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Eliciting Stakeholders' Requirements for Future Energy Systems: A Case Study of Heat Decarbonisation in the UK

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Abstract: It is a truism that whole energy system models underpin the development of policies for energy system decarbonisation. However, recent reviews have thrown doubt on the appropriateness of such models for addressing the multiple goals for future energy systems, in the face of emergent real-world complexity and the evolution of stakeholder's priorities. Without an understanding of the changing priorities of policy makers and expectations of stakeholders for future systems, system objectives and constraints are likely to be ill-defined, and there is a risk that models may be inadvertently instrumentalised. Adopting a system architecture perspective, the authors have undertaken a three-year programme of research to explore strategies for decarbonising heat in the UK, with interaction with and elicitation of needs from stakeholders at its heart. This paper presents the procedure, methods, and results of an exercise in which experts from stakeholder organisations across the energy system were interviewed. Analysis of interview data reveals two broad approaches to heat decarbonisation which can be defined as either adaptive or transformative. Specific insights gained from these interviews enabled our modelling teams to refocus their work for exploration with a wider circle of stakeholders. Results suggests that this iterative approach to formalising model-policy interaction could improve the transparency and legitimacy of modelling and enhance its impact on policy making.

Keywords: energy policy; stakeholder requirements; adaptive/transformative; heat decarbonisation; energy system architecture

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1. Introduction

In the aftermath of COP26, the UNFCCC reports that more than 130 countries have set, or are considering, a mid-century net-zero emissions target; at least seven countries, including the UK, have enshrined such targets into law. As early as 2019, with the publication of the UK Climate Change Committee's Net Zero report [1], and following the breakthrough in offshore wind and photovoltaic prices that has taken place since 2016, the UK has taken a decisive step toward decarbonising its electricity grid, achieving the most rapid decarbonisation of electricity supply in the developed world, through the promotion of renewables [2] and phasing out of coal-fired power stations [3]. Progress in decarbonising sectors of demand which are not currently electrified, has however been more challenging [4]. Chief among these is space and water heat in buildings, c. 80% of which is currently supplied by natural gas, and which accounts for c. 40% of UK final energy use.

Over the last 20 years, successive UK governments have set out high-level objectives for the UK energy system in white papers and other policy documents: they are system resilience, flexibility, cost, equity and sustainability [5,6]. Despite the apparent continuity, these goals have had to be repeatedly reinterpreted and reprioritised: as the search for a strategy for decarbonising heat has intensified [7,8]; as climate ambition has risen, from an initial commitment of 60% (CO_2 only) in 2003 [9], to 80% in 2008 [10], and, in 2019, to net-zero by 2050 [11]; and as the timescale for achieving climate targets has shortened.

Both the UK government and the wider energy sector have long recognised the need for long term strategic planning of energy systems [12], and the necessity of handling problems such as technology choice in the context of a clear understanding of the high levels of complexity of energy systems and the supply chains that sustain them. This undertaking has been supported by a range of whole energy system models, among which MARKAL, UKTM and ESME have been dominant [13–15]. However, reviews undertaken from both modelling and policy perspectives have cast doubt on their efficacy for this task. As early as 2014, Pfenninger et al. had asserted a need for greater temporal and spatial detail to address uncertainty, to provide transparency, to handle real world complexity including the human dimension and to allow optimisation across scales [16]. Specifically, there are questions relating to system operation, and the need to represent both supply chain and energy system dynamics, which become increasingly important as rates of deployment rise [17].

Süsser et al. investigated the influences of models on policy making across 5 European countries and found that while models can be impactful on policymaking and target setting, they can also be instrumentalised to justify pre-determined policy ambitions [18]. In interviewing UK civil servants, Munro and Cairney also found that the use of the term 'system' or 'whole system' was vague and ill-defined. They suggest that better communication and engagement is needed between academics and policymakers to make progress towards harnessing academic systems research from a wide range of disciplines, including modelling, to support the development of transition strategy [19].

Emerging from the above [16–19], it appears that to keep pace with the changing technical, socio-political and economic landscape, the modelling community will need to mobilise a wider set of tools and methods to tackle concrete questions, and to minimise the risk of policy conclusions being constrained by the limitations of a few accepted and established methods [16]. There is, therefore, a need to embed modelling within an overarching conceptual framework that combines top-down and bottom-up perspectives, and which provides space for clarification of the needs and expectations of the policy-makers and stakeholders.

In a previous paper [20] we outlined the potential benefits of adopting a System Architecture framework to help structure the development of energy system decarbonisation strategies and deal with the complexity of the emergent energy system.

Application of System Architecture concepts and methods in the field of energy is not completely new. For example, the concept of "system of systems" has been used to support research on electricity distribution grids and power management in micro-grids [21,22]. However, to apply system architecting to the whole system, with the aim of supporting policy making through the improvement of system modelling is novel.

Crawley et al. assert that the role of the system architect is "to resolve ambiguity, focus creativity, and simplify complexity. The architect seeks to create elegant systems that create value and competitive advantage by defining goals, functions, and boundaries; creating the concept that incorporates the appropriate technology; allocating functionality; and defining interfaces, hierarchy, and abstractions to manage complexity." [23] (p194). While System Architecture has its origins in the aerospace industry, most notably the Apollo Programme [24], we have argued elsewhere that differences between aerospace and energy systems are not sufficient to vitiate the comparison, nor to prevent the adoption of tools and concepts from the System Architecture literature. Crawley et al. cite numerous examples of applications of System Architecture to terrestrial engineering systems.

The foregoing quotation from Crawley et al. relates to the goals of the architect. We distinguish between these goals and the architecture of energy systems, which we have defined as:

> *"The spatial, topological and functional organisation of energy generation, conversion, transmission, distribution, storage, end-use and regulatory systems within the whole energy system."* [20]

This definition captures the conceptual structure and logical organisation of the energy system and its sub-systems, their boundaries, inter-relationships, and associated constraints.

From this perspective, the clarification of goals and understanding of stakeholders' expectations and requirements are foundational to the process of architecting. This is unavoidably challenging, given that the characteristics and operational and regulatory principles of future energy systems will be shaped over coming decades by multiple stakeholders with differing perspectives, which may themselves be conflicting and potentially poorly articulated. Energy systems with their extraordinary complexity and very long-time scales necessitate repeated revisiting of stakeholders' goal and expectations. Formal structures and procedures are needed to bring together stakeholders, policy makers and modellers to foster common understandings, and to communicate the extent to which modelling lags behind changes and challenges that emerge in the real world.

This paper presents results of empirical research into stakeholders' views and expectations using System Architecture concepts, methods, and tools. The paper is set out under the following headings:

Research Context and Design, in which we elucidate the role of whole system energy modelling in policy decision making; the understanding of stakeholders' views and expectations; and the relationship between the two phenomena.

Expert Interview using Q methodology, in which we explain how we have adapted the Q method to elicit stakeholders' expectations and requirements.

Results, in which we present our findings and interpretation.

Discussion, in which we discuss how these findings implicate future strategies for decarbonising heat, and finally.

Conclusion, which sets out the implications of our findings for policy making and governance.

2. Materials and Methods

2.1. Research Context and Design

The work reported in this paper was undertaken as part of a multi-disciplinary research project set up in 2018 to develop and apply an overarching energy system architectural perspective to explore technological and operational problems and opportunities associated with decarbonisation of heat. Led by the second author, the project has been funded by the UK's Engineering and Physical Sciences Research Council (EPSRC), and has supported a team of five modellers, a policy expert, and a social scientist.

The stakeholder research process was carried out by the authors with the support of the modelling team. It was organised in 4 stages (Figure 1). Stage I investigated the extent to which existing models adequately capture the overarching energy policy goals mentioned above. The policy goals derived from qualitative literature review mentioned in the introduction were reworked theoretically as features/criteria of future energy system against which a range of system models could be assessed [17].

Stage II began with recruitment of interviewees from the pool of experts drawn from stakeholder organisations that had already engaged with the wider research programme of which this project was a part. Based on the results of the interviews and further modelling work, stage III was to evaluate a range of technological options/scenarios with a wider circle of stakeholders through scenario presentations and a Pugh Score Exercise. The final stage was to analyse these individual evaluations obtained from the Pugh Score Exercise Score Sheet and accompanying workshop discussions. The outputs sought through this process were:

(a) Identification and ranking of top-level requirements and expectations.
(b) Information relevant to Concepts of Operations (ConOp) for future systems [23,24].

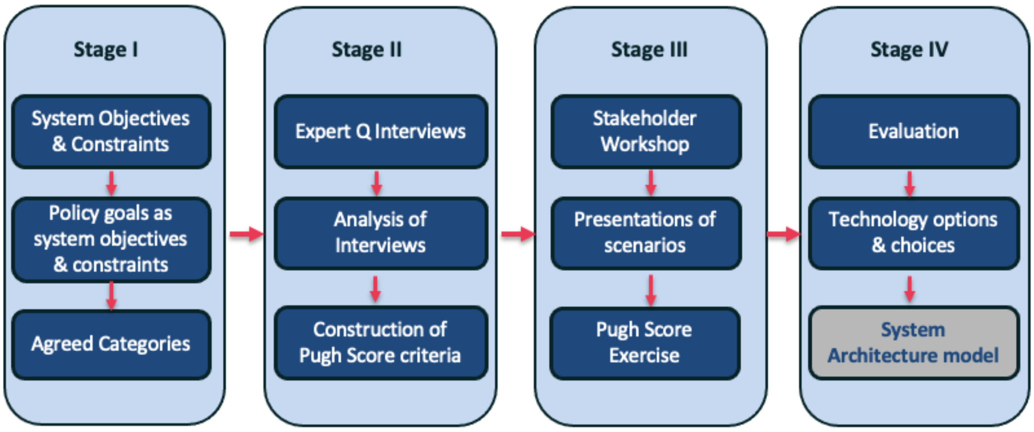

Figure 1. Staged design of the Stakeholder Requirements Process.

Note that the identification of stakeholders' requirements and expectations (the goals, priorities, constraints which form output a), is a pre-requisite for the development of operational objectives, characteristics and ConOps of future energy systems (output b).

Due to limited space, this paper will not cover the whole of the stakeholders' requirements process. The results of Stage III–Stakeholder Workshop are covered in a separate paper [25]. Instead, we present here only the findings of Stage II, the elicitation of stakeholders' top-level requirements and expectations using experts as proxies.

2.2. *Expert Interviews Using Q Methodology*

Q methodology is a primarily qualitative method supported by rigorous statistical techniques, which has been designed for exploring structures of shared subjectivity with small numbers of participants, rather for mapping prevalence of attitudes across larger samples as in conventional surveys [26,27]. It is often used amongst psychologists to explore structure and form within and between subjective opinions and discourses. In recent years, it has become increasingly popular in conservation and environmental research, e.g., [28–31].

Normally, Q methodology requires participants to sort a sample of statements (the concourse) on a grid that approximates a normal distribution. This set of statements is called a Q-sort. Due to the limited time available for the interview, a conventional Q-sort exercise would have been inappropriate and indeed might have triggered some frustration on the part of experts who were interviewed. We therefore replaced the Q-sorting task by a ranking exercise in which the experts were asked simply to rank the five policy goals in order of priority. Experts were encouraged to prioritise, but not required to do so. The key aim of interviews was to collect qualitative data generated in the course of conversation with the interviewer during or after the ranking exercise. An interview guide was constructed to provide a structure for both the interviewer and the experts to engage in a conversation in which the expert's perceptions of the requirements of a decarbonised energy system could be elicited (see Appendix A). The combination of the ranked priorities and the interview data has yielded a comprehensive representation of the perspective of each expert.

2.2.1. The Experts (p-Sample)

Deciding whom to interview should not be an arbitrary choice. Since qualitative research is resource intensive, the selection process must be designed carefully to address the research objectives within the available resources. The authors took the view that experts invited to interviews should possess an institutionalised authority to construct reality. By that, we mean that an expert should have the potential to structure the conditions of action for other actors and should possess expertise that was socially institutionalised in relation not only to an organisation but also to specific problems [32]. In other words, these experts should be capable of envisioning future energy systems, of articulating the potential of the technologies available for decarbonising heat in the UK, and to be in the position to influence others in the energy sector.

Our sampling strategy was, therefore, primarily purposeful [33]. Using the following criteria, the lead author sent an invitation email to twenty experts selected from a stakeholder list provided by the larger project of which the work described here formed a part, and from the authors' own professional networks:

- High to mid-level experts from organisations representing energy generation, transmission, and distribution;
- High to mid-level experts from energy industry associations, and other non-statutory agencies, including agencies representing consumers;
- Independent energy consultants and/or academics;
- High to mid-level policy professionals;
- High-level experienced regulators;
- High-level decision makers in industry.

Of the twenty experts who were contacted, eleven responded to our invitations. The eleven included high-level policy makers, regulators, industrialists, energy system decision-makers, senior scientists in non-governmental and professional and trade organisations, experienced academics and energy advisors and consultants. Interviews were conducted on-line in September/October 2020.

Because most of our experts are well known within the UK energy sector, we have been ethically bound to protect their identities by anonymisation and by paraphrasing their contributions.

2.2.2. Interview Procedure

At the beginning of each interview, the expert interviewee was presented with five cards on each of which, one policy goal was written: Zero Carbon, Resilience, Flexibility, Costs, Equity. They were then asked to rank the five policy goals according to their perceived priorities. The interview lasted for one to one-and-a-half hours depending on the expert's willingness to continue with the conversation. After the conversation, the expert was given an opportunity to change their ranking of these goals.

2.2.3. Q Analysis

The ranked data were transformed into a quasi-Qsort, i.e., with the mid priority = 0, and the highest and lowest priorities 2 and −2 respectively. Since the analysis of data was undertaken using SPSS rather than in dedicated Q software, it was necessary to transpose the matrix containing the experts' rankings, so that experts appeared as variables in columns and their rankings appeared as cases in rows. Because we were interested in the shared subjectivity amongst experts, as indicated by the relative similarities in their rankings of the policy goals, we performed a Principal Component Analysis (PCA, also referred to as a factor analysis) on the transposed matrix to extract the highest 2 factors with eigenvalues greater than unity following 25 rotations in Varimax. Values close to −2 or +2 indicate that the factor strongly influences the expert. Values around zero indicate that the factor has a weak influence on the expert. As will become clear, some experts may have high loadings on both factors.

The values of the first two factors for each expert are shown in Table 1. These values are then plotted on the principal component graph in Figure 2. Experts P1, P7, P3 & P4 appear in a tight cluster close to the right-hand end of the horizontal axis (Factor 1), with loading factors of 0.984, 0.984, 0.941, and 0.818, respectively, and with low loadings on the vertical axis (Factor 2). Note that P3 and P7 occupy identical positions. P6 (Academic), P8 (Transmission) & P9 (Consultant) have progressively lower loadings of 0.738, 0.658, and 0.573, respectively, on Factor 1. Conversely, P11 (Retrofit) and P10 (NGO), are heavily loaded onto Factor 2 (0.989 & 0.886) and weakly loaded onto Factor 1. The views of P2

(Heat Networks) are relatively weakly associated with either factor. P5 (Governance) is negatively loaded onto both Factor 1 and Factor 2 (−0.497 and −0.254 respectively).

Table 1. Factor loadings of experts for top two components.

ID	Influence Status	Field of Expertise	Factor Loadings	
			Factor 1	Factor 2
P1	High	Heat Technologies Industry (Supply side)	0.984	0.084
P2	High	DH networks	0.031	0.239
P3	High	Heat Technologies Industry (Supply and demand-side)	0.941	−0.026
P4	High	Policy	0.818	−0.136
P5	High	Governance	−0.497	−0.254
P6	Medium	Academic	0.738	0.344
P7	Medium	Energy system infrastructure (Distribution)	0.984	0.084
P8	Medium	Energy system infrastructure (Transmission)	0.658	−0.707
P9	High	Energy consultant (Whole system)	0.573	0.531
P10	Medium	NGO (Demand-side)	0.027	0.997
P11	Medium	Industrialist (Retrofit)	0.172	0.992

Extraction Method: Principal Component Analysis. Rotation Method: Varimx with Kaiser Normalisation. Rotation converged in 3 iterations.

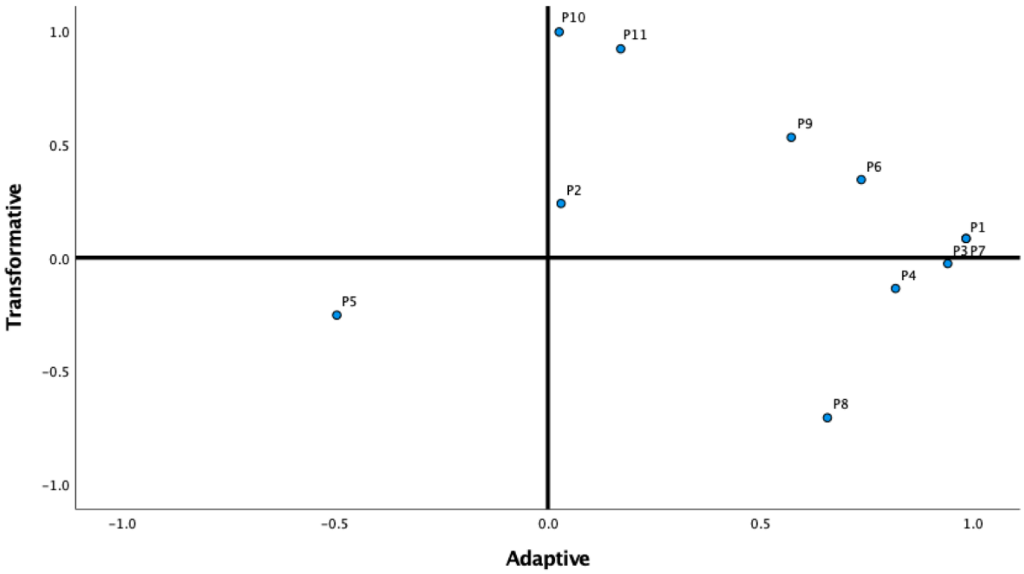

Figure 2. Principal component analysis of approaches to heat decarbonisation.

While the opinions of this group of experts reflect an array of diverse personal experience and the missions of the organisations they represent, there were interesting and potentially significant overlaps in their opinions and perceptions regarding approaches that the UK might take to achieve heat decarbonisation (see Figure 2).

2.2.4. Qualitative Data Analysis

The combination of the Principal Component Analysis and the interview transcripts provided a structure for detailed analysis and interpretation of interview data. The building of a master matrix for coding of interviews using Excel began with the input of each expert's opinions and expectations according to conversation foci, issues raised, heat and heat-related technologies discussed, and their relationship to policy goals of zero carbon, resilience, cost and flexibility and equity. Further analysis produced secondary codes that are related to the implementation of the technologies and policy goals: storage, deployment, customers preference, acceptability, information, behaviours and engagement, policies, market, pricing, and innovations.

In the following section, we look at similarities between experts' expectations in two clusters that lie close to the axes in Figure 2. We then analyse the more diverse spectrum of opinions of the rest of the sample.

3. Results

3.1. Factor 1—The Adaptive Approach

As noted above, experts P1, P7, P3 & P4 form a tight cluster close to the positive end of the horizontal axis in Figure 2. Conversations with these experts appeared to centre on the future role of the gas network as the system transits to zero, the production of hydrogen from dedicated renewables, its role in decarbonising heat at the point of use, and smart grid application of efficient heat technologies. The main issues in which they were interested were the relationship of the gas system to the electricity system, energy efficiency, electrification of heat, and the safety of hydrogen.

P6 (Academic), P8 (Transmission) & P9 (Consultant) have progressively less loading on this axis with values of 0.818, 0.738, 0.658, and 0.573 respectively.

The following aspects emerge from experts' discussion as they articulate the reasons for their prioritisation of the policy goals.

3.1.1. Resilience/Security of Supply

Independently from each other, experts' opinions in the cluster converge on the view that, with increasing penetration of renewables, hydrogen delivered using the existing gas grid would contribute significantly to the resilience of the electricity system. P3 (Heat Technology Industry, both supply & demand side) asserted that 100% electrification of heat was seen as not cost-effective and would be less secure, and that the existing Gas grid could contribute to resilience of the system. P3 stated that switching of customers to hydrogen could be expedited through the installation of hydrogen-ready boilers in the majority of the old housing stock and observed that 80% of the [low pressure] gas grid had been converted from iron to medium density polyethylene, which is compatible with the transport of hydrogen.

While most of the experts with high loadings on Factor 1 prioritised Zero Carbon as a top priority, P4 (Policy) and P8 (Transmission) did not conform to this pattern. While acknowledging Zero Carbon as an important goal for motivating change, P4 asserted that the UK should put resilience and security of supply as a top priority. Similarly, P8 stated that their organisation was entrusted to ensure the system is dependable, reliable, and affordable, and gave resilience the first priority, with cost as second. As will be seen, the above is reflected by generally more cautious positions on the future evolution of the energy system.

3.1.2. Flexibility and Cost Are Related Issues

P1 (Heat Technology Industry) & P7 both ranked flexibility as −2 (last of the five goals). P1 asserted that cost and flexibility are related issues. P1 explained that 'with a system where the gas grid and the use of hydrogen continue to play a role in energy transition, the development of brown or green gas would help to address the various thermal deficiencies of the UK building stock', implying the cost of improving the thermal efficiency of the dwelling stock should be balanced against the cost of providing hydrogen. This idea was echoed by P3, who stated hydrogen would be a most effective way of providing heat in the UK, particularly for the oldest housing stock.

P7 (Distribution), also gave the lowest priority to flexibility. Explaining their choice of priorities from the customer's perspective, P7 considered that customers might need to weigh up the up-front cost of investing in a heat pump versus the running cost. P7 also noted that increased electrification with a proliferation of individual heat pumps would inevitably be linked to the development of smart grids: smart grid management would increase flexibility. With the increased use of electric vehicles, P7 suggested decentralised storage could play an important role in flexibility. P7 thought that the market for big, centralised battery storages appeared to be in decline.

P4 (Policy) did not conceive flexibility as a priority on its own: 'it is simply an enabler for resilience'. P4 explained this conception with the rationale that [increased] flexibility is a feature of the system that the UK is working towards. The more flexible the system, the lower would be the cost, for example, by allowing the accommodation of more renewables. Therefore, the driver for flexibility is to reduce cost, and not for its own sake. However, P4 contended that hydrogen was unlikely to be any cheaper than natural gas, alluding to a complex relationship between the development of hydrogen and the role of natural gas in the transition.

P8 (Transmission), stated that the first goal of their organisation was 'to keep the lights on', and that resilience was the number one priority of this organisation. 'We want to operate the system using the best tools available, making sure that we are keeping the lights on but also keeping the bills as low as possible. [. . .] So, to provide resilience at the cheapest possible cost.' P8 saw flexibility as just another aspect of resilience. P8 further stressed that the role of their organisation is to ensure stability of the system by balancing supply and demand at all times. Practically, what flexibility does for their organisation is to ensure the balancing of generation and demand for electricity and to ensure that grid frequency, nominally 50 Hz, remained within the statutory range of 49.5–50.5 Hz by topping up power deficits from pumped hydro or other stores, or with standby generation. However, in the event of high renewable penetration, flexibility would increasingly be required to ensure a continuous supply of electricity when 'the wind is not blowing and the sun is not shining', and from all the analysis P8 had done so far, it appeared that hydrogen would provide the large-scale flexibility that is currently, mostly provided by gas-fired power stations.

P8 remarked that the role of the electricity transmission system (operated by the Transmission System Operator, National Grid TSO) is not just to connect most of the generation capacity to fifteen regional low-voltage distribution networks (132 kV and below), who in turn supply electricity to consumers: some large consumers are directly connected to the transmission system. Moreover, we may see 'the evolution of the consumer from just passive receiver of energy to sort of more active [. . .] participant in the system'. Area Flexibility is one of the key foci in their organisation's vision for 2030. P8 spoke of a complex evolving situation and did not think that anybody had a complete picture. However, P8 thought that first movement would occur in the distribution system. P8's organisation must consider the extent to which it can participate in, and take advantage of the emergent complex energy market with increasing distributed energy production.

3.1.3. Equity and Choice

In terms of how the future system might support equity or fairness to customers, the concept of customer choice was raised. P1 (Heat Technologies Industry) suggested if the system is cost-effective, it will simultaneously cover the equity issue. Since different people will place different relative value on maintaining a constant internal temperature in their home, P1 suggested providing choice for customers is more important. However, this was not a reference simply to heat pumps or district heat networks. Thus, the possible impact on energy affordability amongst poorer sections of the population due to the high overall system cost, e.g., resulting from the production cost of hydrogen, the cost of upgrading the electricity grid or the cost of providing new heat networks was not systematically explored.

P3 (Heat Technology Industry supply & demand side) echoed P1 in viewing equity as a derivative of the other objectives/goals of the system.

P4 (Policy) was concerned that equity or fairness could be misinterpreted solely as keeping system cost down for the fuel poor. From a policy perspective, the UK has a fuel poverty policy in which many initiatives (Green Homes Grant, Energy Company Obligation, Energy Efficiency for rented properties, and Winter Fuel payments, Cold weather payments, as well as Energy tariff cap) were available to address fuel poverty. Therefore, P4 considered system cost to be of higher priority than equity, in this context.

Equity was the lowest priority for P8, who considered that this was not an issue that a public company was able to deal with. However, and as with P1, individual choice emerged to be an issue for P8, when asked to imagine a world with 100% electrification of heat. P8 commented on the challenge that would be posed by a switch from gas boilers to electric heat-pumps in the UK. It would mean a huge social mobilisation effort, and persuading people to accept a high up-front cost of a heat pump that might not be suitable for certain housing conditions. In addition, P8 asserted that individual choice would be incompatible with district heating.

3.1.4. Impacts of Heat Technologies on System Architecture

In terms of their views on current technologies, P1 did not see gas, or electric heat pumps and heat networks as in competition with each other but rather as complementary within the evolving system [architecture]. P1 and P7 appear to hold different and contrasting visions, with the former stressing some form of technological integration rather than competition, and the latter focusing on pushing the take-up of individual heat pumps without mentioning the possible usage of heat pumps in heat networks. In other words, experts were not explicit in their discussion of how these technologies might be combined and configured to improve system resilience and flexibility, perhaps reflecting an overall lack of discussion or debate around the wider range of possible future system architectures and strategy for deployment of technologies. P3, who articulated a vision of a globalised heat technology market, was cautious about viewing the future of heat supply largely through electrification. P3 suggested that a 100% electrified system might not be cost-effective and could be less secure. Deploying hybrid forms of heat technologies-gas/electric heat pumps, oil/electric heat pumps, as well as hydrogen-ready gas boilers in the domestic market-would contribute to system resilience through the existing gas grid. We note here in passing that hybrid systems are not restricted to hybrid heat pumps in single dwelling; effectively all interconnected energy systems are hybrid systems.

P7 was cautious of the impacts that Feed-In-Tariffs and other subsidies for renewables might have on the development of local nodes of distributed energy generation. P7 suggested that with the introduction of blockchain and dynamic pricing for the management of the energy system, it could become increasingly flexible. However, this interviewee's discussion did not go beyond a vision of smart grids and distributed generation supported by innovative software to balance energy flows. The need for an energy system architecture perspective was implied but never articulated.

3.1.5. Impacts of Storage on System Architecture

Historically, and with the exception of a small number of countries whose electricity systems have been dominated by conventional hydro, energy in most industrialised countries including the UK has been stored in the form of fossil fuels. P4 (Policy) suggested that the requirement to deploy many Terawatt-hours of novel forms of energy storage to replace decommissioned fossil systems [34] would be a significant driver of the evolution of energy system architecture. However, unlike P1 (and P2 who was primarily positively loaded on the Transformative Approach), P4 considered heat networks likely to play only a limited role in the future system due to the non-interventionist tradition of UK energy policy, and the fact that UK culture favours individual choice over collective intervention.

However, from P8′s (Transmission) point of view, district heating is definitely one of the solutions for decarbonising heat, at the lowest cost. It is currently modelling the potential of heat networks for 4–5 million of the UK's approximately 26 million homes. P8 cautioned that the advantages of heat networks should be balanced with the understanding that such networks are only a vector (i.e., a carrier) of heat; the choice of heat production technologies for heat networks, and the extent to which they interconnect gas and electricity systems will be crucial to the success of the decarbonisation process. P8 added, in the future, this would probably mean either electrolytic hydrogen or electricity. Ultimately (and either way), it would lead to an increase in electricity demand. Without directly referring to the concept of system architecture, P8 suggested that the shape of the system would depend on how and where in the system storage was deployed. P8 envisaged the deployment of multiple different kinds of storage (thermal or batteries), operating over different scales, from short-term to inter-seasonal. P8 gave the example: 'You can envisage a world where you have more distributed storage, maybe with small scale cylinders [. . .] If you transition into something like [. . .] using hydrogen for heating across large swathes of the country you will definitely need to have some inter-seasonal storage.'

Another issue that touched upon system architecture thinking was the possibility of closer coupling of industrial and domestic sectors. P4 considered that one of the barriers to such sector coupling is the difficulty of foreseeing the future of the UK's economic base; the industrial and commercial landscape, and therefore the scope for exchange of heat between these and the domestic sector could change significantly by 2050.

3.1.6. Impacts of System Requirements on Investment, Planning and Modelling

P3′s organisation has invested in hydrogen as part of a global strategy. An industrialist, P3 did not agree with a strongly interventionist approach, as it might distort the market. P1 & P3′s interests appeared to be closely aligned. Both experts independently expressed their expectation of government policy that could drive forward investment in the production of hydrogen. They cited positive movement on this front. Government has funded several projects trialling hydrogen production and surveying customer acceptance. These are running in parallel with projects amounting to £14.9 million to promote electrification of heat.

P8 described how changing requirements of the energy system are impacting another important area for their organisation—network investment planning. For example, in accordance with the evolving generation mix, electrification of heat and proliferation of electric vehicles had the potential for a significant impact on the architecture of the energy system.

P8 indicated the need to plan for system resilience by drawing attention to the recent, unexpected reduction of electricity demand due to the COVID19 lockdown. P8 suggested that this kind of response would not be so different from what would be needed to manage curtailment of supply in times of low wind and solar generation. Currently the process involves renegotiation of formal arrangements for disconnecting fossil-fired power stations with stakeholders and the government. P8 said that the pandemic crisis had exposed a lot of weaknesses in the system in terms of commercial arrangements and that [existing] contracts were not necessarily the most appropriate tools available to the organisation for managing the process. There were a lot of challenges to [navigate] around these contracts to secure the system.

In the context of investment and modelling, P4 had concerns over the emphasis on cost optimisation in energy system modelling to support decision-making. P4 suggested that optimisation models with non-zero discount rates tend to try to defer decisions 'to as late as possible', which is inappropriate in the context of infrastructure such as nuclear power stations. Capital intensive projects would need to be spread out overtime. Risk premiums for new infrastructure are a significant issue for investment. Moreover, constraints on deployment rates [which depend on the availability of appropriately trained people, and the time needed to train them] is an issue often missed in models. P4 continued, noting that 'modellers tend to assume massive carbon costs to drive technology deployment, but it does not work. Real constraints, such as those around deployment, should be built into the model[s]. Most of the current models, e.g., ESME and UKTM and also DDM (dynamic dispatch model) do not explore the impact of gaps in energy generation that can arise over longer periods of time. They do not come up with anything like the sort of levels of storage that is required because it's almost been assumed it's there. We could get away with that in the 80% world, but you cannot deliver that at net zero'.

In passing, we note that this exchange exemplifies the sometimes Procrustean work-arounds that modellers use to address complex, real-world questions with their models. A response from modellers, when challenged directly, is that such high carbon prices are just a proxy for the overall level of the policy response, and they should not be understood to mean that carbon price would be the only or even the main policy lever. It is possible that modellers have not communicated this clearly. However, the potential for mis-interpretation that is likely to result from collapsing a broad spectrum of policy responses onto the single measure of carbon pricing is obvious, as is the need for explicit modelling of supply chain dynamics.

3.2. Factor 2—The Transformative Approach

Factor 2 covers the opinions of 5 experts from different sectors, P10 (NGO), P11 an industrialist with a significant role in domestic retrofit, P9 an energy consultant, P6 an academic, P2, and an international expert on District Heating networks.

The factor loadings of these experts are: 0.997, 0.922, 0.531, 0.344 and 0.239 respectively. P5 had negative loading on both dimensions (−0.497, −0.254). P5's views or expectations of the system could be interpreted as largely independent of either approach, adaptive or transformative.

P11, P10, and P6 represent a view of the future system as transformative and dynamic. P6 & P9′s views appear to be closer to that of P1, P3 & P7 whose views were more weighted towards Factor 1, from which perspective system resilience has a higher priority. P11, an industrialist working on innovative approaches to retrofit, and P10, who works for an NGO, appear to lean towards an expectation that the future system would be more transformative/dynamic. P2, a heat networks expert, occupied a position between adaptive and transformative approaches, diametrically opposite that of P5 (Governance).

3.2.1. Resilience and Flexibility Are Dynamically Related

P11 (retrofit) represents the demand side of the energy system. P11′s focus is on highly innovative retrofit technology in conjunction with small-scale communal heating, in low rise housing. Faced with the ranking exercise, P11 described it as a 'Hobson's Choice', i.e., no choice at all. P11 explained that the difficulty in prioritisation of these goals stems from the fact that Zero Carbon is the ultimate goal, which the other goals should subserve. These choices all involve trade-offs against the costs of the system. For example, P11 said, if 'we opted for resilience, we would need to build in redundancy which is costly'. Choosing one over the other would not achieve the optimal balance across them. If we focus on grid resilience, heat pump performance is important to minimise the expenditure in improving infrastructure. Therefore, P11 suggested that we need a joined-up strategy that would recognise the limitations of [existing] system infrastructure on one hand and incentivise the take-up of heat pumps on the other.

Perceiving flexibility as a means to deliver resilience rather than as an end in itself, P6 also found prioritising these goals difficult. However, P6 ranked resilience (with cost) as significantly more important than the other goals (ranked +1), while other experts in this group gave this goal a much lower priority (0, 0, −1, −1). Appearing to justify the choice for themself, P6 remarked: 'if what [flexibility] means is to deliver a cost-effective resilient energy system, there is no reason for fundamentally wanting the electricity system to be flexible'. P6 offered no specific opinion on how the system could be made more resilient but was intrigued by the possible role of gas, and particularly the gas transmission system, in the future. For P6, system flexibility is required over multiple timescales, each involving different choices of technology, ranging from the intra-day level, for which battery storage or demand-side management including 'heat storage in [building] fabric' can be used, through to seasonal storage. 'Well, the only things we've got at the moment that store energy at [seasonal] scale are gas fields, LNG . . . salt cavern storage, we use a little bit at seasonal scale, but they're not big stores so we actually rely on import capacity. What we flex to manage the variability in long term heat demand—we flex import capacity. It's hard to imagine we would do anything else in future.' It is easy to be wise after the event, but we note that in the 18 months following this interview, the price of natural gas on the mainland UK day-ahead market increased roughly three-fold, and the UK's ability to import gas declined significantly.

P9 (Consultant) who took an unambiguously firm stand on the role that hydrogen could play in the future of heat, ranked resilience and flexibility as −1 and −2, suggesting that these goals could be taken care of by other players in the system without stating who these players were. Conversely, having had experience in the country which has arguably the most successful heat networks in the world, P2 (heat networks) asserted with absolute conviction that heat networks have a significant role to play in the flexibility of an energy system. P2 stated that the large number of dwellings connected to heat networks in their home country provided high flexibility, and that with future developments [including the integration of electric heat pumps and large heat stores], heat networks would be able to make a significant contribution to resilience.

P2 was the only expert who addressed the challenge of the concept of evolvability of an energy system in the face of changing needs and new technologies. P2 attested to the evolvability of heat networks, based on experience and knowledge of their role in energy policy in this interviewee's home country over the past 40–50 years. P2 asserted that because of the aggregated nature and dominance of heat networks, as new heating technologies had come on stream 'every 10 years for the past 40, 50 years', making changes had been easy as there had been no need to deal with individual solutions. It would have been 'very difficult, very expensive to do that on an individual basis'.

3.2.2. Costs

Although it was clear that the term 'cost' in most policy documents refers to 'system cost', individual experts attributed different and/or broader meanings to it. For example, P6 suggested that a key question driving system cost was how reliable we wanted our energy system to be. The desire to have a continuous supply of electricity is associated with specific consumers and places. P6 stated that outages would mean more to the City of London than to suburbs or rural England, implying that loss of power to the City might take down vital global institutions. 'We need to work out how reliable we want our electricity system to be [. . .] we are not even close to really understanding that debate at the moment.'

Based on the recent assessment work carried across many countries in Europe, P2 was decisive that an energy system that is dominated by heat networks would result in lower system costs for transitioning to zero. However, P2 stated that heat networks might not necessarily be the solution for the UK, since those in this interviewee's home country are operated as non-profit entities under a different form of governance. The price of heat is based on the principles set by law, which require it to be set according to the overall cost for supplying heat. P2 explained that variations in production cost were primarily due to the differences in fuel or heat sources used. For examples, using waste-heat from thermal power plants, cement works, or readily available biomass. Therefore, prices differed from area to area. Prices are also affected by economies of scale, i.e., heat supplied by large-scale networks in P2's home country is usually cheaper than by smaller networks. P2 remarked that heat networks in the UK are generally too small, and that the numbers of complaints from customers was high, compared with '3 or 4 handfuls/year' in this interviewee's home country. The average number of dwellings per heat network in P2′s home country is roughly two orders of magnitude larger than in the UK.

3.2.3. Equity

From a broader societal perspective, P6 challenged the premise upon which the concept of equity is based. P6 contested the argument that system choice should not be slightly preferential to the better off, as that would leave people behind. P6 stated that 'in an unfair world where we accept that there are millionaires and billionaires, and some people have bigger houses than others, private capital is needed to accelerate the decarbonisation of the energy system. In other words, to choose technology based on equity does not reflect the world in which we operate: it would not only risk policy paralysis but might also risk taking some of the options off the table that are needed to accelerate overall system change.

From a real-world perspective, rather than dismissing the concept of 'equity', P11 offered thoughts on how we might provide for energy equity in the process of decarbonising the heating system. Experience with retrofitting vulnerable people's houses had impressed upon P11 the importance of affordability and the reality of fuel poverty. P11 had witnessed people 'who can pay very little [and who] mostly suffer from cold.' Therefore, if gas heating is to be banned, then the alternatives must be affordable for the most vulnerable. P11 suggested that the option of hydrogen might be inequitable as its effect would be to push total costs up.

3.2.4. Impacts of Heat Technology on System Architecture

Commenting on whether the UK could improve the resilience of its energy system by installing more heat networks, P2 pointed out that the UK is very much dependent on gas, which is a resilient infrastructure. To maintain such a level of flexibility (because of the increasing penetration of renewables), having a water-based system for the 'last mile ... in between the gas field and the North Sea and individual consumers would be the best of both worlds.' Interestingly, the Last Mile concept was also espoused by expert P1 who affiliated strongly with the adaptive approach.

While adamant that gas boilers should no longer be installed in new housing, P6 was unsure whether current heat pump technology could fully support decarbonisation. P6 asserted that an energy efficiency (fabric first) approach in housing construction could reduce the demand for heating. This would then enable electric heat pumps to play a major role in decarbonising heat.

P6 was unpersuaded by the case for decarbonising the local gas network. P6's arguments in this area were partly about cost. However, P6 laid more emphasis on the risk that a decision to repurpose the gas grid would delay other action at local level. To bring about transformation, a decision to electrify heat would promote local innovation and action; a push 'to get on and deliver the household solution'. It would also be necessary to 'task the network companies with upgrading the electricity system as you need to [but] you do not have to do it all overnight because you can be a bit reactive as the network starts to get strained'.

P11, with experience of combining communal heating with heat pumps and deep retrofit of dwellings, offered a system view of the relationship between grid resilience, heat technologies, and the thermal efficiency of the housing stock. P11 suggested that to successfully decarbonise heat would require a joined-up strategy that recognised the limitations of the energy infrastructure on one hand, to minimise the expenditure on improving the infrastructure, and incentivised the take-up of heat pumps at a rate that the infrastructure itself would be able to cope with.

P6′s main expertise is in electric vehicle (EV) technology. P6 suggested that EV batteries would be key for improving system resilience and flexibility. For P6, increasing numbers of EVs would provide an 'amazing storage asset' for decarbonising the electricity supply system as more and more wind and solar are brought in.

3.2.5. Implications of System Requirements for Investment, Planning and Modelling

In contrast to experts whose opinions aligned with Factor 1, the Adaptive Approach, there was little discussion about investment or planning among experts whose aligned with the Transformative Approach. The academic, P6, was the only expert who raised the issue of implications of technological choices for planning and modelling. Similar to P4, P6 was critical of the reliance on energy system models for planning, especially cost optimisation models. 'I am quite cynical about models, especially cost optimisation models. I am really drawn to a way of working with them which is more conversational, where we've got a bit more acceptance of what's missing from the models, what they do and do not do at the moment? Is there anything that they can never do? What aspects of this problem are they missing?' P6 was concerned that some of the recommendations from modelling 'might have pointed in the wrong direction for all of the best reasons'. P6 suggested that modelling teams could have been more productive if they spoke directly with stakeholders about what was missing from their models.

3.3. Expert Stakeholders' Expectations on Governance

P5 (Governance) viewed resilience and flexibility not as separate categories but as subsets of the overarching goal of decarbonisation—a position close to that of P11. P5's position, loaded negatively on both factors, appears consistent with their professionally neutral position on the direction of technical evolution of the energy system.

P5 asserted that the duty of regulators is to maintain an appropriate perspective in the light of the principal-agent relationship implicit in their role in the governance of the energy system. P5 placed the highest priority on the customers that the system serves. Hence, the goal of equity was ranked highest (+2). For P5, system costs in the current discourse could be over-simplified. Being a welfare economist, P5 extended their discussion of equity to cost, stressing the importance of considering how system cost is socialised, i.e., how benefits and welfare costs are distributed across customers and society as a whole. P5 thought that consideration should also be given to the issue of intergenerational transfers, particularly in connection with decisions that are made today that might pass on expensive assets to future generations. This risk (which can never be avoided completely), should be mitigated through clear policy and transparent forms of regulation.

P5 viewed resilience and flexibility not as separate categories, but as subsets of the overarching goal of decarbonisation. Therefore, ranking these two goals below equity and cost did not mean that they were less important.

Looking towards the future, P5 thought that digitalisation would increase flexibility through improved demand side management. In a market economy, P5 suggested that the selection of heat technologies for the future is best left to the market rather than being placed in the hands of the government. Subsidies would just distort the market.

On the impacts of selection of technologies on system architecture and modelling, P5 was confident that current renewable technologies could be combined to produce good outcomes for customers. However, trade-offs would be needed if these technologies were to combine [effectively and appropriately?] in the system. P5 remarked that policy goals such as equity, resilience/security of supply and costs are constraints imposed on technologists/modellers. Costs for improving resilience and underpinning security of supply in the context of high penetration of renewables should also be quantified, and resources depletion rates should be included to give higher relative value to the benefits of renewable energy. Detailed discussion about metrics for these constraints and the associated costs for implementing and integrating renewable technologies should be part of the discourse.

4. Discussion

Stakeholder research is not new. However, there has been comparatively little formal literature on the elicitation of stakeholders' expectations and requirements, and none from a system architecture perspective. Studies that have been published tend to be theoretical and to rely mainly on published literature for analysis and characterisation of stakeholders' interests (e.g., [31,32]). No empirical research has been conducted specifically to inquire into the expectations of stakeholders and their views on the role of heat supply technologies and how these might be configured in and impact on the architecture of a energy future system.

While the five policy goals introduced at the start of this paper have been repeated in successive government reports and White Papers over the last two decades, experts in our study had not been confronted with them as a set of system requirements in any other formal discussions. The ranking exercise and the ensuing articulation of their choices show that experts appreciate the dynamic and interacting nature of these goals, and the need to prioritise them, but they differed in the priorities that they assigned. Their perceptions of how these goals might be fulfilled through a diversity of technological options reflect their own roles and the complex socio-technical nature of the energy system.

The two factors that emerge from this study can be seen as representing two broad strategic approaches to heat decarbonisation, each covering a spectrum of technical options, and how they might be deployed. However, close analysis reveals each approach to be an agglomeration of views and insights, with each expert interpreting heat technologies differently in relation to policy goals.

Factor 1, which we characterise as Adaptive, is cautious about pursuing heat supply largely through electrification. Resilience is the top or second priority of this approach and is strongly associated with the transformation of the existing gas grid into a hydrogen network. The key role of hydrogen is seen as to secure supply: 'to keep the lights on' as well as dealing with the apparently intractable problems and uncertainties entailed in improving the thermal efficiency of the UK housing stock, ensuring the performance of individual heat pumps, and managing the intermittency of renewables.

Deploying hybrid forms of heat technologies, e.g., hydrogen-ready boilers, particularly for the domestic market through the gas grid is perceived both to contribute to resilience, and to ease the requirement for tightly coordinated intervention across the energy system.

With resilience as the top priority, flexibility is seen as just another aspect of resilience, a means-to-an-end, and an enabler of resilience. In an operational context, hydrogen is seen as providing the large-scale flexibility needed in the electricity system, using existing technology such as gas-fired power stations. We note here in passing that, as in many countries, the existing UK electricity system is supported by two main types of gas-fired power station—open cycle gas turbine and combined cycle gas turbine. These have significantly different cost and performance characteristics, but perform overlapping functions. These include frequency stabilisation and provision of electricity at times of peak demand, and in the case of open cycle systems, provision of auxiliary generation capacity at the sites of large fossil-fired or nuclear power stations.

Individual electric and hybrid heat pumps, and heat networks are seen as having a part to play. In principle, use of hydrogen in conjunction with heat networks opens up multiple additional options for supporting the electricity system. However, for hydrogen proponents, and in the absence of an architectural perspective, the role of heat networks is perceived as limited.

The transformative approach, Factor 2, can be characterised by a more diverse pattern of priorities, and diverse technical solutions for decarbonising heat, with equity generally ranked higher than other goals. Individuals loaded onto this Factor were reluctant to rank resilience above flexibility. The expert who had longest experience in heat networks offered historical evidence of their evolvability, though in the context of another country, which was enabled by economies of scale, and the elimination of the need to intervene further in individual dwellings that had been connected to a heat network. However, hydrogen was strongly advocated by one expert aligned with this factor.

Contested opinions were espoused by experts on the treatment of storage and the concept of the Last Mile. The term "Last Mile" was used as a shorthand to refer to decisions that must be made around the potential roles of heat networks in the context of an expansion of the number of homes heated by individual heat pumps as envisaged in 2020 by the UK Government or a corresponding expansion of heat networks, would impact significantly on both the gas and the electricity network. While some see heat networks having a limited role in decarbonisation, others suggest that a transformed district heating sector would open additional opportunities for realising economies of scale with respect to operation, and support integration of storage and other technologies at the mesoscale within the energy system, thereby contributing to increased system flexibility and resilience.

Both approaches view storage as key to future decarbonisation, but differ in respect of what forms of storage to deploy, and whether to adapt or transform the existing energy system to accommodate them. Economies of scale with respect both to operation and capital costs mean that the selection of locations for deployment of storage within the energy system is not arbitrary [20]: opportunities for deployment of storage in all energy futures depend to a significant extent on the topology of energy transmission and distribution systems. Conversely, in the light of the large requirements for flexibility in the emerging energy system, storage may confer increasing economic advantage on architectures and technologies that facilitate its integration. As a result of insights gained from the expert interviews, our modelling team:

- began work to define evolvability and to use UKTM to quantify it [17,35];
- extended the ESTIMO model to include the option of hydrogen for heating;
- developed scenarios that compared three different heat supply architectures for the Pugh scoring exercise in the Stakeholder Workshop [25];
- undertook pairwise comparisons (an initial step in trade space analysis [23]) using the ESTIMO model to understand relationships between energy storage, interconnector and generation capacities that would be needed to support a future fully decarbonised energy system [34];

The question of the future treatment of heat impacts significantly on the architecture of the energy system and implicates all of the system goals that were considered by stakeholders in research reported here. Implicit in this question, are socio-cultural and political issues such as consumers' acceptability/adoptability and fairness that needed to be considered but were not covered in great detail in these expert interviews. There was for example, little discussion about the feasibility of a much larger and strategic deployment of heat networks given the paucity of existing industrial capacity in the UK, and the presence of a thriving gas industry and of a gas grid that already connects c. 85% of UK dwellings. Nor of the complexity of the wider context within which decisions will be made. This context includes the accelerating deployment of electric vehicles, and the likely emergence of domestic cooling demand over coming decades, both likely to require the upgrading of the electricity transmission and distribution system, regardless of choice of heat technologies.

Regardless of the route by which it is ultimately achieved, implementation of a fully decarbonised energy system relying wholly or mainly on renewable sources of primary electricity, will require a profound reshaping of existing gas and electricity systems and of the connections between them. It will also require a regulatory and governance system supporting a market design that assigns an adequate value to scarcity and appropriately rewards system security. This is a complex decision space in which solutions will be hotly contested and negotiated by all stakeholders, and upon which energy modelling currently sheds insufficient light. The System Architecture literature represents a rich source of tools and techniques to shape and focus the work of energy system modellers and to resolve different perspectives on the future of the UK energy system. The work presented in this paper has begun the process of adapting these tools and techniques to the energy domain, but much more remains to be done.

5. Conclusions

Energy system goals and objectives have evolved over the past decade and the task of meeting them has become increasingly complex, urgent and demanding as the timescale for decarbonisation has shortened and as the deployment of low and zero carbon technologies has accelerated. Modelling remains a dominant source of information and insight for policy makers. However, current energy models do not capture key elements of the problems faced by policy makers and other energy system stakeholders.

Our research has begun to tackle these concerns by appropriating the framework of System Architecture, within which stakeholders' requirements of the energy system are paramount. Information and insights from this work have helped modellers generate improved hypotheses for exploring the landscape of technology options and trajectories. Our innovative approach to capturing and understanding stakeholders' expectations and requirements has revealed the complexity of their responses to multiple policy objectives, and their concerns with respect to a number of issues that emerge in the course of real world implementation. In the process, our research has also demonstrated a method by which the policy and modelling gap could be closed.

Reflecting on methodology, the schematic (Figure 2) generated by Principal Component Analysis in Q methodology lays bare the different perspectives and relative positioning and partitioning of each expert's priorities. The configurations of the ranked data form a scaffolding for the qualitative analysis which provides a much richer understanding of experts' positions in relation to each other than would have been possible with conventional interviewing methods. As an example, the opposing views of P5 (governance) on the one hand, and on the other of P6 (academic) and P9 (energy consultant) on equity, reflects their differing professional roles. The former is duty bound to protect consumers, while the latter were at liberty to place higher value on other system objectives.

Different approaches to decarbonisation of heat that this research has revealed, reflect not just different institutional and corporate interests, but also different understandings of potential vulnerabilities that emerge from the rapidly changing sociotechnical landscape. In a liberalised market economy, the need to maintain energy system resilience and flexibility in the face of endogenous and exogenous volatility is a formidable challenge.

There are fundamental reasons for expecting similar sets of energy system objectives to exist, and analogous questions around prioritisation to arise in any energy system operated within a liberalised regulatory framework. It is therefore likely that our approach will be transferrable to other jurisdictions.

Amidst debate in academia, the decarbonisation of the energy system will go on, with policy increasingly constrained by real-world considerations such as supply chain capabilities and dynamics. The modelling community will have to work hard, and open itself to wider sources of insight from empirical and qualitative research to ensure that its efforts amount to more than forecasting through the rear-view mirror.

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Abbreviations

UNFCCC	United Nations Framework Convention on Climate Change
COP26	26th UN Climate Change Conference (Conference of the Parties)
MARKAL	MARKet ALlocation model
UKTM	UK Times Model—an implementation of MARKAL for the UK
ESME	Energy System Modelling Environment
SPSS	Statistical Package for the Social Sciences
ConOp	Concept of Operations
DDM	Dynamic Dispatch Model
DH	District Heat
LNG	Liquified Natural Gas

Appendix A. Stakeholders' Requirements Interviewing Guide

Note that this guide will be adapted in the light of individual interviewees' areas of responsibility and expertise.

Appendix A.1. Brief Introduction

Referring to the participant information sheet, the researcher will reiterate the purpose of the interview and reassure the interviewee that the interview will focus on their own expertise and knowledge around policy, research and/or practice with respect to decarbonisation of heat/electricity. The researcher will ask for permission to record the interview and will reiterate the interviewee's right for data protection and the duty of the researcher to guarantee confidentiality and anonymity. The interviewee will be asked to sign the consent form.

Appendix A.2. Role and Responsibilities in Interviewee's Organisation

Could you tell us a bit about your role and responsibility in your organisation?

- In general
- Specific objectives

Appendix A.3. FLASH CARDS (Ask Interviewee to Rank the Following)

Zero Carbon, Flexibility, Resilience (Security), Cost, Equity.

Cost: What are the main trends affecting cost, e.g., interest rates, investment and subsidies?

Equity: Might increasing capital intensity of the system affect equity? Fixed charges will dominate. Will poor people be able to take advantages of dynamic pricing?

Appendix A.4. Heating/Cooling Technologies (Industry, Policy)

1. Could you comment on current heating and cooling technologies and their roles in decarbonisation of the existing energy system? Prompts:
    - Heat pumps, including hybrid heat pumps. Where do you see hybrids being deployed within the whole system?
    - District heating
    - Condensing boilers (natural gas and/or H_2 and biogas)
    - Others: Biomass

How do/will these technologies (components) interact within the constraints of the whole system?

2. What experiences has your organisation had with policies for promoting these technologies in the recent past?
    - RHPP (Renewable Heat Premium Payment Scheme)
    - Green Deal

3. How do these experiences inform your organisation's view of future strategies in relation to the promotion of these technologies and other technologies in this area? Prompts:
    - compatibility of CO_2 emissions from natural gas in a net zero system?
    - role of possible of carbon capture technologies?
4. What risks would you test your future strategies against (under the worst condition)? Prompt:
    - loss of gas imports?
5. While the Heat Challenge project has had a primary focus on decarbonising heat in the domestic sector, this cannot be considered in isolation from the whole energy supply system. So, in relation to the areas that we have touched upon:

Could you tell us how your organisation sees/imagines future energy and more specifically, heat supply systems? What do you expect the big picture to look like?

Prompts:

- The role of variable renewables [percentage that might be achieved in comparison with other sources of energy]
- The role of gas and gas infrastructure?
- Conversion technologies (vector shifting, vector coupling)

6. What is your view of gas as a transition fuel? Prompts:
    - Natural gas
    - Liquid natural gas? Fracking?
    - H_2 from steam methane reforming (SMR) of natural gas
    - H_2 from electrolysis
7. How might a significant increase in the number of prosumers (or embedded energy technologies) impact on policies and policy making—prompting, or reacting to:
    - Generation
    - Transmission
    - Distribution
    - Market structure
    - Governance
8. How would deployment of the technologies that you have mentioned and the increase in embedded energy production impact on future energy infrastructure?
9. What do you think is the role of storage in the energy system? Prompts:
    - Grid Storage
    - Distributed Storage, e.g., EV, thermal stores, chemical storage
    - Biomass
    - Geothermal
    - Heat, chemical and electricity (different prices/decay)
10. How would these trajectories/transformations impact on the policy and strategies with respect to: Prompts:
    - business models expect in industry and commerce and energy
    - pricing, e.g., dynamic and nodal?
    - Investments: foreign? Interest rates
    - Carbon taxation
    - Customers
    - Regulations
11. In view of your comments and with respect to the goals of your organisation in relation to energy system decarbonisation, in what ways do you think the energy system should evolve in order to achieve those goals?

End

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