreements on UK energy network pathways

Though diverse views were expressed, experts agreed more or less on several discourses (Figure 6). For example, there was more consensus on "Decentralized architecture for gas and electricity" and "need for change in regulation for net zero" than on "an all-electrified future by 2050 is feasible" and "significant role for hydrogen."

As discussed in section 4.2, some possible pathways emerged, and these were based on how the experts perceived the dominance of a particular energy vector. These included an electricity-dominant pathway and a balanced gas and electricity pathway with the gas sector dominated by hydrogen. We observed that experts envisioned pathways based on their convictions about the future role of the gas network. Thus, experts against an electricity-dominant archetype doubted that flexibility and grid integration challenges could be resolved within the period. Proponents of the all-electric and no-gas futures believe hydrogen is not currently practicable to replace natural gas.

It seems the structural architecture choices depended on experts' beliefs regarding what electric vehicle charging approaches will emerge dominant, the role of natural gas and hydrogen, and how domestic heating will be decarbonized. For example, the proponents of a hydrogen/gas-dominated sector are convinced that the gas network will be more local and less regional.

Experts working in the electricity sector were not especially keen on an all-electric future while experts with gas network experience were particular advocates of hydrogen and MVEN futures. The future of a more decentralized architecture for electricity was not contested although opinions were divided around decentralization intensities (fair, significant, and extreme levels of decentralization). We observed that the more decentralized their choice, the more they agreed on a reduced transmission role for balancing.

6.3 MVEN perspectives and developments

The interviews revealed that most experts were conversant with the whole systems approach and MES. Regarding MVEN, experts who did not support a continued role for gaseous fuels in the UK energy system (proponents of an all-electric future) were generally less knowledgeable and less persuaded about the benefits of an MVEN approach. Most industry advocates for hydrogen as a natural gas substitute had a gas network background/experience and were most likely to support MVEN. Nonetheless, those who perceived a balanced gas and electricity pathway were also knowledgeable about MVEN and often believed it would bring benefits.

Since the interviews were conducted, the need for greater integration in planning electricity and gas networks has been recognized in policy circles. In April 2022, the energy regulator Ofgem published a document setting out plans to create a "Future System Operator" (FSO) to be a trusted and expert body at the center of the gas and electricity systems. These plans stated that the FSO would adopt a "whole system" remit across electricity, gas, and hydrogen (BEIS and Ofgem, 2022). In the summer of 2024, these plans came to fruition with the launch of a new independent, public corporation known as the National Energy System Operator (NESO). NESO oversees the planning and delivery of the integrated system needed to secure the UK's energy security, net-zero and affordability goals. Among the ways it will do this is through the development of two network plans (DESNZ, 2024b). These are a Strategic Spatial Energy Plan (SSEP) for the whole energy system, identifying the optimal locations for generation, storage and networks required to meet net zero, which will be complemented by Regional Energy Strategic Plans (RESPs) to provide coordination and accountability in the way that regional electricity and gas networks are planned.

These new developments in the policy and regulatory landscape can be seen as starting to implement many of the ideas that are represented by an MVEN approach, and it is anticipated that NESO may gain more powers over time. The focus on not only national-scale issues but also on the regional level through the RESPs responds to what many experts saw as the particular value of the MVEN approach at the regional and local levels. Nevertheless, some aspects highlighted by the interviews on issues such as the sharing of data still need to be worked on, and there are already questions about how both the SSEP and RESPs will be able to reflect the diverse range of stakeholder views on the most appropriate pathway forward for energy networks.

6.4 Implications for policy, regulation, and society

The challenges and opportunities facing energy networks in the UK are driving some of the most significant changes in policy and regulation that have been seen since privatization more than 30 years ago. Some of the most critical challenges for the policy environment identified by the expert interviews were:

- Determining a clear pathway for developing energy networks to support the energy transition and net-zero targets.
- Managing significant new investments in electricity transmission and distribution to take account of increased electricity generation from low-carbon sources and to meet increased demand from heating and transport.
- Balancing the necessity of investments ahead of need so as not to hold back the energy transition while also minimizing the risk of stranded investments and protecting today's consumers from unnecessary costs.
- Addressing the probable decline in gas demand and its implications for how the costs of gas networks are recovered.
- Operating an electricity system with significant proportions of variable renewables while maintaining security of supply.
- Determining and mapping out regions or places where MVEN is applicable in the UK and demonstrating its value with the right policy package.

Since the interviews were undertaken, there are signs that the policy and regulatory framework is starting to change in recognition of many of these challenges. Fundamental to this new approach has been the passing of the Energy Act 2023 which addresses a wide range of topics including new governance arrangements through the creation of NESO, giving Ofgem the power to be the economic regulator of heat networks for the first time, a range of measures to promote use of hydrogen and further development of nuclear power.

Other recent developments of particular relevance to energy networks include the publication of the Winser report (Winser, 2023) which provided the Government with a set of recommendations to accelerate the delivery of strategic electricity transmission projects and a Review of Electricity Market Arrangements which, among other things, is exploring the need for new network charging approaches (including the possibility of locational pricing) and how to make the networks more flexible and reduce constraint costs (DESNZ, 2024a).

However, significant challenges remain, not least how to develop a holistic, integrated and equitable approach to protect consumers, and vulnerable consumers in particular, by minimizing costs and maximizing benefits. Addressing vulnerability seems to be high on the priority list of a range of actors, including energy policymakers, the regulator and the industry (Ofgem, 2019). Addressing this challenge is, therefore, likely to be an ongoing and shared endeavor.

6.5 Theoretical reflections on UK energy networks' transition pathways

We analyzed expert views on the development of UK energy networks using this framework and reflect here on the evidence of specific themes relating to the energy transition. We found that the UK's ambition to tackle climate change is causing multiple socio-technological developments and interactions as energy networks evolve within the current regime as they respond to the challenges posed by landscape pressures. This response involves multiple actors, and leads to technological innovation (e.g., P2G and hydrogen networks) and new operating and planning strategies (MVEN and RESP). The need for regulatory and institutional restructuring (as now manifested in the role of NESO as a multi-vector central planner) highlighted by experts reinforces the value of the co-evolutionary dimension of socio-technological transition theories. Energy networks and other actors are finding opportunities in distributed generation and the adoption of new regulatory strategies (RIIO, SSEP, and RESP) and market designs (locational pricing and ancillary markets) to address emerging challenges.

Regarding multi-system interaction, the case of energy networks demonstrates the need to understand complex systems interactions. First, each network is linked to and interacts with several other systems at different points along the supply value chain. Second, given the interdependence and interactions of energy networks with various other energy systems and sub-systems, they present ideal opportunities to study multi-system interaction dynamics. Gas and electricity networks (dominant actors) will remain competitive and interdependent in the short term. However, in the long run, the gas network will need to embrace new low carbon fuels, such as hydrogen and biomethane, if it is to have a continued role. District heating prominence or growth in the UK is heavily dependent on government policy toward heat decarbonization, including the rate of decline in the use of gas and the uptake of heat pumps. Evidence from experts envisages that the transition could change the existing relationship between the gas and electricity networks as they move from being competitive to a more symbiotic one. This is because the electricity network is favored by the landscape pressures, leading to demand-side changes in fuels (for example, electrification of heat and transport). However, the electricity network requires more innovation in operations and planning, and continuous cooperation with the gas network.

We identified several systems interactions in the MVEN approach, which span the energy network and technological infrastructure, policy and regulatory systems, markets and institutional arrangements, and impacts on society and industry. We identified three broad types of interactions namely hard, (physical and technological system interactions i. e. networks-energy transfer technologies-digital infrastructure) soft (policy, regulation and markets, and consumer interactions of multiple energy networks i.e. heat, gas, electricity) and hard-soft (physical infrastructure, market designs, institutional, policy and regulatory) systems interactions.

We have broadly reflected on multi-system interactions in the transition of UK energy networks. We have demonstrated that the MVEN approach internalizes supply and demand-side dynamics, while hosting energy transfer/exchange technologies. Thus, MVEN could be used to understand systems of system interactions, focusing on the type of interactions, the direction of causes and effects, material flows, knowledge exchanges, system alignments and tensions. Such insights are critical to understanding and managing the needed coordination in MVEN. The multi-systems perspective value is reflected in the MVEN approach, as experts are concerned about the cascading effects of system failures across networks. Thus, critically examining system interactions and the cascading effects of system changes is imperative for MVEN implementation.

Finally, sharing costs and benefits for interacting systems is an MVEN challenge. Since these systems deliberately interact to solve a common objective, it is important for systems analysis to capture the nature/distribution of costs and benefits. Thus, studying the MVEN approach has demonstrated the need to expand the scope of multi-system interactions analysis to include how costs and benefits are distributed between systems in a regime.

7 Conclusions

Our investigations on the energy networks challenges, opportunities and future pathways have demonstrated consensus amongst experts on the need for a low-carbon energy transition to support the UK's net zero climate goal. There is a widespread agreement that substantial investment will be required in electricity transmission and distribution networks, both to integrate large volumes of renewable electricity generation, including from offshore wind farms and to meet the growing demand for electricity from heat and transport. In contrast, the future for gas networks is more uncertain and contested, with a decline in the use of natural gas being seen as inevitable but markedly diverging views on the extent to which it might be replaced by hydrogen. Heat networks currently play only a small role in the UK and didn't receive much attention in interviews, although a modest expansion in urban areas was expected by most experts.

Regarding our research questions on future energy networks policy and regulation, a key challenge is how to enable energy networks to help drive the low-carbon transition by allowing investments ahead of need while ensuring that this does not impose unnecessary costs on consumers. The questions of cost and how to pay for the necessary investments were also important issues for experts who believed that there was a future for both electricity and a gaseous fuel in the energy system. Our investigations on the potential of the MVEN approach in the UK show that experts think that an MVEN approach that integrates planning and operation across multiple energy vectors could bring benefits in terms of greater efficiency and reduced costs, but also brings the risk of cascading failures. In the UK, MVEN is seen to be more applicable in local and regional settings. The Energy Act 2023 and other policy developments are trying to address both the challenges and opportunities identified by the experts, but it is too early to say to what extent these recent changes will be successful in enabling energy networks to be a driver of, rather than a barrier to, a net-zero UK energy system.

Employing a sustainable socio-technological transition framework and perspectives from the multi-system interactions literature has enhanced our understanding of the energy transition. We relied on multi-systems perspectives to understand and validate experts' views on UK energy networks transition pathways. Upon reflecting on multi-system interactions and the MVEN case, we have demonstrated that systems can be deliberately integrated to interact and solve particular system challenges. We identified three broad kinds of interactions: hard interactions, soft interactions and soft-hard interactions, and highlighted the need to expand the analytical perspective to include the distribution/nature of costs and benefits between multiple systems as they interact. Given that MVEN is a possible approach that deliberately links systems, future research to study, identify and characterize systems interactions could contribute to our understanding of multi-system interactions as they apply to energy networks and so help inform policy developments in the area.

While Great Britain's energy system is unique, the goal to drastically reduce greenhouse gas emissions and the challenges that this poses to energy networks will be shared by many developed countries, as will some of the solutions. The findings from this paper should, therefore, be of interest to other countries facing similar issues.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by BESS+ FREC is a cross-faculty research Ethics Committee reviewing applications from the Faculties of Business, Environment and Social Sciences at the University of Leeds. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RO: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. PT: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the UK Engineering and Physical Sciences Research Council through the Supergen Energy Networks Hub [grant references: EP/S00078X/2 and EP/Y016114/1].

Acknowledgments

We would like to thank those individuals and organizations who participated in our research and contributed to the design and data collection.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsuep.2025.1514717/full#supplementary-material

References

ADE, R. R. (2018). Market Report: Heat Networks in the UK. In *The Association for Decentralised Energy*. Available online at: https://www.theade.co.uk/assets/docs/resources/HeatNetworksintheUK_v5websingle~pages.pdf (Accessed December 12, 2024).

Andersen, A. D., and Markard, J. (2020). Multi-technology interaction in socio-technical transitions: how recent dynamics in HVDC technology can inform transition theories. *Tech. Forecast. Soc. Change* 151:119802. doi: 10.1016/j.techfore.2019.119802

Baker, L., and Phillips, J. (2019). Tensions in the transition: the politics of electricity distribution in South Africa. *Environ. Plann. C: Polit. Space* 37, 177–196. doi: 10.1177/2399654418778590

BEIS (2021). *Heat and Buildings Strategy*. Available online at: https://assets.publishing.service.gov.uk/media/61d450eb8fa8f54c14eb14e4/6.7408_BEIS_Clean_Heat_Heat___Buildings_Strategy_Stage_2_v5_WEB.pdf (Accessed December 10, 2024).

BEIS and Ofgem (2022). Future *System Operator*. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1066720/future-system-operator-consultation-govt-response.pdf (Accessed February 20, 2024).

Bogner, A., Littig, B., and Menz, W. (2009). "*Introduction: Expert Interviews — An Introduction to a New Methodological Debate*," in *Interviewing Expert* (Palgrave Macmillan UK: Springer), pp. 1–13. doi: 10.1057/9780230244276_1

Bolton, R., and Foxon, J. (2011). Governing infrastructure networks for a low carbon economy: co-evolutionary of technologies and institutions in uk electricity distribution networks. *Compet. Regul. Netw. Ind.* 12, 2–26. doi: 10.1177/178359171101200101

Bolton, R., and Foxon, T. J. (2015). A socio-technical perspective on low carbon investment challenges - Insights for UK energy policy. *Environ. Innov. Soc. Transit.* 14, 165–181. doi: 10.1016/j.eist.2014.07.005

Broad, O., Hawker, G., and Dodds, P. E. (2020). Decarbonising the UK residential sector: the dependence of national abatement on flexible and local views of the future. *Energy Policy* 140:111321. doi: 10.1016/j.enpol.2020.111321

Chaudry, M., Abeysekera, M., Hosseini, S. H. R., Jenkins, N., and Wu, J. (2015). Uncertainties in decarbonising heat in the UK. *Energy Policy* 87, 623–640. doi: 10.1016/j.enpol.2015.07.019

Child, M., and Breyer, C. (2017). Transition and transformation: a review of the concept of change in the progress towards future sustainable energy systems. *Energy Policy* 107, 11–26. doi: 10.1016/j.enpol.2017.04.022

Competition and Markets Authority, R. R. (2018). *Heat networks market study. July*, 109. Available online at: http://www.nationalarchives.gov.uk/doc/open-government- (Accessed July 23, 2024).

Crisp, R., Cole, I., Eadson, W., Ferrari, E., Powell, R., and While, A. (2017). Tackling poverty through housing and planning policy in city regions Tackling poverty through housing and planning policy in city regions Final report. Available online at: http://www.jrf.org.uk (Accessed May 2, 2024).

DECC. (2013). *The Future of Heating: Meeting the Challenge*. London: Department of Energy and Climate Change.

DESNZ, R. R. (2024a). *Review of Electricity Market Arrangements Second Consultation Document*. Available online at: https://assets.publishing.service.gov.uk/media/65ef6694133c220011cd37cd/review-electricity-market-arrangements-second-consultation-document.pdf (Accessed May 2, 2024).

DESNZ, R. R. (2024b). *Strategy and Policy Statement for Energy Policy in Great Britain*. (Accessed May 3, 2024).

DESNZ, R. R., and Ofgem, R. R. (2024). *Heat networks regulation-consumer protection Government response April 2024 2*. Available online at: https://assets.publishing.service.gov.uk/media/66432989b7249a4c6e9d3369/heat-networks-consumer-protection-government-response.pdf (Accessed May 5, 2024).

Döringer, S. (2021). 'The problem-centred expert interview'. Combining qualitative interviewing approaches for investigating implicit expert knowledge. *Int. J. Soc. Res. Methodol.* 24, 265–278. doi: 10.1080/13645579.2020.1766777

Elzen, B., Geel, F. V., and Green, K. (2004). *System Innovation and the Transition to Sustainability*. Cheltenham: Edward Elgar Publishing. doi: 10.4337/9781845423421

ETI, R. R. (2018). *District Heat Networks in The UK Potential, Barriers and Opportunities*. Available online at: https://d2umxnkyjne36n.cloudfront.net/insightReports/District-Heat-Networks-in-the-UK-Final.pdf?mtime=20181105145836 (Accessed April 4, 2024).

Ewijk, S. V. (2014). *Energy Innovation: Do Niche Markets Really Matter?* Available online at: https://energycentral.com/c/ec/energy-innovation-do-niche-markets-really-matter (Accessed February 6, 2024).

Fischer, A. R. H., Wentholt, M. T. A., Rowe, G., and Frewer, L. J. (2014). Expert involvement in policy development: a systematic review of current practice. *Sci. Public Policy* 41, 332–343. doi: 10.1093/scipol/sct062

Foxon, T. J. (2011). A coevolutionary framework for analysing a transition to a sustainable low carbon economy. *Ecol. Econ.* 70, 2258–2267. doi: 10.1016/j.ecolecon.2011.07.014

Foxon, T. J. (2013). Transition pathways for a UK low carbon electricity future. *Energy Policy*. 52, 10–24. doi: 10.1016/j.enpol.2012.04.001

Foxon, T. J., Hammond, G. P., and Pearson, P. J. G. (2010). Developing transition pathways for a low carbon electricity system in the UK. *Techn. Forecast. Soc. Change* 77, 1203–1213. doi: 10.1016/j.techfore.2010.04.002

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res. Policy* 31, 1257–1274. doi: 10.1016/S0048-7333(02)00062-8

Geels, F. W., and Schot, J. (2007). Typology of sociotechnical transition pathways. *Res. Policy* 36, 399–417. doi: 10.1016/j.respol.2007.01.003

Helm, D. (2017). *Cost of Energy Review*. Available online at: https://www.dieterhelm.co.uk/energy/energy/cost-of-energyreview-independent-report/ (Accessed September 21, 2024).

HM Government, R. R. (2021a). *British Energy Security Strategy*. Available online at: https://www.gov.uk/government/publications/british-energy-security-strategy (Accessed December 12, 2024).

HM Government, R. R. (2021b). *Net Zero Strategy : Build Back Greener Net Zero* Strategy : Build Back Greener.

Hosseini, S. H. R., Allahham, A., Walker, S. L., and Taylor, P. (2020). Optimal planning and operation of multi-vector energy networks: a systematic review. *Renew. Sustain. Energy Rev.* 133:110216. doi: 10.1016/j.rser.2020.110216

Kahrl, F., Williams, J., Jianhua, D., and Junfeng, H. (2011). Challenges to China's transition to a low carbon electricity system. *Energy Policy* 39, 4032–4041. doi: 10.1016/j.enpol.2011.01.031

Kaiser, R. (2014). Qualitative Experteninterviews. *Qualitative Experteninterviews.* New York: Springer. doi: 10.1007/978-3-658-02479-6

Karlsen, J. E., and Karlsen, H. (2007). Expert groups as production units for shared knowledge in energy foresights. *Foresight* 9, 37–49. doi: 10.1108/14636680710727534

Kattirtzi, M., and Winskel, M. (2020). When experts disagree: using the Policy Delphi method to analyze divergent expert expectations and preferences on UK energy futures. *Tech. Forecast. Soc. Change* 153:119924. doi: 10.1016/j.techfore.2020.119924

Kemp, R., Schot, J., and Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Tech. Anal. Strategic Manag.* 10, 175–198. doi: 10.1080/09537329808524310

Konrad, K., Truffer, B., and Voß, J. P. (2008). Multi-regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors. *J. Clean. Product.* 16, 1190–1202. doi: 10.1016/j.jclepro.2007.08.014

Kucharski, J. B., and Unesaki, H. (2018). An institutional analysis of the Japanese energy transition. *Environ. Innov. Soc. Trans.* 29, 126–143. doi: 10.1016/j.eist.2018.07.004

Kuusi, O. (1999). Expertise In The Future Use Of Generic Technologies - Epistemic and Methodological Considerations Concerning Delphi *Studies*. 1–284.

Lockwood, M. (2016). Creating protective space for innovation in electricity distribution networks in Great Britain: the politics of institutional change. *Environ. Innov. Soc. Trans.* 18, 111–127. doi: 10.1016/j.eist.2015.05.007

Mancarella, P. (2014). MES: an overview of concepts and evaluation models. *Energy* 65, 1–17. doi: 10.1016/j.energy.2013.10.041

Mancarella, P., Andersson, G., Peças-Lopes, J. A., and Bell, K. R. W. (2016). Modelling of integrated multi-energy systems: Drivers, requirements, and opportunities. *19th Power Systems Computation Conference, PSCC 2016*. doi: 10.1109/PSCC.2016.7541031

Martinot, E. (2016). Grid integration of renewable energy: flexibility, innovation, and experience. *Ann. Rev. Environ. Res.* 41, 223–251. doi: 10.1146/annurev-environ-110615-085725

Meuser, M., and Nagel, U. (2009). *The Expert Interview and Changes in Knowledge Production*. *Interviewing Experts*. New York: Springer, 17–42. doi: 10.1057/9780230244276_2

National Audit Office, R. R. (2024). *Decarbonising home heating*. Available online at: https://www.nao.org.uk/wp-content/uploads/2024/03/Decarbonising-home-heating-HC-581.pdf (Accessed November 11, 2024).

National Electricity System Operator (2024). *Electricity System Operator Markets Roadmap*.

National Gas, R. R. (2024). *National Gas launches as owner of Britain's gas network*. Available online at: https://www.nationalgas.com/National_Gas_launch (Accessed December 11, 2024).

Nepal, R., and Jamasb, T. (2015). Caught between theory and practice: Government, market, and regulatory failure in electricity sector reforms. *Econ. Anal. Policy* 46, 16–24. doi: 10.1016/j.eap.2015.03.001

NESO (2024). *Clean Power by 2030*. London: National Energy System Operator. Available online at: https://www.neso.energy/document/346651/download (Accessed February 20, 2025).

NGESO, R. R. (2021). *Enabling the DSO Transition*. Available online at: https://www.nationalgrideso.com/document/190271/download (Accessed September 3, 2024).

Oduro, R. A., and Taylor, P. G. (2023). Future pathways for energy networks: a review of international experiences in high income countries. *Renew. Sustain. Energy Rev.* 171:113002. doi: 10.1016/j.rser.2022.113002

Ofgem, R. R. (2018). *Decision-RIIO-2 Framework 2*. Available online at: http://www.ofgem.gov.uk

Ofgem, R. R. (2019). *Vulnerable consumers in the energy market: 2019*. Available online at: http://www.ofgem.gov.uk

Ofgem, R. R. (2023). RIIO-ED1 Network *Performance Summary 2020-21*. Available online at: https://www.ofgem.gov.uk/sites/default/files/2023-03/RIIO-ED1%20Network%20Performance%20Summary%202021-22.pdf (Accessed September 3, 2024).

Ofgem, R. R. (2024). *gas_licencees*. Available online at: https://www.ofgem.gov.uk/sites/default/files/2024-06/gas_licencees.pdf

Ofgem. (2010). *RIIO: A New Way to Regulate Energy Networks-Final Decision*. London: Office of Gas and Electricity Markets.

PwC, BDEW, and GIZ (2016). *Delphi Energy Future 2040*. In Delphi Studie.

Rosenbloom, D. (2019). A clash of socio-technical systems: exploring actor interactions around electrification and electricity trade in unfolding low-carbon pathways for Ontario. *Energy Res. Soc. Sci.* 49, 219–232. doi: 10.1016/j.erss.2018.10.015

Rosenbloom, D. (2020). Engaging with multi-system interactions in sustainability transitions: a comment on the transitions research agenda. *Environ. Innov. Soc. Trans.* 34, 336–340. doi: 10.1016/j.eist.2019.10.003

Rosenow, J. (2022). Is heating homes with hydrogen all but a pipe dream? An evidence review. *Joule* 6, 2225–2228. doi: 10.1016/j.joule.2022.08.015

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

Ruggiero, S., Varho, V., and Rikkonen, P. (2015). Transition to distributed energy generation in Finland: prospects and barriers. *Energy Policy* 86, 433–443. doi: 10.1016/j.enpol.2015.07.024

Simpson, G. (2017). Network operators and the transition to decentralised electricity: an Australian socio-technical case study. *Energy Policy* 110, 422–433. doi: 10.1016/j.enpol.2017.08.042

Smith, A., and Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. *Res. Policy* 41, 1025–1036. doi: 10.1016/j.respol.2011.12.012

Taylor, P. C., Abeysekera, M., Bian, Y., Cetenović, D., Deakin, M., Ehsan, A., et al. (2021). An interdisciplinary research perspective on the future of multi-vector energy networks. *Int. J. Electr. Power Energy Syst.* 135:107492. doi: 10.1016/j.ijepes.2021.107492

Van De Poel, I. (2003). The transformation of technological regimes. *Res. Policy* 32, 49–68. doi: 10.1016/S0048-7333(01)00195-0

Von Soest, C. (2023). Why do we speak to experts? Reviving the strength of the expert interview method. *Perspect. Polit.* 21, 277–287. doi: 10.1017/S1537592722001116

Wang, Y., and Shao, C. (2019). Optimal operation model of the multi-energy network in the distribution system. *Proceedings - IEEE International Conference on Energy Internet, ICEI* 2019, 368–373. doi: 10.1109/ICEI.2019.00071

Whinskel, M., Kattirtzi, M., Lowes, R., Woodman, B., and Poulter, H. (2019). *Disrupting the UK energy system : causes, impacts and policy implications*. In Ukerc.

Winser, N. (2023). *Electricity Networks Commissioner Report*. Available online at: https://assets.publishing.service.gov.uk/media/64c8e96e19f5622360f3c0f0/electricity-networks-commissioner-letter-to-desnz-secretary.pdf (Accessed June 7, 2024).

Winskel, M., and Kattirtzi, M. (2020). Transitions, disruptions and revolutions: Expert views on prospects for a smart and local energy revolution in the UK. *Energy Policy* 147:111815. doi: 10.1016/j.enpol.2020.111815

Yan, M., He, Y., Shahidehpour, M., Ai, X., Li, Z., and Wen, J. (2018). Coordinated Regional-District operation of integrated energy systems for resilience enhancement in natural disasters. *IEEE Trans. Smart Grid* 10, 4881–4892. doi: 10.1109/TSG.2018.2870358

Zhang, S., and Andrews-Speed, P. (2020). State versus market in China's low-carbon energy transition: an institutional perspective. *Energy Res. Soc. Sci.* 66:101503. doi: 10.1016/j.erss.2020.101503