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The Role of Domestic Heat Pumps in Providing Flexibility to the UK Electricity System

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Abstract: Widespread adoption of residential heat pumps is predicted to create challenges for national and local electricity systems. Flexible operation of heat pumps could help smooth peak demand and better utilise renewables. Achieving these benefits involves many stakeholders from the heat pump and electricity sectors with different perspectives and expectations. This work brought together 52 experts from different parts of the UK system to discuss and debate the role of heat pump flexibility in a decarbonised electricity system in 2035. A co-production research model was adopted, designed to integrate diverse forms of knowledge and perspectives in the co-production of knowledge on heat pump flexibility. A series of participatory activities were undertaken including a one-day workshop. Elements of a common vision emerged, such as the anticipated widespread flexible operation of heat pumps as the cheapest way of running a heat pump and the likelihood of a highly automated and remote-controlled manner of operation. Disagreements and unknowns also emerged. This work aims to support stakeholders in planning for the social, technical and economic aspects of flexible heat pump operation in their own organisations.

Keywords: flexibility; heat pumps; demand response; electricity system; buildings

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1. Introduction

1.1. Background and Research Objectives

Decarbonisation of energy supplies in mitigating climate change entails some major changes to energy systems in many countries: firstly, the electrification of sectors such as heat and transport which previously used liquid or gaseous fossil fuels [1]; secondly, the shift to renewable electricity generation such as wind and solar whose supply is variable, as opposed to flexible as in fossil-fuelled electricity generation; thirdly, the introduction of new forms of energy storage to allow better alignment of energy supply and demand [2]; and fourthly, to account for residual mismatch, the increased role of the demand sector in providing flexibility to the system [3].

Residential heat pumps are expected to be a key technology enabling the transition in some countries [1], and UK's Sixth Carbon Budget aims to switch 11 million homes to heat pumps by 2035 [4]. While this can significantly reduce carbon emissions [5], it can also create new challenges for the electricity system both seasonally and within days [6,7] through increased winter demand, exacerbation of existing demand peaks and creation of new ones. While heat pumps cannot shift their operation for long periods, they are still being explored as one way to smooth out electricity demand over the day [8]. This may entail increasing their output when electricity prices are low and reducing or stopping it at times of high prices or grid constraints [9].

Flexible operation of heat pumps is driven by the needs of the electricity system and is not how consumers would normally operate their heating, nor is it the most energy-efficient way to run heat pumps. Operating heat pumps in this way may therefore affect important concerns such as household thermal comfort and heat pump performance. This raises the issue of how to ensure that flexibility is implemented in a way which is not detrimental to household life while reliably delivering energy flexibility across a range of heterogeneous configurations of heat pumps and homes in which no one stakeholder is responsible but in which many are involved.

This article describes and reflects upon an attempt to make progress in planning for heat pump flexibility by bringing together 52 experts from across the UK system for the first time in a discussion workshop. The research objectives were as follows:

1. Contribute different knowledge of and viewpoints in the nature of flexible heat pump operation across sectors;
2. Reach a shared understanding of the factors that influence the implementation of flexible heat pump operation;
3. Collaborate to attempt to co-develop a vision for the role of heat pumps in providing flexibility to the electricity system in the medium term (i.e., 2035).

The flexible operation of heat pumps is referred to in the remainder of this paper as 'heat pump flexibility'.

1.2. Domestic Heat Pumps in the UK

A heat pump is a technology in which energy is used to move heat from a colder source to a warmer sink, using a thermodynamic refrigeration cycle. There are many types of heat pump, but the most common in domestic UK applications uses outdoor air as the heat source and water as the heat sink, using electricity to power the vapour compression cycle and providing both space heating and domestic hot water [10]. There also exist in the UK housing stock smaller numbers of ground source heat pumps and hybrid heat pumps (which are a combination of an electric heat pump and a gas or oil boiler) [11]. Reversible air-to-air heat pumps exist in the domestic market in small numbers, although these are less common as they are currently ineligible for government subsidies.

Figure 1 shows a typical domestic air-to-water heat pump installation in the UK. Units typically draw up to around 4 kW of electrical power [7] although domestic products drawing up to 8 kW are available (e.g., [12]). Most are sized for continuous operation plus a small margin for cold start [13]; however, there is some evidence that a significant minority are run intermittently [14]. Based on current usage patterns, the predicted increase in national electricity demand on a cold winter day from mass adoption of heat pumps was calculated by Watson et al. [6], and these results are illustrated in Figure 2 for different levels of uptake. Distribution networks will also be strongly affected by heat pump and electric vehicle uptake [15,16], and demand-side flexibility, including from heat pumps, is predicted to play a "vital role" in the net-zero power system [17].

Figure 1. Typical UK domestic heat pump outdoor unit.

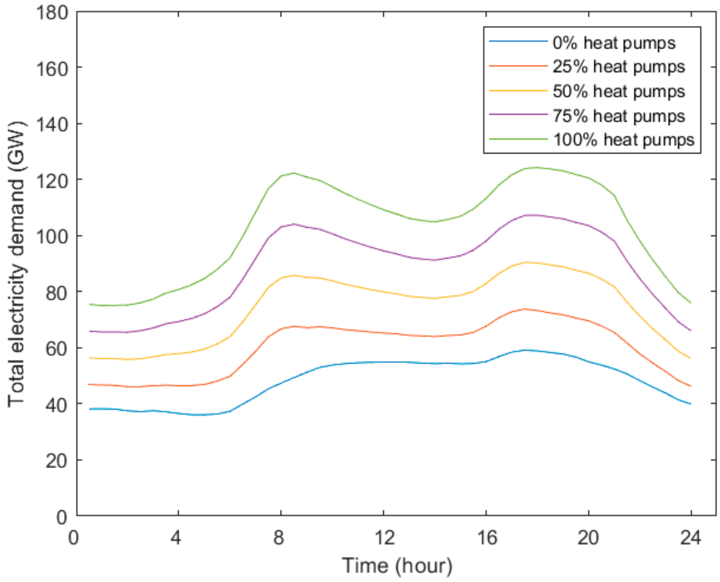

Figure 2. Predicted electricity demand on a very cold day from different levels of heat pump uptake. Reproduced with permission from [6].

1.3. Different Visions of Heat Pump Flexibility

Heat pump flexibility involves multiple physical components and human/organisational stakeholders and, as such, can be thought of a system spanning different sectors. The UK system and stakeholders are shown in Figure 3.

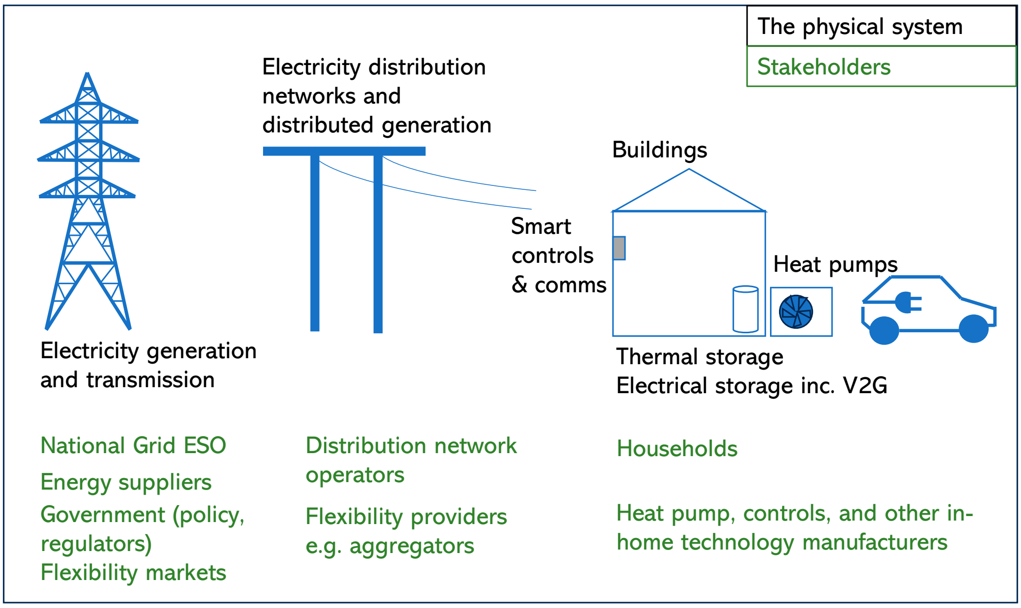

Figure 3. Illustration of the components and organisations involved in or affected by heat pump flexibility.

The motivation for this work arose from perceiving differences in visions and conceptualisations of heat pump flexibility across different sectors within the above system. One perspective found in the electricity sector characterises heat pumps as "distributed assets" [18] along with other residential technologies such as electric vehicles, small-scale batteries and rooftop solar panels. This classification does not earmark heat pumps as being different from these other technologies: all represent potential sources of flexibility joined to the low-voltage electricity distribution network.

Conversely, the UK heat pump sector does not necessarily see itself as a provider of services "upstream" in the electricity system; instead, its main priorities are wide-scale deployment of heat pumps and ensuring good technical performance [19]. A key challenge is reducing capital and running costs [20] to increase affordability [21]. In the absence of time-of-use tariffs, the best way to reduce running costs is to ensure high energy efficiency, in turn achieved with low flow temperatures [22]. This contrasts with strategies used for flexible operation, which are likely to increase flow temperatures at certain times (for a visual illustration of this principle, please see [23]).

The UK policy sector is anticipating the use of heat pump flexibility illustrated by the government consultation on a smart mandate for appliances including heat pumps [24]. The potential use of heat pump demand response to lower electricity system costs is explored by government-commissioned modelling studies such as [25,26] which include assumptions about thermal storage and/or the use of pre-heating.

Finally, the academic literature contains a range of perspectives on heat pump flexibility. The range of grid services heat pumps could technically provide is explored by [27] and their technical potential in UK regions is calculated using modelling methods in [28–30]. Practical options for controlling heat pump flexibility are explored in a lab environment in [31] and in homes in [32], and UK-based field trials are described in [33,34]. A notable recent contribution is the energy justice perspective [35–37] which begins to explore themes such as fairness, household empowerment, vulnerable customers and those who cannot participate for various reasons. This perspective emphasises the householder and the positive and negative implications of heat pump flexibility for different segments of the population. Therefore, the academic literature itself offers multiple different perspectives on heat pump flexibility, and no single study has attempted to engage with all these aspects.

1.4. Combining Different Perspectives through Stakeholder Engagement

It has been acknowledged that there is value in bringing together different stakeholders in the deliberation and formulation of strategies or policy options to ensure both their social legitimacy and relevance [38,39]. Authors including Corburn [40,41] stress that understanding the knowledge and values across individuals and groups can provide insights into why collective action towards particular goals or policies may not work in practice. As a result, the processes of engagement and participation have emerged as significant forces in policymaking. Participation and engagement promote more open and interactive knowledge systems, where a diversity of knowledge types and viewpoints are shared and created. Creating opportunities for the involvement of a range of stakeholders to capture and understand divergences and share and co-produce knowledge can create the conditions for the successful implementation of policies and strategies. From a research perspective, scholars argue that research quality and rigor are improved by the integration of researchers' theoretical and methodological expertise with nonacademic participants' real-world knowledge and experiences [42].

Pineo et al. [43] note that, in built environment studies, there has been increasing emphasis on participatory, collaborative and transformative processes within research and practice, leading to new forms and types of knowledge production. The co-production of knowledge involves processes where a "plurality of knowledge sources are combined, usually to address specific problems" ([44], p. 221). McGookin et al. [45], in their systematic review of participatory methods in energy system modelling and planning, also noted that "…the most commonly noted benefit of taking a participative approach was that this would improve the legitimacy and robustness of results". Within the context of heat pumps, there are different visions and viewpoints around achieving flexibility, as outlined above; some of these differences are due to how important heat pump flexibility is perceived to be by different stakeholders. Co-production processes can be a way of sharing viewpoints, engendering trust and reaching common ground among the different groups and stakeholders within this context.

2. Materials and Methods

2.1. Research Approach

We adopted a co-production model from [46], informed by participatory methods, to structure the research approach in a way that integrates diverse forms of knowledge and perspectives in the co-production of knowledge on heat pump flexibility. The authors outline six building blocks in the co-production process, which have been adapted and simplified by others including [47]. The model includes the following: i. identification of key actors and building of partnerships, ii. building of common ground, iii. co-exploration of need, iv. co-development of solutions, v. co-delivery of solutions, and vi. evaluation of the product and the process. The six building blocks are summarised in Table 1 below.

Table 1. Building blocks in co-production (adapted from [46]).

Building Block	Example of Processes within the Building Block
Identification of key actors and building partnerships	Inclusion of all relevant actors; identification of partnerships and networks
Building of common ground	Develop agreed principles and ways of working together; reach a common purpose
Co-exploration of needs	Space for ongoing interaction and relationship building; jointly identify issues to work on; form a mutual understanding of all actors' needs and priorities
Co-development of solutions	Jointly develop an output; enable knowledge exchange amongst all partners; gain consensus agreement of the group; develop plans
Co-delivery of solutions	Build capacity amongst the group; respect contributions
Evaluation	Review and co-evaluate the product and the process; document successes or failures in the process

Engagement- and dialogue-based activities are critical for sharing and co-producing knowledge, throughout all the building blocks, but important questions remain over *whose* knowledge is shared and generated and *how* engagement happens in practice. Reason & Bradbury [48] note that when using participatory or engaged approaches, researchers need to be *"both situated and reflexive"* alongside being explicit about the perspectives from which knowledge is created.

Carter et al. [46] note that co-production can be used in all or some building blocks depending on the problem to be addressed. Within this study, we have adopted a selection of the 'building blocks' model, applied reflectively, for the engagement between research and practice to generate useful and useable knowledge for action in relation to heat pump flexibility.

We worked, over six months, on the activities outlined in Table 2, which although followed a three-stage process, were iterative in manner. Through our research design, we gathered input from a range of 'experts': people with experience or knowledge in the area of heat pumps or electricity systems who potentially held a key role in enabling heat pump flexibility. We adopted engagement activities that would yield information and insights but also provide a space for dialogue, discussion and agreement.

Table 2. Research objectives, research activities and corresponding co-production processes.

Research Objective	Research Activities and Participants Involved	Alignment to Co-Production Building Blocks
Contribute different knowledge of and viewpoints on the nature of heat pump flexibility across sectors	Development of position paper (summarising key research) Circulation and review of position paper by academic experts (n = 6)	Identification of key actors and build partnerships and common ground
Reach a shared understanding	Expert workshop (n = 52)	Co-exploration of needs
Co-produce an emerging vision for heat pump flexibility	Development and circulation of summary of findings to experts (n = 52) Comments and edits received on summary of findings	Co-development of solutions

2.2. Developing the Position Paper

"To begin a process of research co-production, problems need to be collaboratively identified" [49]. We used the development of a position paper to help identify and frame the 'problem'. The position paper intended to summarise the key debates associated with the topic. It consisted of a problem statement setting out the unknowns and the importance of resolving them and a list of five key areas for debate and discussion at the forthcoming workshop: electricity network requirements, heat pumps, homes, households and governance. These five areas were then used to structure both the workshop and the findings.

The drafted position paper was circulated to six academic experts, from different academic research groups who had different areas of speciality, with the aim of including a range of relevant discussion topics. Since the experts were from slightly different fields (e.g., buildings, electricity systems and governance) we wanted to make sure we had captured the main 'issues' and items which needed to be discussed in the workshop. This activity was a building block to understand identify key areas and topics (i.e., finding common ground) that be might of interest to stakeholders related to heat pump flexibility. The feedback received at this stage led to relatively minor changes, such as further suggestions of discussion questions which were then incorporated. The position paper was sent out to everyone who signed up to the participatory workshop described below. This was carried out three weeks before the workshop in order that participants could identify areas which were not raised in the position paper and suggest these for discussion at the workshop.

2.3. The Participatory Workshop

We organised a participatory workshop to bring together stakeholders with experience and knowledge on heat pump flexibility, open up a dialogue and reach a shared understanding to co-produce a vision for heat pump flexibility. This activity aimed to create dialogue around specific topics, alongside stimulating discussion and gaining agreement on proposed solutions.

The half-day workshop took place on 14 June 2023 in London with practitioners and researchers. Participants were purposively sampled in order to represent the whole system (see Figure 3), with quotas intended for each sector. We recruited participants by sending personal email invites; most invitees were not known personally to the research team but were found through recommendations from our contacts or from LinkedIn.

We aimed to host up to 60 participants and invited around 120, and the number who came on the day was 52. The intended and actual spread of sectors is shown in Figure 4. The workshop was of great interest to academics and thus more attended than had been envisaged; this was partially balanced by giving them facilitation roles where their aim was to capture opinions from those outside academia. It was more difficult to recruit from other sectors. Effort was made to recruit female participants and speakers since the sector was perceived by the research team to be male-dominated; attendance was 76% male. The research team also attempted to invite households from two different heat pump flexibility trials in order to hear their perspectives directly, but there were practical barriers to this, and in the end, this was not possible.

The workshop was approved through a departmental low-risk ethics process, and all the participants received an information sheet and consent form and gave signed consent prior to participating.

The aims of the workshop, as shared with participants, were

- To collaborate in the creation of a shared vision;
- To find points of consensus and disagreement (not necessarily to resolve them);
- To provide a networking opportunity for the heat pump flexibility community;
- To learn from existing trials and initiatives.

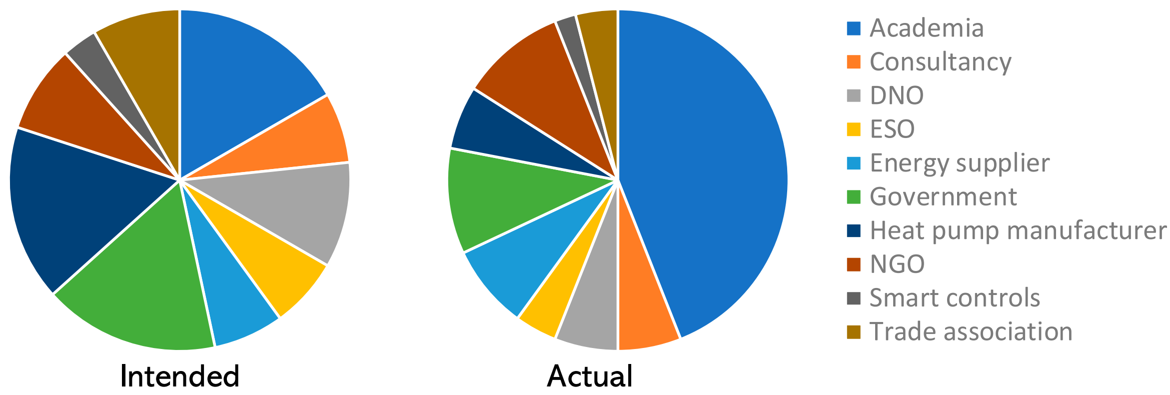

Figure 4. Participants by sector. Intended and actual. Acronyms as follows: DNO: Distribution Network Operator; ESO: Energy System Operator; NGO: Non-Governmental Organisation.

The workshop was led by two researchers from UCL and the University of Oxford. The workshop agenda (Table 3) involved a combination of presentations and discussions. The presentations were designed to give some quantitative information about the problem and solution (e.g., how much flexibility does the electricity system require; how much flexibility per heat pump have recent trials achieved). The morning discussions then used this information as a starting point and explored the unknowns raised in the position paper via a series of questions per group. For this session, participants were encouraged to join the discussion they knew the most about. In the afternoon, each group attempted to create a structured vision which consisted of completing a number of statements about different aspects of heat pump flexibility; these were designed to be compared to one another in order to observe the level of consensus across the groups. For this session, participants were encouraged to mix with those from other sectors.

Table 3. Participatory workshop agenda.

Activity	Details
Morning scene-setting presentations	Flexibility requirements and the potential role of heat pumps
Morning discussion groups	Policy, electricity networks, households, homes, heat pumps
Plenary, lunch, networking	
Afternoon presentations	Findings from two recent trials of heat pump flexibility
Afternoon vision exercise (in groups)	Complete a series of statements, e.g., "The % of homes with heat pumps participating in heat pump flexibility in 2035 will be. . ."
Plenary, networking	

These workshop activities aimed to provide a space for interaction and relationship-building, identify issues of interest across different sectors, and attempt forming a mutual understanding of all actors' needs and priorities (i.e., co-exploration of needs).

2.4. Analysis of Data from Workshop

We adopted a reflexive thematic analysis approach [50]. This interpretative approach to qualitative data acknowledges the role of the researcher in knowledge generation, and the researcher's subjectivity in the research process. The positionality of the researcher plays an important role in any research project. This is particularly so in research where the focus is on the co-production of knowledge. Considering the interest of this study is the co-production of knowledge towards a vision for heat pump flexibility, we felt that that reflexivity is vital for conceptualising and undertaking thematic analysis of the data.

The audio recordings from each breakout group formed the data for this study and were processed as follows. Each recording was transcribed using AI software; however, this led to poor quality transcription; therefore, the recordings were listened to and the transcriptions corrected. Each verbal contribution was associated with the type of organisation the relevant participant worked in.

The transcripts were coded multiple times. The first round of coding was deductive, using the topics in the position paper and the vision statement templates as codes. During this process, new codes emerging from the data were written down and kept aside. The second round of coding used these new emergent codes, and further emergent codes were written down; the third round of coding used these latest emergent codes.

The codes were then structured into five themes; each theme covered a different aspect of the intended output: the role of heat pumps in providing electricity system flexibility in 2035. Most themes could have been predicted before the analysis, e.g., "implications of heat pump flexibility for customers"; however, one theme, "use cases for heat pump flexibility", was new and unexpected: a crucial part of the argument. In order to present the results, the themes were ordered into a logical order.

Using a reflexive approach involves making explicit the influence of the researchers in the data collection, analysis and writing up process. The lead researcher (JC) was responsible for the conceptualisation, investigation and analysis of the work; their research expertise and interests relate to the transition to a low-carbon energy system: heating, cooling, flexibility and building performance. Their positionality affected the results in several key ways: firstly, in what is missing. One participant during the workshop said, "*We ought to have a group on markets*"; this was not an area of expertise of those who designed the workshop and thus had not featured prominently in the design. Conversely, other topics were prominent, for example, two of the authors have previously studied the role of heating systems in heat pump flexibility and concluded that this is an important aspect, hence it being more likely to be identified in the workshop data.

2.5. Stakeholder Checking and Critique of Interim Findings

An initial summary of findings was drafted and circulated to the participants (n = 52) for feedback. This stage was included to provide participants with an opportunity to reflect and refine on the points raised in the workshop. This was a key stage to validate the findings that came out of the workshop discussions and review the knowledge claims from their perspectives. It was an attempt to jointly develop an output, but the production of the summary of findings was led by the lead researcher (JC). A small number of comments were received in the interim summary of findings, for example, noting the omission of some topics and seeking to change the language on the report of recent trials to reinforce the preliminary nature of the results. These edits were made, and the revised document was circulated to all workshop participants, in an attempt to co-create joint actions to achieve heat pump flexibility.

3. Results

The results are presented below by theme.

3.1. Use Cases for Heat Pump Flexibility

Two use cases for heat pump flexibility were proposed: wholesale energy arbitrage (balancing electricity supply and demand on a several-hourly basis) and electricity distribution network constraint management. Participants from multiple organisations expressed the view that most of the monetary value of shifting heat pump operation was in the first use case.

Energy arbitrage use cases were acknowledged to be restricted by the temporal limits of heat demand shifting. Many participants believed that heat pumps can switch off without loss in comfort for around 2 h, which could contribute significantly to smoothing the peak demand in UK winter evenings, but their role in matching variable wind power generation will be limited as wind output mainly varies over days, not hours.

Electricity distribution network use cases were currently being explored by distribution network representatives who stated that such use cases depended on how short a notice period customers would accept. Several participants emphasised that procuring flexibility is more expensive than substation reinforcement in some areas, and that in new developments, distribution networks would be sized appropriately to not depend on flexibility. One participant predicted that in areas with large numbers of flats, storage heaters would provide all the required flexibility while heat pumps were left to run normally instead of flexibly, "*having to work against their nature*".

Finally, the debate was raised as to how heat pump flexibility will compete with grid-scale multi-day/-week energy storage as investment in the latter is ramped up and whether/at what point in time supply-side flexibility might render heat pump flexibility unnecessary.

3.2. Volume of Heat Pump Flexibility in 2035

Discussion groups were asked to state what proportion of heat pumps they predicted would participate in flexibility by 2035. The groups who attempted this arrived at the conclusion that participation in heat pump flexibility would be widespread, with 50–90% of domestic heat pumps participating.

Some participants addressed the question by predicting how many households will not run their heat pumps flexibly: one stated that 20% are "*wedded to*" a two-burst heating approach, and another brought survey evidence in which 20% of respondents "*were against the principle of it at all*". Other proposed reasons for not running heat pumps flexibly included the ability to afford expensive electricity at peak times and social factors (vulnerability and the inability to shift heating due to the presence of young children) which would render households unable to provide flexibility.

Only one group attempted to quantify the nationally aggregated flexibility in physical units. Using research findings from presentations earlier in the day showing an average per-household load reduction of 0.75 kW—assuming 20% of homes have heat pumps and a maximum of 90% of these households participate, and furthermore assuming that they all participate at once—this leads to an upper bound of around 4 GW.

3.3. Practical Implementation of Heat Pump Flexibility

Participants agreed that, overall, heat pumps will be turned up/down or on/off for a period of time, during which internal conditions should be maintained using either the thermal inertia of the building or a dedicated thermal store. The period of demand shifting was perceived to be bounded by the imperative to maintain comfort for the household, as opposed to being set by electricity system stakeholders.

Using the building itself as the heat store was believed to allow around two hours of space-heating load shifting or less if households are already living at low temperatures. This duration may be extended by preheating, but some participants raised concerns around comfort and energy use; more work is required to understand this concern. The role of in-home thermal storage for space heating was disagreed upon, with some participants stating it will be a "*key part*" of integrating renewables and managing peak demand and others being concerned about space or cost. In-home thermal storage for hot water, which exists in the majority of homes with heat pumps, was noted to allow up to 12 h of heat pump hot water load shifting.

Most participants thought that heat pumps could not shift or drop space heating operation at the coldest times of year, when they would be running constantly at full output. From a network perspective, this was identified to be a time when most flexibility would be required. This dilemma was not resolved at the workshop.

The majority of participants agreed that heat pump operation would need to be highly automated and remotely controlled in order to gain the widespread uptake of flexibility described above. It was also widely agreed that these levels of participation require flexible operation to be the cheapest way of running a heat pump. These requirements led to important unknowns being expressed: the acceptability of remote control to a large number of people and how to manage the pricing/incentive structure to make flexible operation the least costly form of operation.

3.4. Implications for Customers

A strong message emerged that the high levels of heat pump flexibility anticipated could only be achieved if householders stayed comfortable. Furthermore, it was felt that households would differ in their comfort 'envelope' and that it was therefore important not to enforce a preprogrammed band of temperature based on an average but a tailored service. Some participants also thought customers should not even notice heat shifting being carried out, but not all agreed that this was feasible. Multiple participants presented research evidence that hot water provision at the time of day demanded by the household cannot be compromised and that failing to deliver this could mean customers no longer engage in flexibility at all.

In line with the above highly automated view of heat pump flexibility, little engagement for the customer was envisaged after an initial period of setting their preferences, e.g., temperature bounds or times which they did not want to be controlled remotely. Participants felt that customers should, however, be provided with an override. There were differing opinions on the necessary level of understanding from customers, both in terms of the bigger picture of why shifting was being carried out and also how to operate their own heat pump. One heat pump manufacturer expressed concern:

> *"...we've been educating people to use heat pumps for 10–15 years by leaving them on all the time, and now all of a sudden, you actually don't leave them on all the time?"*

Participants wanted the arrangement to be fair and recognised that it would need to be fair to be acceptable; however, what this would look like was not resolved within the workshop. The issue raised the most often was that temperatures dropping may not be acceptable for some vulnerable groups, who would then get hit with very high electricity prices at peak times. A second issue was the need for manual engagement from people who do not have smart homes or digital literacy, creating extra work for them.

3.5. Implications for Heat Pumps and Heating Systems

It was agreed that heat pumps will need to be able to turn on, off, up and down according to external signals, according to the likely forthcoming smart mandate for electric appliances. Participants had different views on who should remotely control heat pumps, but the predominant view was that it did not matter as long as the correct protocol was used to enable interoperability and that heat pumps were not damaged by being operated in ways for which they had not been tested.

However, flexible operation, as opposed to constant operation, means that heat pumps will run less efficiently, due to several factors, e.g., higher flow temperatures and possible addition of more space heating storage into the system. There was some concern expressed by heat pump industry representatives that this would make heat pumps more expensive to run. Other participants addressed this by emphasising that off-peak electricity prices need to be low enough (or equivalent financial incentives) to account for, e.g., flow temperatures being higher, to incentivise flexible operation.

Representatives from the heat pump industry agreed that heat pump size should not be increased in order to facilitate participation in flexibility (e.g., by being able to warm up spaces more quickly). This is because heat pumps are already oversized for most of a year's thermal demand, so further oversizing would compromise efficiency. However, changes to heating system setups may be necessary. For example, one participant noted that a thermostatic radiator valve could negate a heat pump's attempts to preheat a room, and two participants mentioned radiator sizes as a limiting factor in how responsive a heat pump can be. How this system approach can be implemented to ensure the provision of intended flexibility was not discussed.

3.6. Summary

In summary, elements of a shared vision emerged. It was agreed by most that heat pump flexibility will be the following: widespread, highly automated, limited by not negatively affecting thermal comfort, incentivised mainly by electricity prices, and useful for hourly energy arbitrage, and network management although not in all circumstances.

Some elements were not agreed upon, including the following: the role of enabling technologies such as thermal stores, how to address equity issues, and whether/how customers should feel part of the system.

Importantly, the vision relies on several key assumptions including high levels of customer acceptance, effective financial incentivisation, and heat pumps and heating systems interacting correctly. These are discussed below.

4. Discussion

4.1. Reflection on the Findings

From combining the expertise of electricity system representatives and participants who had carried out heat pump flexibility trials, an important conclusion emerged that it is technically possible to use heat pumps to shift hot water and space heating demand out of the highest part of the winter evening peak and to alleviate local network constraints. This finding may not apply on the coldest days, and it may not extend to other peaks such as the new morning peak created by heat pumps [6] due to comfort constraints.

If current trials provide an accurate reflection of the amount of heat pump flexibility available per household, then nationally there could be up to 4 GW of heat pump flexibility available. However, this scaling-up relies on some significant assumptions. Firstly, widespread participation of heat pump flexibility requires it to be the cheapest way to run a heat pump, whilst currently, it is more expensive. This will have to be taken into account in electricity pricing: the aim of demand response is to reduce system costs, but how this affects the prices for different users will depend on supplier pricing policies which are uncertain. Secondly, high uptake relies on widespread customer acceptance of flexible operation which for many will be remotely controlled. A recent UK survey has shown that half of customers are not currently willing to allow third-party control of heating [51], although this is likely to change over time as flexibility of other domestic loads such as car charging becomes more familiar. Thirdly, flexible heat pump operation must integrate with existing heating systems such that it is not negated or contradicted by control logic elsewhere in the heating system; yet, no stakeholder currently has visibility over this aspect (apart from exceptionally well-informed householders). All of these assumptions and uncertainties require more research.

The above uncertainties, however, need to be balanced against a potentially larger uncertainty regarding the evolution of the energy system in the coming decades. Alternative solutions to provide flexibility are subject to current study, such as vehicle-to-grid and significant grid-scale energy storage, for example using hydrogen. The requirements on—and market for—all storage technologies will evolve and some—such as large-scale hydrogen storage—if ready by 2035, may be able to meet national energy arbitrage needs [52]. However, investment in such solutions sits against an uncertain economic and policy landscape, presenting financial risk. Therefore, assets such as electric vehicles and heat pumps which are already being deployed—where the primary cost is not associated with flexibility, where flexibility potential scales with deployment (and therefore increased need for flexibility), and which can also provide more local grid services—may prove attractive in managing the risk of providing flexibility services at an affordable cost.

4.2. Reflection on the Research Approach

The co-production approach worked well in that the "plurality of knowledge sources" [44] led to different sectors adjusting their expectations for heat pump flexibility. On the one hand, the heat pump and building sectors helped bound the expectations of the electricity sector. Three such examples were the following: that heat pump flexibility cannot be relied upon during very cold days, that it is likely to increase energy consumption, so this must be factored into cost calculations, and that disrupting households' hot water supply may lead them to opt out of flexibility entirely. On the other hand, the electricity sector made a case to the heat pump sector that heat pumps will need to be flexible.

A less-successful aspect of the co-production approach was the workshop participant representation by sector, which was more heavily skewed towards academia and away from industry than intended. A workshop approach meant that although recruitment aimed to represent each sector through quotas, data were collected from whoever turned up on the day; therefore, those who dropped out at late notice (mainly from industry) were not represented. This will have affected what data were collected and the outcomes of discussions on the day. If individual interviews had been used instead of a participatory approach, this would have happened to a lesser extent as recruitment could have carried on until each sector had been adequately represented. However, this would have missed out on the mutual adjustment of expectations described above, as well as the other benefits of research co-production outlined by [49] as "more diffuse and subtle impact on relationships, knowledge sharing, and in engendering culture shifts and research capacity-building".

The demographic make-up of the workshop participants was primarily males in senior roles. This invokes a trade-off: while the participants were key decision makers in the heat pump and electricity sectors—and, therefore, their views were important to capture in order to describe the potential future of heat pump flexibility—they did not represent the full spectrum of stakeholders including end-users.

The summary-of-findings document was sent round participants and agreed upon. This represents an emerging, rather than finalised, common vision of heat pump flexibility and highlights both the areas of consensus and of disagreement. From the perspective of the building blocks set out in Section 2, this emerging vision began to address the 'co-development of solutions' stage whilst highlighting the need to be adaptable due to uncertainties in the evolution of the energy system, energy prices and, therefore, what sort of flexibility will be required.

5. Conclusions

Using heat pumps to shift electrical loads out of periods of expensive and/or constrained electricity has been proposed as a grid management solution and whole-system cost-reduction option in recent years [53,54]. However, as a solution which spans many stakeholders, it has been conceptualised in multiple ways, and different actors have different assumptions about what is possible, cost effective, and acceptable to households. In this work, stakeholders from across the system met for the first time to attempt to co-develop a vision for the role of heat pump flexibility in future electricity systems.

The participants agreed on some key areas: the technical possibility of heat pump flexibility to serve certain electricity system needs and the potential for widespread uptake. However, the financial incentives were less clear, compounded by the concern of the heat pump industry that flexible operation is inefficient way to run heat pumps and that this must be costed in. Participants were also unsure on whether it would be acceptable to the mass market, how to not unfairly penalise those who cannot participate, and who should be responsible for ensuring it works (both from an electricity system and a household perspective).

The co-production approach was found to help stakeholders from different sectors share knowledge and mutually adjust expectations. There is no central 'orchestrator' of heat pump flexibility, and so, progress will occur via many stakeholders developing products which can work together to deliver this flexibility at a lower cost than other forms. Although different countries have different approaches to distributing control across various actors in the system (e.g., flexibility markets, voluntary mechanisms, requirements on Original Equipment Manufacturers, power systems direct-load-control automation), in all countries, there are multiple stakeholders involved, and the co-production approach used in this study could help them align their expectations and plan their future work in this area.

In the UK's case, continued dialogue and joint projects will advance progress through the remaining building blocks set out in Section 2; for example, a workshop for the heat pump and heating system industry on innovation needs for delivering flexibility is planned, which will work to enable the 'co-delivery of solutions' step. Government innovation funding such as the interoperable demand-side response programme [55] has so far led to development of a smart heat pump and other products which link different parts of the system together.

In conclusion, this work has found that there is broad interest in domestic heat pump flexibility across multiple UK stakeholders. Agreement has been established on a number of important issues including what the electricity system needs are, what heat pumps can do to contribute a solution, and what conditions are necessary for heat pump flexibility to become widespread. Areas of disagreement requiring more work have been identified, and bringing this group of stakeholders together for the first time has helped build the capacity to tackle these challenges.

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