Department for
Business, Energy
& Industrial Strategy

Heat Pump Ready: Supporting Information

Background on innovation needs

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Executive summary

Background and method

This Rapid Evidence Assessment (REA) was undertaken by Mott Macdonald and Ricardo Energy & Environment on behalf of BEIS to review the available evidence on heat pump innovation. The findings from the REA may be used to help to identify innovation needs for future innovation programmes in the heat pump space.

The evidence review considered behind the meter and front of meter areas related to: consumers, technology, large scale deployment impacts, business models, the supply chain, and installer or installation issues.

The REA used a defined methodology to review the evidence base on heat pump innovation for the large-scale deployment in residential buildings. The REA used four questions to help focus and guide the research.

1. **Financial Innovations:** What are the necessary financial innovations required to deliver a large-scale roll-out of heat pumps in the United Kingdom (UK)? This includes the state of relevant financing models, and the gaps that exist in this area.

2. **Low Voltage Grid Issues:** What are the Low Voltage (LV) grid issues associated with the concentrated deployment of heat pumps and how can we mitigate these[1]? What is the necessary size of a heat pump cluster to achieve appropriate grid impact learnings?

3. **Roll-out Facilitation:** What are the necessary innovations or learnings required to facilitate the large-scale roll-out of heat pumps? What tools or established processes of stakeholder coordination exist that could support the effective roll-out of heat pumps and are there examples of coordinated deployment?

4. **Performance and Deployment:** What are the technological improvements to the heat pump system and tools that could be developed to support any of the above aims - i.e. the large-scale deployment of heat pumps in the UK?

The REA involved identifying and screening relevant academic and grey literature[2], extracting information and classifying the evidence, analysing and synthesising the results. In total, 1,543 publications were identified. After the screening process was completed, a subset of 136 relevant publications were reviewed by technical experts[3] in domestic heat pump technology, project economics, electricity networks, and technology deployment.

[1] Research on Demand Side Response (DSR) explored how it could lessen grid impacts or avoid grid upgrades rather than its potential as a source of revenue generation.
[2] Grey literature refers to non-peer-reviewed reports / publications. For example, it includes reports published by consultancies or white papers published by organisations.
[3] Technical specialists were used for each question to extract information from the relevant evidence, appraise the evidence, and identify any innovation gaps. Their findings inform this report.

Findings

Question 1 – Financial Innovations

The evidence assessed for Question 1 addressed financial innovations related to large-scale heat pump deployment. The evidence suggests that there is scope for innovative financial approaches to provide financial assistance to cover some of the upfront cost of heat pumps and other energy efficiency measures, with the cost to be recovered in the long-term from the consumer. It also suggests that the consumer experience of heat pump deployment needs to be simplified, potentially by providing a single point of contact (for system design, installation and financing) or outcome-based service.

Models attempting to address these barriers include the successful Property Assessed Clean Energy (PACE) model deployed at scale in North America and being trialled in Europe. PACE funds the upfront costs of energy efficiency and renewable energy measures (e.g. heat pumps) through a secured loan, with costs repaid over a set time period through the owners property tax bill (typically 10 to 20 years). Another model is heat-as-a service (HaaS), which provides the consumer with a heat plan as opposed to charging for fuel use. The relevant literature includes a considerable range of business models, but only a few were found to have been trialled or deployed at scale. Recommendations for future innovation programmes include trials of different innovative finance models at scale in the UK and an assessment of business model suitability for different consumer groups.

Question 2 - Low Voltage Grid Issues

The literature reviewed for Question 2 looked at the research and modelling of the impacts of heat pumps on the electrical grid, solely or combined with other renewable technologies, and strategies to manage those impacts. The findings suggest that in addition to variation caused by the specific technical characteristics of the local low voltage (LV) network, building thermal characteristics and external environment conditions have an impact on the electricity demand from heat pumps, and the number of heat pumps that can be supported.

The impact of heat pump clustering and the effectiveness of flexibility to manage heat pump impacts are heavily dependent upon the building fabric performance and the environmental conditions, as well as how the strategies are implemented.

The evidence reviewed emphasises that each low voltage feeder is unique with regards to how it is loaded, with some feeders handling 100% heat pump penetration while others may only be able to handle lower levels of heat pump penetration. The loading in cold winter periods, when heat pump efficiency is reduced also needs to be assessed.

This research area would benefit from a greater supply of trial data and a closer look at how to mitigate the causes of grid impacts. Common suggestions include energy efficiency improvements, the combining of systems with energy storage and load shifting through demand side response and aggregated load control. Load shifting however, is challenging and further innovation is required in this area to deliver a strategy for supply flexibility that limits the impact on the grid whilst also benefiting customers.

Question 3 - Roll-out Facilitation

The literature reviewed for Question 3 looked at the evidence regarding innovations and learnings required to facilitate a large-scale rollout of heat pumps and associated technologies. The primary conclusion is that for a large-scale heat pump roll-out to be effective, the coordination between stakeholders is a primary challenge to be addressed. A consumer-focused framework which considers area characteristics that define the stakeholder engagement strategy may lead to increased take-up. This could include aspects on how to identify, engage, and coordinate, resources, and information flow between stakeholder groups.

Building on this, to help support data flows between stakeholders and devices, the reviewed literature highlights opportunities from the digitalisation of home energy services, supported through the genuine interoperability of the systems employed. Digitalisation will only be realised through the development and successful integration of smart controls into households. This process requires coordination at various stages within the supply chain. To aid the development of smart controls, modelling and forecasting tools can be used in conjunction with trials, in order to provide a low regret means to designing a nationwide rollout scheme. Potential areas of focus for trials include, but are not limited to: local area energy modelling, which can support development of localised, smart energy plans; forecasting of financial models; and low-carbon heating solutions that consumers actually value. Any such trial of tools should be designed to inform decisions through accurate, wide-spread data collection and sharing, and be utilised to find appropriate platform upon which these tasks can be delivered in a user-friendly, repeatable, and reliable way.

The themes identified by the REA in relation to the roll-out facilitation, should be considered holistically. The success of each subject identified is dependent upon the success of the others, highlighting the necessity for a coordinated framework incorporating all items raised. Innovation demonstrations or trials could be an important, controlled step in defining this framework methodology.

Question 4 - Performance and Deployment

The evidence assessed for Question 4, addressed the heat pump performance gap, technical improvements that could be made to the heat pump system, and tools to aid their deployment. Whilst there do not appear to be any housing archetypes which are unsuited to heat pumps, the characteristics and performance of individual properties may vary. The research indicates that innovation to increase the repeatability of the performance of heat pumps would be of significant benefit in increasing heat pump deployment. This includes innovative tools for system design, a more modular approach to heat pump systems, innovations to allow heat pumps to operate at lower temperatures in heating mode, to develop plug and play software and to improve user interfaces. The evidence also suggests that monitoring of heat pump systems is a way of identifying systems where there is a performance gap and identifying remedial action. Innovations to make this monitoring and optimisation more automated could be of significant benefit.

There was little evidence identified associated with specific tools available to aid deployment. This highlights the need for further innovation to be focussed in this area.

Table 1: Summary of recommendations for further innovation

Research Question	Recommendations for future innovation
Question 1 – financial innovations	Trial different finance business models at scale (for example: prosumer business models, heat pump rental models, one-stop-shops, heat-as-a-service, pay-for-performance models, on-bill financing, and PACE financing mechanisms) to understand how effective they are and identify the models most suitable for different consumer profiles.
Question 2 – low voltage grid issues	Gather in-situ trial data on the impact of concentrated heat pump deployment on the low voltage grid (with a heat pump penetration level of >20%). Future trials to look at how mitigation measures, such as the combining of systems with energy storage and flexible load management, can reduce the impact of heat pump roll out on the LV grid.
Question 3 – roll-out facilitation	Develop tools, methodologies and frameworks to aid the coordination effort across local and national stakeholders (i.e., homeowners, installers, finance providers, local authorities, community groups, electrical network operators etc). Trials and innovation activity that consider all aspects holistically/simultaneously are particularly important.
Question 4 – performance and deployment	Gain a better understanding of how the gap in heat pump performance will benefit from the ongoing monitoring, control and optimisation of individual systems and how innovation, such as 3D printing and modularisation, could help reduce the cost and deliver repeatable as-designed performance levels. Trial different methods of optimising heat pumps post-installation and understand whether interventions such as guidance or regulations could reduce the performance gap.

1 Introduction

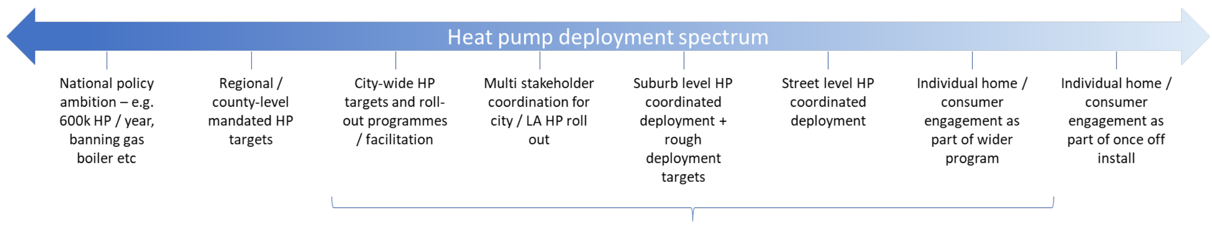
1.1 Background

This Rapid Evidence Assessment (REA) was designed to provide an understanding of the existing evidence base on heat pump innovation in the United Kingdom (UK) and internationally as well as identifying the gaps in the research. The approach provided a systematic search and quality assessment of the publicly accessible evidence following a defined methodology to gain an understanding of the volume and quality of evidence on a particular issue. This may be used in scoping future innovation programmes as well as supporting any future research.

The REA began in May 2021 with an initial search of publicly accessible relevant literature using search terms related to the research questions below. As part of this process the evidence was screened to ensure it met search parameters and could be defined as relevant. This was followed by the extraction of evidence and a critical appraisal by technical specialists[4] in the relevant fields before they synthesised their findings.

The review included behind the meter and in front of the meter areas[5] related to consumers, technology (the grid as well as electric heating), large scale deployment impacts, business models, the supply chain, installer/installation issues and markets. The scope of heat pump deployment covered by the REA is defined in Figure 1.

Figure 1: Scope of the REA



1.2 Research Questions

The following research questions have been designed to help focus and guide the REA:

1. Financial Innovations: Unlocking the necessary financial innovations required to deliver a large-scale roll-out of heat pumps in the UK.
    a. What is the state of relevant financing models and examples of (consumer and supply chain) finance solutions being deployed on scale?

[4] Technical specialists were used for each question to extract information from the relevant evidence, appraise the evidence, and identify any gaps. Their findings inform this report.
[5] "Behind the meter" refers to anything that happens on the energy user's side of the meter, whilst anything that happens on the electricity supply side of the meter is "in front of the meter".

   b. What gaps exist to fully internalising the benefits of heat pumps and heat pump clusters through financial products and consumer offers?

2. Low Voltage Grid Issues: Determining the Low Voltage (LV) grid issues associated with concentrated deployment of heat pumps and how we can overcome these?[6]
   a. What is the necessary size of deployment of a heat pump cluster to achieve the appropriate grid impact learnings?
   b. How can we mitigate grid impacts?

3. Roll-out Facilitation: How can we facilitate the large-scale (often concentrated) roll-out of heat pumps - what are the necessary innovations or learnings?
   a. What existing tools or established processes of coordination (between the many stakeholder involved) could support in the effective roll-out of heat pumps?
      i. These include the necessary technical, consumer, and installer tools (e.g. heat mapping software, installer tools, building models).
      ii. Are there examples (anywhere in the world) of this kind of coordinated deployment?
      iii. This includes how the coordination between the different stakeholders should be set-up (e.g. Local authority lead, energy supplier lead, Distribution Network Operator (DNO)/Distribution System Operator (DSO) lead), who shares what data etc.

4. Performance and Deployment: What are the technological improvements to the heat pump system (i.e. includes thermal store, heat distribution system etc) and tools that could be developed to support any of the above aims - i.e. a large-scale efficient roll-out of heat pumps in the UK?
   a. Part of this should also look into technological performance improvements that could be made (that realistically could be deployed in the UK within the next ~3 years).
      i. Perhaps looking at the way other countries structure their heat pump systems would be useful in this regard perhaps they use a greater degree of thermal storage etc.

[6] This REA was not interested in Demand Side Response (DSR) as a potential source of revenue generation (e.g., as part of a business model using time of use (ToU) tariffs), but in how DSR could lessen grid impacts or avoid grid upgrades.

ii. Are there any tools that have been developed that will assist in the deployment of heat pumps?

Regarding questions 3 and 4 the focus of the research was on overcoming the practical barriers to a large-scale roll-out of domestic heat pumps rather than on the theoretical aspects of improving heat pump technology, or on modelling their uptake or impact. A desired outcome of the REA was a set of "learnings" from other countries experiences of heat pump roll-outs.

1.3 Overview of the Research Methodology

An overview of the REA methodology is presented in Figure 2. An initial keyword search was conducted in a publicly accessible search engine to identify relevant academic and grey literature for screening. The library referred to in Figure 2 is stored in the Zotero™ reference management tool[7]. The extraction and classification, analysis and synthesis, identification of gaps was undertaken by technical specialists with detailed knowledge of domestic heat pump technology, project economics, electricity networks or technology deployment.

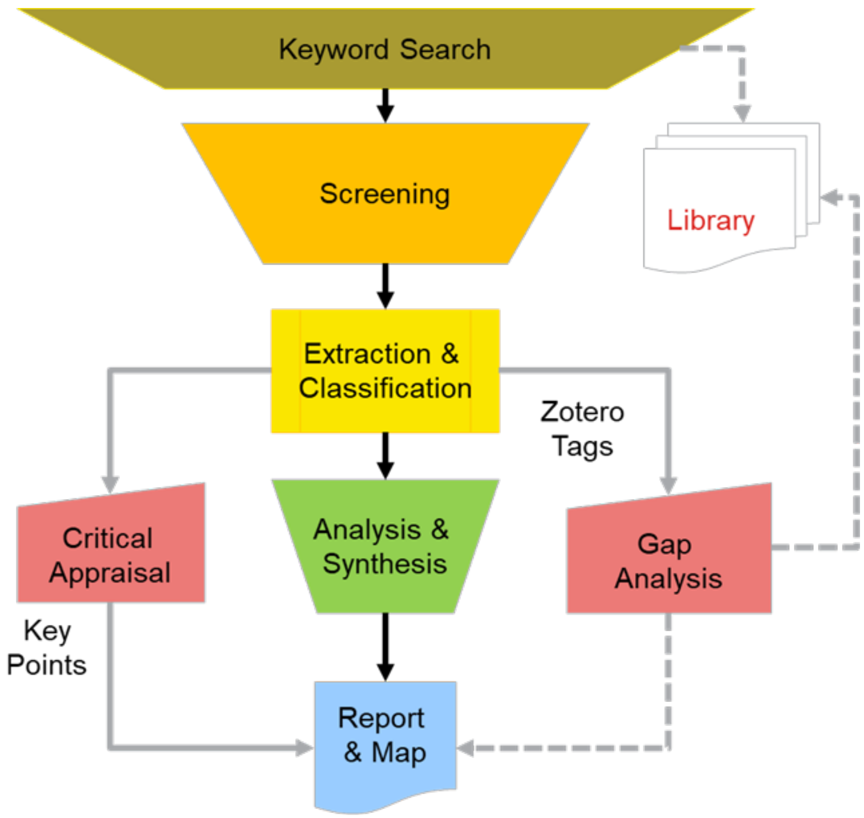


Figure 2: Overview of the REA methodology

[7] Zotero is an open-source reference management tool that was used to collect, organise and share research between research team members in different organisations and locations. Zotero is a registered trademark of the Corporation for Digital Scholarship.

1.4 Screening the Search Results

Once the Review Team completed the initial search for material, a screening session took place to outline the most relevant/reliable sources of information. This was undertaken by following a set of predetermined inclusion and exclusion criteria:

- Geographical references: UK, Northern Europe, Canada, USA, Japan, New Zealand. The geographies were selected in consultation with BEIS based on similar climate, published a considerable number of peer reviewed papers on the application of heat pumps and/or were known to have a significant installed base of heat pumps.
  - Business models from a broader geographical area were also considered.
- Language restrictions: only evidence published in English was used.
  - Literature that appeared key but was in another language was flagged for potential follow-up/translation.
- Date restrictions: only evidence from after 2011 was accessed.

1.5 Approach and Report Structure

An "open book" approach was adopted in which specialist reviewers were invited to propose additional publications that could fill the gaps in the evidence base. These publications were reviewed by the research team and quality assured before inclusion. This approach was adopted to ensure that the results of more recent research work were included in the evidence base.

This report includes a synthesis of the literature appraisal, discussion of findings, identification of the key research gaps, and recommendations on how the gaps can be addressed (e.g. technical research, demonstration project, policy intervention).

The detailed methodology used for this REA can be found in Appendix A and a full bibliography of literature reviewed by the technical experts can be found at the end of the report.

2 Evidence Statements

2.1 Overview of Findings

Following final classification of the literature, a quantitative analysis of the evidence base yielded the following insights:

- The evidence base collated for Question 3 (roll-out facilitation) contains the highest number of publications (442/1,543) and Question 1 (financial innovations) the lowest (181/1,543).
- Question 2 (low voltage grid issues) had the highest number of publications reviewed by a technical specialist (45/136) and Question 3 the lowest (21/136). The screening process defined the majority (over 90%) of publications as not relevant for all questions.
- Most of the publications reviewed by the technical specialists were written by academics (85/136) located in the United Kingdom (63/136) or Northern Europe (37/136), with none of those reviewed being from Japan or New Zealand.
- The scale of heat pump deployment was not specified in over half of the publications reviewed (75/136). Of those publications specifying a scale of deployment, over half defined it as a regional scale (37/136).
- The relevant evidence did not feature a large number of heat pump trials. Those that were included mostly involved a small number (<100) of installations (20/136).

A more detailed quantitative analysis of the evidence base can be found in Appendix B.

2.2 Question 1 – Financial Innovations

The review for Question 1 addressed the state of finance and business models for heat pumps and includes some examples of their deployment at scale. The assessment also identifies gaps that will enable the benefits of heat pumps and heat pump clusters to be fully realised through financial products or consumer offers.

In total, 30 publications were reviewed by the technical expert for Question 1. Detailed evidence statements from the publications reviewed by the technical experts can be found in Appendix C1.

2.2.1 State of the Art Summary

An assessment of the evidence identified the following widespread key barriers to large-scale heat pump deployment:

- Affordability: the high cost of heat pumps.
- Lack of availability: lack of a strong market presence.
- Lack of awareness: of systems and benefits by households and the industry.
- Acceptance: heat pumps are perceived to be harder to install and use.
- Consumer willingness: resistance against potential disruption during installations.
- Consumer behaviour: demanding and using heat as if it were being produced by fossil fuel boiler.
- Long-term demand: lack of certainty required for investors and businesses.

The evidence base presented several different financial innovations that attempt to address the barriers to the large-scale deployment of heat pumps. These include **prosumer business models[8], heat pump rental models, one-stop-shops[9], heat-as-a-service, pay-for-performance models[10], on-bill financing[11], and PACE financing mechanisms** (which are long-term financing repaid through property taxes). Relevant findings related to these financial innovations are summarised below.

The **prosumer business model** is for consumers who produce and consume electricity with benefits from offsetting their consumption and or receiving a payment for exporting to the grid (Brown et al., 2019). This model is only applicable if a heat pump is coupled with energy production (e.g., solar photovoltaic) or storage (e.g., thermal storage), which will result in a higher initial cost. The **rental business model** removes the need for the consumer to cover the upfront costs of energy efficiency measures and can provide an all-inclusive service for the occupant for a monthly fee (Nelson, 2019).

Another example of an all-inclusive service is the **one-stop-shop model**, which provides a single point of contact for covering all the necessary steps to install a low carbon heating system and associated measures (e.g. design/system choice, financing, installation, maintenance etc.). This model can reduce information asymmetry (i.e. any one party in the supply chain / install process taking advantage of another due to the lack of information or insight), the time to install and potentially costs through a more integrated and efficient supply chain (Holland et al., 2019; Walker et al., 2021). Examples include the Saint John Energy programme (Nelson et al., 2019) in New Brunswick, Canada, and the SuperHomes 2030 project (Auvray et al., 2021) in Ireland.

[8] A prosumer is a consumer that both produces and consumes energy.
[9] A one-stop-shop model is where there is a single point of contact for the customer that integrates financing, project management, design and support services.
[10] Pay for performance uses energy bill savings to pay providers for energy efficiency upgrades.
[11] On-bill financing covers the upfront cost of efficiency measures with a loan repaid through the utility bill.

Heat-as-a-service (HaaS) is another business model being trialled in several different locations, including the UK. This model offers a heating plan and service charged periodically, resulting in cost certainty for the consumer (Holland et al., 2019). A potential barrier to this model is the ability of consumers in the UK to switch energy providers, as the service is designed to be paid off over the long-term (Brown et al., 2020; Britton et al., 2021). HaaS is also limited by current market regulations in the UK and may require supportive policies[12], as well as more research and innovation to be a success. This could include ensuring that smart devices and data are interoperable and secure, so that different systems are compatible, and data can be shared (Hardy and Mazur, 2020).

An example of a HaaS trial is the Smart Systems and Heat Phase 2 (SSH2) programme (Holland et al., 2019). This trial found that the use of a heat plan provided a clear benefit for participants by providing cost certainty. The trial also found consumers more readily supported a flexible HaaS energy plan that allowed them to change the terms of service when they understood how it provided financial savings. HaaS will require increased collaboration between trusted industry partners on a local basis to be deployed successfully. More work is required to demonstrate if the service can be made commercially viable.

Further HaaS trials have taken place in Bristol (Bristol Energy) and Nottingham (Energiesprong Initiative) as reported by Marques et al., (2019) and Brown et al. (2020). Both of these trials have focused on social housing and aim to improve occupant health and wellbeing while also providing energy savings. The analyses of these trials concluded that more trials are needed to address consumer concerns and lack of understanding of HaaS, more supportive HaaS policies are required, and there also the need for further integration across supply chain stakeholders to enable HaaS.

The **pay-for-performance business model** is similar to HaaS, as it places the risk of poor performance on the provider. This model uses energy bill savings to pay providers and supports careful selection and implementation of the efficiency measures as well as quality control (Nelson, 2019).

Business models deployed on a larger scale in North America include **on-bill financing**, which covers the cost of measures through a long-term loan repaid through the utility bill. Nelson (2019) considers this model to be effective, as loan repayments are made by the occupiers and can be transferred to future tenants. Walker et al. (2021) criticise this model as it can be difficult to transfer the loan between homeowners and places financial risk (e.g., the risk of default) on the consumer.

The **PACE financing mechanism**, deployed at scale in the US and Canada, allows a homeowner to finance the up-front costs of measures including heat pumps (Nelson, 2019; Walker et., 2021). The loan is often attached to a property (using an asset backed security) and repaid through property tax levies, making this model suitable for owner occupiers. Several European countries are developing feasibility studies based on this model (i.e., Euro

[12] There are strict consumer regulations that protect the ability for consumers to switch energy suppliers (ideally HaaS operates with a single supplier). Also, supply Licensing conditions and tariff rules tend not to be supportive of HaaS.

PACE programme) (Vaze et al., 2020). A recommendation for the Euro PACE programme, and more generally business models for heat decarbonisation, is **demand aggregation financing**. This model aggregates demand (i.e., retrofitting multiple homes in a given location at the same time) to increase the savings per unit with measures funded through low-interest loans, purchase agreements (Kircher and Zhang, 2021), or energy service providers (Holland et al., 2019). The latter aggregate their service to sell consumer flexibility to energy markets, which offsets the customer's bill.

The evidence base suggests that an important measure to help overcome the initial barriers and increase demand is the use of **government and private funded incentives**. This is important due to the current price difference between natural gas and electricity (Nelson et al., 2019), the higher cost of heat pumps versus fossil fuel alternatives (Lowes et al., 2021), and the need to support low-income households. The cheaper cost of gas was cited as a significant challenge in a publication reviewed by Singh Gaur et al. (2021).

Research also suggested that it will be important to explore **regulatory changes to better facilitate innovative business models (e.g. allow companies to charge for a heat outcome rather than a certain number of kWh), and to ensure that business models work for consumers in all situations** (Hardy and Mazur, 2020).

2.2.2 Critical Appraisal of Evidence for Question 1

While the level of confidence in the findings for Question 1 is high as the evidence is informed by several robust publications, the consistency of the evidence is mixed with studies using different methods in a variety of different contexts. **There is a convergence on the need to spread the cost of heat pumps (and other energy efficiency measures) over time, but there is less agreement on which financial innovation should be used.**

2.3 Question 2 – Low Voltage Grid Issues

Publications reviewed for Question 2 looked at the causes of LV grid issues caused as a result of using heat pumps, the levels of heat pump penetration (the proportion of homes on that network with a heat pump) where LV grid issues become evident, and the effectiveness of flexibility measures such as Demand Side Response (DSR) in mitigating these issues. LV grid issues are defined in this case as for example causing voltage problems, and overheating of the infrastructure, resulting in protection measures being triggered.

In total, 45 publications were reviewed by the technical expert for Question 2. Detailed evidence statements from the publications reviewed by the technical experts can be found in Appendix C2.

2.3.1 State of the Art Summary

Research indicates that the level of heat pump penetration on an individual LV network that can be accommodated before LV grid issues are realised, varies depending on the technical characteristics of the LV network, the building fabric, environmental factors and how the systems are used. It should be noted however, that **few papers use in-situ trial data on the impact of heat pumps or discuss how to mitigate the causes of grid impacts**.

The building fabric characteristics, are highlighted in a number of publications as being a key factor in how much power is required to run the systems and in turn the impact on the grid. Buildings with a poor **fabric energy efficiency** (poorly insulated and a high rate of heat loss) significantly increase the LV grid issues associated with the use of heat pumps (GLA, Etude, 2018, Belton et al, 2014). This factor comes into sharper focus as a result of the **environmental condition**. During the winter period, heat pumps draw a higher electrical load, which coupled with the **simultaneous nature of the heat pump operation**, creates a significant peak relative to seasonal differences seen on LV networks which do not serve heat pumps. This leads to significantly more headroom being required on the wider network (not just the local LV network) to account for these peak conditions. Improving the fabric performance of buildings will dramatically reduce these grid impacts and can result in a peak electrical demand that is up to 50% lower (Pena-Bello et al. 2021).

Regional factors are also shown to influence the level of grid impacts, and aside from environmental conditions, rural feeders are also shown to be more prone to issues (Protopapadaki et al, 2017)

The literature that reviews the **technical aspects of the LV network,** highlights that cable and transformer rating, type and size, as well as the general load profile significantly influence the impact from loading and voltage issues. As each LV network is different, each LV network will respond differently as heat pump penetration increases (Bilton et al, 2014).

With all of the above variables, it is clear that different LV networks will react differently to different levels of heat pump penetration. While some feeders can handle 100% heat pump penetration, some grid issues have been modelled or realised at very low penetration levels. For example, during the winter peak, some LV grid issues have been realised at heat pump penetration levels of 5% (Bilton et al, 2014). Some publications identify a general level of **heat pump penetration of >20%** as being the point at which LV network issues could become noticeable (Navarro-Espinosa et al, 2016; Bilton et al, 2014).

With regards to the implications of clustering and flexibility in the use of the electrical supply, (such as Demand Side Response (DSR), aggregated load control, and other short and long period flexibility measures), effectiveness again is heavily dependent upon the building fabric performance and the environmental conditions, as well as how the strategies are implemented.

The use of flexible supply strategies alongside heat pumps produces mixed results, including higher peaks and congestion at low-tariff periods (Mata et al, 2020), overheating and noise concerns during low-tariff periods, and also higher than expected consumption during the high-tariff periods[13] (Sweetnam et al, 2019). High levels of heat loss from the home and a low thermal inertia, limit how long a heat pump system might be able to ramp down before levels of comfort in the home are affected. This reaches a point where flexibility in supply is not effective

[13] These higher than expected peaks were partly due to participant intervention and partly due to the physical nature of the dwelling and heating systems.

(Delta Energy and Environment, 2018; GLA, Etude, 2018). However, a number of publications have suggested effective use of DSR with heat pumps accompanied by thermal storage and photovoltaics in buildings with a high fabric performance (Rinaldi et al, 2021). Previous trials have found that in most cases demand can be shifted by approximately 1 hour by using the thermal inertia of the building fabric (Greater Manchester Combined Authority, 2017).

To enable the provision of flexible services to the grid requires the deployment of **effective metering and controls infrastructure** for measuring and billing based on hourly or half-hourly consumption. The users' engagement is another important factor of DSR. Aspects of the **ease of use of the control system** were shown to be important in determining participants' attitudes towards using it. Effective user control also improved performance through the use of smarter Model Predictive Control (MPC) strategies in place of simpler Rule Based Control (RBC) strategies[14] (Péan et al, 2019).

From a grid management point of view, the effectiveness of network flexibility and DSR will depend on the control objective (e.g. if the objective of the control function is to minimise costs, energy costs will need to be known). This will require data to be collected from homes (e.g. heat pump efficiency, external temperature, building thermal characteristics and electric consumption of buildings) and made available to optimise how the control is implemented. The occurrence of conflicting DSR requests from the balancing responsible party (e.g. National Grid), the distribution network operators and their impact on the availability of DSR is also a question that remains (Delta Energy and Environment, 2018). The simultaneous nature of the way the heat pump systems function represents a significant change in how networks operate and in turn represents a significant challenge to how they are designed and managed going forward that will require significant innovation (Protopapadaki et al, 2017).

2.3.2 Critical Appraisal of Evidence for Question 2

The level of confidence in the findings of the REA for Question 2 is medium to high, as they have been informed by several robust publications with high quality methodologies, albeit with a lack of field data on large scale trials. The consistency of the evidence is also medium to high with studies using similar methods to look at the grid challenges. There is convergence on the need to improve the level of monitoring of both homes and network equipment and increase the understanding of how the heat pumps will work in practice.

2.4 Question 3 – Roll-Out Facilitation

The evidence for Question 3 is focused on innovations or learnings that will help facilitate the large-scale roll-out of heat pumps and associated technologies. Relevant publications discuss previous large-scale heat transformations; established physical / analytical tools, or processes,

[14] RBC are simple heuristic methods which generally have the form "if (condition is verified), then (action is triggered)". MPC is a more complex optimization problem strategy, which relies on a model of the building to project its behaviour in the future.

that would be necessary for successful deployment; and how coordination between the various stakeholders should be managed.

In total, 21 publications were reviewed by the technical expert for Question 3. Detailed evidence statements from the publications reviewed by the technical experts can be found in Appendix C3.

2.4.1 State of the Art Summary

The evidence reviewed is limited in providing explicit commentary on the design of a coordination framework / methodology between the different stakeholders, that is specific to a UK-wide rollout of heat pump technologies. Nevertheless, required actions and key themes can be inferred, and examples can be found of relevant pilot studies within the UK. However, for the main part, these studies comment only on the importance of coordination, and instead focus more predominantly on the technological, financial, and social aspects of low-carbon heating.

It is worth noting that previous examples of large-scale deployments of heating transitions in the UK, namely gas central heating, can offer a local example of the type of coordination effort that is required, albeit with adaptions required for low-carbon technologies. Further, the saturation of heat pump technologies across Finland presents a solid case study (Sovacool and Martiskainen, 2020). In both cases, the rollout was facilitated by the development of relevant policies, engagement programmes, certification and standards, and new market structures (Lowes et al., 2021); learnings from these case studies have been synthesised in the summary below.

It has been noted throughout the literature that for a large-scale heat transformation to be effective, the coordination between stakeholders becomes the primary aspect worth considering. This point has been discussed directly (Lowes et al., 2021; Greater Manchester Combined Authority, 2017), as well as being inferred several times, in publications that looked initially to analyse other important factors (Auvrey, 2021; Sovacool and Martiskainen, 2020; Western Power Distribution, 2019; Energy Systems Catapult, 2019; Lowe et al., 2017; Frontier Economics, 2013). A consumer-focused framework which considers area characteristics that define the stakeholder engagement strategy may lead to increased take-up. This could include aspects on how to identify, engage, and coordinate, resources, and information flow between stakeholder groups. This ensures that the transition is smooth and offers the necessary consumer protection (Lowes et al., 2021); provides opportunity for challenges to be quickly identified and operational resources to be reallocated accordingly (Greater Manchester Combined Authority, 2017); and minimises cost and disruption to consumers (Scottish and Southern Electricity Networks, 2021).

Irrespective of the type or focus of the study, the literatures point towards the benefits of taking one of two approaches. The first should be a **consumer-centric** approach to aspects of design and deployment, that could ultimately influence consumer satisfaction (Auvrey, 2021; Sovacool and Martiskainen, 2020; Energy Systems Catapult, 2019; Western Power Distribution, 2019; Snape et al., 2015). The second should be a **place-based** approach to aspects that are in some way affected by their locality; this could be in relation to, but not limited to, types of building stock, demographics, climatic and geographic considerations, and local regulations (Auvrey, 2021; Owen at al., 2013).

The themes that have arisen from this process, and that are deemed important for the future design of a large-scale roll-out of heat pumps are presented below.

There exists a significant requirement for the **digitalisation** of home energy services. This would, amongst other benefits, afford the consumer a greater level of transparency regarding their billing and metering information (Auvrey, 2021), which in turn can reveal customer preferences and aid in system design (Energy Systems Catapult, 2019). Additionally, a better understanding of the performance gap would be ascertained, which would inform and hence improve the effectiveness of deployment (Lowe et al., 2017). Digitalisation cannot, however, be met by a myriad of conflicting control systems, the benefits of this market transformation are realised through the genuine interoperability of the systems employed (Energy Systems Catapult, 2019). This would ultimately allow, amongst other aspects, more detailed and accurate billing and energy use information to be provided to the consumer (Auvrey, 2021), a requirement for improved consumer satisfaction; the seamless and remote collection of usage data (Energy Systems Catapult, 2019), and high-quality monitoring, a means to improve the effectiveness of all future pilot studies (Lowe et al., 2017). Digitalisation will be realised through the development and successful integration of smart controls into households (Lowe et al., 2017), a process that requires coordination not only during installation, but equally, during the manufacturing stages of the systems (Auvrey, 2021). Failure to integrate control and monitoring systems effectively increases consumer disruption and dissatisfaction, reduces system efficiencies, and hinders future schemes and technological developments, which benefit from data collection. (Auvrey, 2021; Energy Systems Catapult, 2019; Lowe et al., 2017).

Modelling and forecasting tools that help predict short- and medium-term local area energy demand as well as devise financial services (such as HaaS) would benefit significantly with the advent of new data collection techniques. This data collection would be on the back of the digitalisation of home energy use; the collection of energy usage data hence becomes imperative (Energy Systems Catapult, 2019). Further, these modelling tools can and should be used in conjunction with trials, to provide a low regret means of designing a nationwide heat pump roll-out scheme. It was noted during the analysis that monitoring can provide a better understanding of the performance gap, in turn allowing for more effective design specification (Lowe et al., 2017). It can additionally provide a means to design, model and test financial mechanisms (Western Power Distribution, 2019; Greater Manchester Combined Authority, 2017) and new policy interventions (Frontier Economics, 2013).

The importance of **trials** cannot be understated (Greater Manchester Combined Authority, 2017). The justification for this statement can be found amongst the suggested actions of the majority of the referenced literature, as the vast majority of the papers herein suggest further trial periods / pilot studies would be required to develop their conclusions. The output of trial programmes, if successfully designed and coordinated, provides benefits to many stakeholder groups. For example, manufacturers and researchers benefit from so-called ‘research sites’ that are used to develop relevant technologies (Auvrey, 2021).

Further, governmental trials can be used to develop and set design standards involved in all relevant aspects of a low carbon heat transformation; this in turn may need to be backed up by the tightening of Building Regulations (Lowes et al., 2021; Sovacool and Martiskainen, 2020) and certification schemes for installers and manufacturers (Western Power Distribution, 2019).

Pilot studies can also be used to document the effects of **targeted policy intervention**, either of a single new policy (Energy Systems Catapult, 2019), or preferably, a framework of policies that can act to engage in a more coordinated sense, across social, environmental, and economic drivers, in the interest of successful deployment and cost effectiveness (Frontier Economics, 2013). It is worth noting that for digitalisation, a key identified theme within itself, the extent to which it may be realised at scale may be influenced by relevant policies which act to both stimulate the market and provide a framework for their integration into the wider energy network, i.e., the integration of home heating within a decarbonised built environment (Western Power Distribution, 2019).

2.4.2 Critical Appraisal of Evidence for Question 3

The level of confidence in the findings of the REA for Question 3 is medium to high. Some publications were seen to have high quality methodologies, but the relevance of the evidence, for the main part, is not totally specific to the question. The consistency of the evidence is mixed with studies using different methods in a variety of different contexts. Despite this, the evidence base was consistent in the themes that arose during the analysis, with many papers tending to reach similar conclusions towards similar conclusions and suggesting similar future work. For this reason and considering the varying angles that researchers have previously investigated this problem, it is encouraging to note the similarity in conclusion, this in turn giving confidence in the findings.

2.5 Question 4 – Performance and Deployment

Question 4 provides evidence on technical improvements that could be made to the heat pump system and introduces tools that exist or could be developed to support the roll-out of heat pumps. The evidence base also explores how heat pump systems may be structured outside of the UK.

In total, 40 publications were reviewed by the technical expert for Question 4. Detailed evidence statements from publications reviewed by the technical experts can be found in Appendix C4.

2.5.1 State of the Art Summary

The performance gap represents the projected performance of a heat pump system compared to their actual performance. Studies found that there are installation performance varies. This suggests that innovations which allow existing heat pump technology to perform in a more repeatable way could be of significant benefit in closing the gap.

Publications discussing the performance gap show progress can also be made to close it through monitoring, analysis, problem identification, installation of remedial works, and subsequent verification through ongoing monitoring (Heat Pump Centre, 2020). Carefully designed and installed systems achieve good performance (Dunbain and Wickins, 2012).

This could include measures such as:

- Easy to use modelling tools to design and specify systems more accurately.
- System elements such as hot water cylinders or buffer tanks could be **pre-plumbed** or **integrated** into heat pump enclosures.
- **Modular heat pump systems** whereby all elements of a system are available from a range of modules to be connected together to form a complete and working system.
- **Open source control systems** that can link different products, with user interfaces which are easier to understand and avoid incorrect operation practices.
- Plug and play heat pump systems which require fewer adjustment to settings at installation, commissioning and operation, including control of defrost cycles.
- **Monitoring systems** which identify problems and then alert the user or installer.

In addition, the reviewed evidence indicated there are technology innovations which could further improve heat pump performance:

- Improvements to the thermal performance of the building envelope; and heat emitters that provide higher heat outputs at lower flow temperatures.
- Increased use of buffer capacity to avoid short cycling, speed control of circulation pumps to minimise energy usage and ensure water flow rates allow optimum heat pump performance.
- Digitisation and integration of control systems so that separate control systems can communicate and optimise overall performance.
- Development and deployment of machine learning and **Artificial Intelligence (AI) algorithms** to improve monitoring systems .

Some specific factors were identified in the literature for which these innovations could be important in addressing. It was found factors such as above average compressor modulation and compressor cycling have a negative effect on Air Source Heat Pump (ASHP) performance due to component stressing and high start-up currents. One study stated that data showed energy consumption for defrost cycles should be around 1% of total annual energy consumed for a well-designed and installed heat pump system, even after considering variations in external temperatures (O’Reilly et al., 2019).

Analysis of data from the RHPP scheme shows median SPF (H2 boundary[15]) of air source heat pumps of 2.65 and ground source heat pumps of 2.81. It stated, "a wide distribution of seasonal performance factors (SPF) was observed." Reasons for this included measurement error and real differences in efficiency (Lowe et al., 2017). There was no single factor that accounted for good or poor performance and statistical analysis showed fewer clear results than could be expected. The one factor identified which could have an effect on the SPF (H2) is that a large proportion of ASHPs have 10 minute on-to-on cycling patterns. This is consistent with other studies which observed a range in heat pump SPF in real installations in the UK domestic.

Monitoring of low carbon buildings in other countries show that higher heat pump performance can be achieved than those given above. In many projects, SPF values in the range of 5 and higher are reached over multiple years (Heat Pump Centre, 2020). This indicates the level of performance that is possible when heat pumps are installed in high-performance buildings, and are optimised through monitoring and remedial work where required. **Several studies suggest that there is not one overriding factor that affects heat pump performance, but more careful design, installation, commissioning, and operation are all required to ensure a high-performance system.** Studies suggest it is always important to:

- Maximise the source temperature at the heat pump evaporator inlet.
- Minimise the temperature at the heat pump condenser outlet.
- Minimise the energy used by secondary equipment.

Some heat pump systems were found to be using electric immersion heaters as a means of increasing the hot water temperature for legionella control. Where this is the case, the improper set up of the controls for immersion heaters was found to be a reason for increased electricity consumption.

While a wide range of remedial actions have been suggested by different studies (such as increasing the source temperature and minimising interruptions in the heat pump cycle), in some cases the remedial actions and resulting advice is contradictory between studies. Publications with recommendations on how to close the performance gap were largely based on monitoring a small number of installations (Dunbain et al., 2013; Lowe et al., 2017; Hughes et al., 2018). Furthermore, the evidence base contains few results from recent UK trials in domestic properties.

Publications reviewed were found not to assess to a significant extent which tools will assist in the deployment of heat pumps. However, a number of barriers were encountered by real world trials, such as the properties not being suitable for heat pumps, householders considering the works required to install a heat pump system to be too much disruption or delays associated with assessment of network reinforcement requirements for large scale heat pump rollout

[15] The SPF H2 boundary evaluates the performance of the refrigeration cycle and includes the source-side circulation pump.

(Caird, Roy and Potter, 2012). Tools to identify areas where network reinforcement will be required could be of importance to the deployment of heat pumps in clusters.

There was research observed into specific modelling methods, however this focused on the advantages, disadvantages, and accuracy of the modelling algorithms themselves rather than the user interface and widespread use (Dott et al., 2013).

The evidence indicates that the optimisation of heat pump systems is currently largely dependent on the individual skills, knowledge, and quality assurance processes of design, install and maintenance contractors.

One paper was found to provide a comprehensive list of topics for further research and innovation to support the deployment of heat pumps at scale. (RHC-ETIP and EHPA, 2021). This includes innovations on design such as to increase the modularity of heat pump systems; optimise source and sink systems (in particular their temperatures and energy consumption); increase ease of connection to other technologies and storage media. With regards to manufacturing, the paper suggests that new computer modelling simulation tools to provide a flexible, user-friendly interface to overcome design challenges and create more efficient systems as well as to mass production and **3D printing of components** such as heat exchangers, could be of benefit. The paper considers other aspects where there is the potential for research and innovation to provide significant benefit, and which would be relevant to the deployment of heat pumps. These include: to improve the robustness of the supply chain; plug and play software and hardware to improve ease of installation; improvement of maintenance and operation via better user interfaces (UI); the deployment of **Internet of Things (IOT) connectivity** for data gathering; **AI algorithms for optimisation**; and predictive maintenance.

The evidence suggests that while there have been trials into improving the performance of heat pump systems, there are many innovations which could facilitate large-scale deployment but are not yet at the stage of large-scale in-situ trials.

2.5.2 Critical Appraisal of Evidence for Question 4

Medium confidence has been assigned to the findings for Question 4, as while the evidence statements are informed by a number of publications with robust methodologies, the consistency of the evidence is mixed as there is no real convergence on the causes of the performance gap or the remedial actions and some contradictions. However, there is some agreement that performance issues and solutions differ between installations, and heat pump systems should be monitored and optimised post-commissioning.

3 Conclusions and Recommendations

The following section discusses the implications of the findings for each research question and provides recommendations for future innovation programme design.

3.1 Question 1 – Financial Innovations

3.1.1 Implications of Findings

This REA has shown that considerable research has been undertaken on the business models needed to stimulate the uptake of domestic heat pumps, particularly when coupled with other energy efficiency measures. However, while there is plenty of discussion of the different models few have been trialled in-situ and at scale, particularly in the UK and Northern Europe, although this is starting to change.

The key themes running through the evidence are the need to cover the upfront cost of heat pumps, integrate the purchase with other retrofit measures (such as solar photovoltaics (PV), storage etc), and reduce the complexity for the consumer. This can be achieved through the PACE model and one-stop-shop model being trialled in North America and Europe, and the HaaS model featured in several publications and being trialled in the UK. The HaaS model will require further trials and development to increase consumer understanding and address their concerns around the disruption and long-term commitment. This model may also require changes to regulation and closer stakeholder collaboration.

An important finding relevant to unlocking deployment is the need to understand the willingness (and ability) of different consumer profiles to cover the costs of energy efficiency measures. These consumer profiles largely determine the way that business models need to be structured and deployed.

3.1.2 Gap Analysis and Suggestions for Further Innovation

This section outlines the gaps that were identified in the evidence base for Question 1 and includes recommendations for innovation programme design:

- Further trials and development of HaaS is required to increase consumer understanding, identify what motivates consumers, and address concerns around the disruption and long-term commitment element associated with HaaS.
- Additionally, it is recommended to trial HaaS, for the following reasons: to perform large-scale trials with data capture, optimisation, user-friendly controls, and most importantly, to demonstrate if the model is commercially viable.
- The PACE programme in the US could also be trialled, as it is an owner-occupier model for financing heat pumps and other energy efficiency measures that could be made possible in the UK.

- Financial innovations, such as HaaS or PACE, should consider the need to finance a package of energy efficiency measures (e.g. insulation upgrades in addition to a heat pumps), as required to improve heating system performance and achieve long term savings.
- Any further analysis should consider the "outside the house" variables that influence a consumer decision and are government linked, such as a possible carbon tax on gas used for domestic heating and changes in energy prices.
- Due to the current barriers and uncertainty in this space (and lack of market conditions) an innovation programme would potentially be an opportunity to examine various business models across different customer groups at scale. This could help to identify the most suitable financial innovations for a large-scale roll-out of heat pumps.

3.2 Question 2 - Low Voltage Grid Issues

3.2.1 Implications of Findings

The level of impact that the electrification of heat, through the use of heat pumps, will have on the LV network will depend on a number of factors. These include:

- The rate of uptake.
- The building stock fabric performance.
- Regional differences.
- Environmental conditions including winter temperatures.
- Flexibility measures related to how the electrical supply and in turn the heat pumps are used.
- How the heat pump systems are used.
- Technical characteristics of the LV network, including cable and transformer rating, type and size, and the general load profile (i.e. existing network headroom).

The body of evidence suggests that LV network issues (e.g. voltage problems or overloading) can be expected from a level of heat pump penetration on the LV network. This penetration level will be highly dependent on the variables listed above. For example, a poorly insulated building with a low fabric energy efficiency will have a significantly higher peak electrical demand than a well-insulated building with a high fabric energy efficiency, a problem that comes into focus during the winter peak, where on some LV networks, issues can be seen with 5% heat pump penetration. Furthermore, rural LV networks are generally more prone to overloading and under-voltage problems than urban ones. This highlights the need for transformer headroom to manage these winter peaks and a clear strategy for reducing these peaks (for example, through improving the building stock's thermal performance).

Other strategies looking at flexibility in the way the electrical supply is used have been investigated to try to flatten peaks in electrical demand. This includes clustering, where a group of buildings can be managed through advanced control strategies to optimize energy consumption, and demand side flexibility (DSR) which enables users to manage when their heat pumps operate in order to avoid peak time tariffs.

Again, these strategies are heavily dependent on buildings with a good fabric efficiency and thermal inertia, with poorly performing buildings not able to maintain comfortable temperature levels for long enough while also avoiding peak time tariffs. DSR has seen mixed results in practice with some overheating and noise concerns during low-tariff periods, and also some higher than expected consumption during high-tariff periods.

The users' engagement is another important factor of DSR. Ease of use of the control system were shown to be important in determining participants' attitudes towards using DSR.

Moving forward it is clear that further research is required to gather in-situ trial data of appropriate size, as well as looking at how the grid impact will vary depending on the type of home, and heat pump usage.

3.2.2 Gap Analysis and Suggestions for Further Innovation

This section outlines the gaps that were identified in the evidence base for Question 2 (low voltage grid issues) and includes recommendations for innovation programme design:

- The availability of field data is limited especially at a larger scale. In order for a deployment programme to achieve the appropriate grid impact learnings, the deployment size should target achieving heat pump penetration across at least 20% of dwellings on an individual LV network.

  The grid impact of medium and large clusters of buildings (greater than 100) needs to be investigated, both through simulations and real field trials. Data from field trials is limited for small scale deployment and almost missing for medium and large scale. Managing and aggregating the capacity of individual buildings equipped with heat pumps into a larger scale storage system constitutes a promising topic for future innovation.
- Technological innovations are required to improve the performance of flexibility services to the grid (Demand Side Response, aggregated load control, and other short and long period flexibility measures) such that low tariff concession and peaks are managed. Enabling customers to share half hourly electricity usage, heat pump usage and comfort data easily with the network provider (possibly through the development of integrated household controls and monitoring systems) will enable the network provider to assess the impact of these services on the customer comfort and the network load profile.
- When assessing the feasibility and potential of using heat pumps to provide flexibility services, there is a lack of standardized modelling and calculation approaches. Learnings from individual case studies should be used to identify generally applicable approaches and baseline the types of flexibility services heat pumps could provide.

- The availability of in-situ data related to the impact of heat pump clusters on urban low voltage grids is limited. Future impact assessments should include a broader range of heat pumps systems, building types, and geographic locations.
- Further research should also identify the technological changes to be carried out on the grid (i.e. existing electrical LV infrastructure, cabling, substations, feeder pillars, existing residential consumer units etc) as well as the cost implications of upgrades, on a local and/or regional basis.
- The impact of heat pumps on power quality and harmonic disturbances should be further investigated.

3.3 Question 3 – Roll-Out Facilitation

3.3.1 Implications of Findings

A clear theme running through the body of evidence, is the benefit of effective coordination between relevant stakeholder groups. A consumer-focused framework which considers area characteristics that define the stakeholder engagement strategy may lead to increased take-up. This could include aspects on how to identify, engage, and coordinate, resources, and information flow between stakeholder groups.

There exists a significant requirement for the digitalisation of home energy services, given the benefits this can provide regarding improved transparency, local area energy planning, system design, performance monitoring and the development of individually tailored service models. Digitalisation will however need to be supported through the interoperability of the systems employed. Digitalisation will only be realised through the development and successful integration of smart controls into households, a process that requires coordination at various stages in the supply chain. To aid this development, modelling and forecasting tools can be used in conjunction with trials to provide a low regret means of informing nationwide rollout. These tools should be designed to inform decisions through accurate, wide-spread data collection. Finally, the reviewed literatures highlight the likely benefits of a consumer-centric approach; specified standards and regulations related to all themes identified herein; and, be modelled and ultimately tested through pilot studies.

3.3.2 Gap Analysis and Suggestions for Further Innovation

The following section outlines the key gaps to be addressed in the collated evidence for Question 3:

- Collection of analytical data on the effectiveness of different heat pump trials with respect to overcoming the roll-out barriers. This should include completed and, where possible, part completed heat pump trials undertaken already in the UK, with recommendations for targeted innovation to increase the overall success.
- A review of tools required in the design, implementation and management of heat pumps and associated technologies, including how the tools have performed, what

improvements are required through innovation, and what tools need to be created. Based on the evidence used in this section, it is important that this covers an analysis into financial mechanisms, smart controls and monitoring, and how ‘smart’ heating fits into the wider consideration of decarbonising the built environment (e.g. total home energy use; the integration of home heating with electric vehicle charging).

- An increased understanding of how more effective and accurate modelling of local and household energy demand approaches can assist in both scheme design and management, and operational ease-of-use and performance. It is worth noting that the evidence base for Q3 suggests using the social aspects of this kind of rollout, e.g. consumer engagement and satisfaction as a metric to compare the effectiveness of various modelling scenarios.
- Collection of energy use and thermal comfort data from trials that have already implemented heat pumps into households, and the development of more advanced monitoring technologies and data manipulation techniques for future heat pump trails is required. This will help improve modelling tools, give a better understanding of local climatic effects on heat demand, understand social aspects (such as how users use their heating systems in practice), better link up quantitative data with qualitative observations to further understand the impact of technical considerations on consumers, and aid in the digitalisation of home heating. Examples of some of the types of data it would be useful to collect would be:
    - Unit electricity consumption - ideally at half hourly intervals or more
    - Inlet and return temperatures + flow rates (to calculate overall performance when combined with the point above) - ideally at half hourly intervals or more
    - Indoor and outdoor temperatures actual + desired set points - ideally at half hourly intervals or more
    - System fault codes
    - Qualitative: customer feedback on their comfort and ease of operating their heating system
- There is an apparent lack of city-scale quantitative assessments that take a place-based approach to evaluating required innovations and coordination efforts for large-scale heat pump deployment. It has been noted that Individual studies tend to analyse heat pump rollouts through the lens of a single factor, e.g., the social aspects of heating technologies rooted around consumer confidence; the environmental and technical aspects of heat pump deployment; the governance required for a transition to low-carbon heating; the financial mechanisms required to dictate market evolution; or the logistical aspects of technology and stakeholder coordination. This assessment would not only be required to index and hence evaluate these, and other considerations, simultaneously, but also provide recommendations that are locally relevant.
- The evidence details the required interactions and processes specific to each stakeholder group, but mostly for interactions that occur around the end-user (i.e., installer and consumer). There is a lack of evidence on previous coordination efforts (or

the efforts required to be successful) and future interventions for all the stakeholder groups involved; this including contributors within the manufacturing, financial and political sectors, to name a few. It is suggested that a more holistic approach is required, formed of a robust, consumer-centric, and placed-based framework / methodology that defines stakeholder engagement at all levels.

3.4 Question 4 – Performance and Deployment

3.4.1 Implications of Findings

To bring the actual performance of heat pump systems closer to the projected performance, innovations which allow existing heat pump technology to perform in a more repeatable way could be of significant benefit. Several studies observed that there are installations where the performance gap is very small and there are installations where there is a significant gap.

A study of heat pumps in high performing (near net zero) buildings in other countries in Europe observed SPF of around 5 over multiple years, but very few instances of SPF around this figure were observed in UK studies. Additional performance improvements to increase the SPF of heat pump installations beyond what is currently observed are likely to be possible through innovation and further research.

While there are differences in regulations (such as legionella control) between jurisdictions, it suggests that a combined approach of installing good quality heat pump installations and a high performing building envelope can achieve significant performance increases over those currently observed in the UK.

The need for heat pump user interfaces to be easier to understand and adjust, innovations to increase the source temperature or reduce the sink temperature were cited by several studies as ways of improving real world heat pump performance.

The disruption associated with installing heat pumps was cited as a challenge in recruiting householders to heat pump field trials in housing association properties, which indicates that even without considering the capital cost of heat pumps – the disruption is currently a barrier to deployment and innovations to reduce the disruption associated with installing heat pumps could reduce this barrier. However, there were no relevant reviews or assessments of tools that could be used to increase the uptake or effectiveness of heat pump clusters.

Innovations could be considered to improve the performance of heat pumps when providing hot water and the ease of installation. Heat pumps which are optimised for hot water are available (including as integrated units containing domestic hot water cylinders) and these have the potential to avoid the need for immersion heaters to operate. However, heat pumps of this type were not considered in any of the studies reviewed. Additional benefits of hot water heat pumps which could be investigated by any future study could include: use recovered heat from within a dwelling to increase source temperature; allowing a separate heat pump system to be optimised for low temperature space heating; simplify controls systems and user interfaces, separate demand management on heating and hot water; hot water heat pumps providing hot water to buildings which are not suitable for space heating.

3.4.2 Gap Analysis and Suggestions for Further Innovation

This REA identified a wide range of areas of possible innovation in heat pumps themselves as well as other elements of heat pump systems.

It is worth noting that any future innovation programme could consider a wider range of innovation topics which are not covered by real world trials reviewed as part of this REA but have been identified as having the potential to be of significant benefit. This includes in design, manufacturing, and installation as well as operation and maintenance.

Potential areas where research and innovation are listed as being of significant benefit include:

- Design improvements:
    - Increase the modularity of heat pump systems.
    - Innovations which improve the ease of design and installation of low temperature systems, optimisation of source and sink temperatures and energy consumption, and/or reduce their cost.
    - Increase ease of connection to other technologies and storage media.
- Manufacturing:
    - New computer modelling simulation tools to provide a flexible, user friendly, interface to overcome design challenges and create more efficient systems.
    - Mass production and 3D printing of components such as heat exchangers.
    - Improve the resilience of the supply chain resilience.
- Installation:
    - Plug and play software and hardware.
- Monitoring, maintenance, and operation:
    - User interface (UI) improvements, Internet of Things (IOT) data gathering and connectivity, AI algorithms for optimisation, remote diagnostics & predictive maintenance.
    - Innovation for the user interface of heat pump systems could significantly improve how easy the systems are to be operated and maintained. This has the potential to reduce the number of instances of poor user experience or performance, which are caused by control systems being used incorrectly.
    - Innovation to reduce the cost of monitoring, analysis and optimisation of heat pump space heating and domestic hot water systems. In particular to identify any ancillary equipment (i.e., immersion heaters, circulation pumps) that are

operating unnecessarily or inefficiently. The performance of the heat pump system should be recorded before and after any optimisation work, so as to quantify the benefit of the remedial action and, where possible, consider whether interventions such as installation guidance, standards or regulations could reduce the performance gap in future installations.

  - Opportunities to conduct analysis of heat pump performance data using techniques such as machine learning or Artificial Intelligence (AI) should be considered.

The following list includes additional recommendations for future innovation programmes and research:

- Further trials using a large number of heat pump installations with conclusions based on up-to-date installation, commissioning, and operation practices in the UK.
- The evidence suggests that the actions needed to close the performance gap may differ between individual installations, but there is a lack of research addressing the potential improvements resulting from on-going monitoring and optimisation. A heat pump innovation programme would provide an opportunity to trial different approaches to the optimisation of domestic heat pumps on a larger scale.
- A further "horizon scanning" evidence assessment framed as looking for laboratory trials etc of opportunities and innovations which are at a lower TRL (Technology Readiness Level).
- There are a number of second order factors that should be considered in relation to the uptake and performance of heat pumps. These include a broad range of factors such as noise, or the use of low Global Warming Potential (GWP) technologies, that are not specific to the research questions addressed in this document. Further assessment of opportunities is recommended as a next step.

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Appendix A: REA Methodology

A1 Introduction

The REA methodology set out below includes the eight stages for an evidence review as defined in Warren (2000) and included a pilot study to test the effectiveness of different selections of key words in finding relevant research work that addressed each of the four research questions. As the volume of documents identified during this initial study was too large to review within the time and budget available for the work, the scope of the search was narrowed to papers that reviewed research work by prefixing the search terms with “Review of”. To provide a more rounded final report, we also decided to identify relevant grey literature by repeating each key word search in the main google search engine. We also adopted an “open book” approach in which expert reviewers from inside and outside the project team were invited to propose additional publications that could fill the gaps in the evidence base. These publications were reviewed by the research team and quality assured before inclusion.

This hybrid approach was adopted to ensure that the results of more recent research work including recent domestic heat pump trials (particularly in the UK) were included in the evidence base.

A2 Objectives

The objectives of the REA were:

- Provide a list of relevant literature sources.
- A synthesis and appraisal of the literature.
- A map of the current evidence base (an analysis framework).
- A summary of the existing evidence.
- Identification of the key research gaps.
- A ranking of these gaps and recommendations on how best each gap can be addressed going forward (e.g. technical research, demonstration project, policy intervention).

A3 Research Questions

The following research questions have been designed to help focus and guide the REA:

1. Financial Innovations: Unlocking the necessary financial innovations required to deliver a large-scale roll-out of heat pumps in the UK.
    a. What is the state of relevant financing models and examples of (consumer and supply chain) finance solutions being deployed on scale?

   b. What gaps exist to fully internalising the benefits of heat pumps and heat pump clusters through financial products and consumer offers?

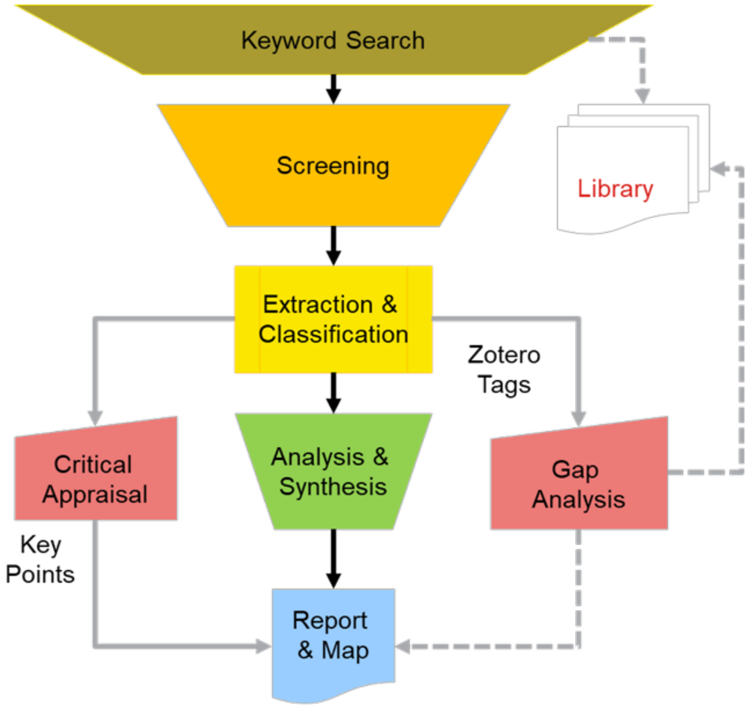
2. Low Voltage Grid Issues: Determining the Low Voltage (LV) grid issues associated with concentrated deployment of heat pumps and how we can overcome these?
   a. What is the necessary size of deployment of a heat pump cluster to achieve the appropriate grid impact learnings?
   b. How can we mitigate grid impacts?
3. Roll-out Facilitation: How can we facilitate the large-scale (often concentrated) roll-out of heat pumps - what are the necessary innovations or learnings?
   a. What existing tools or established processes of coordination (between the many stakeholders involved) could support in the effective roll-out of heat pumps?
      i. These include the necessary technical, consumer, installer and finance tools (e.g. heat mapping software, installer tools, building models).
      ii. Are there examples (anywhere in the world) of this kind of coordinated deployment?
      iii. This includes how the coordination between the different stakeholder should be set-up (e.g. Local authority lead, energy supplier lead, Distribution Network Operator (DNO)/Distribution System Operator (DSO) lead), who shares what data etc.
4. Performance and Deployment: What are the technological improvements to the heat pump system (i.e. includes thermal store, heat distribution system etc) and tools that could be developed to support any of the above aims - i.e. a large scale efficient roll-out of heat pumps in the UK?
   a. Part of this should also look into technological performance improvements that could be made (that realistically could be deployed in the UK within the next ~3 years).
      i. Perhaps looking at the way other countries structure their heat pump systems would be useful in this regard. e.g. perhaps they use a greater degree of thermal storage etc.
   b. Are there any tools that have been developed that will assist in the deployment of heat pumps?

Regarding question 3 and 4, the focus of the research was on overcoming the practical barriers to a large-scale roll-out of domestic heat pumps rather than on the theoretical aspects of improving heat pump technology, or on modelling their uptake or impact. A desired outcome of the REA was a set of “learnings” from other countries experience of heat pump roll-outs.

A4 Overview of the REA Methodology

An overview of the REA methodology is presented in Figure 3:

Figure 3: Overview of the REA methodology



The initial keyword search and screening of relevant literature was undertaken by analysts with general technical background under the supervision of a principal consultant with experience of managing research across a wide range of technologies. The library referred to in Figure 3 is Zotero™ [16]. The extraction and classification, analysis and synthesis, and identification of any gaps, was undertaken by technical experts[17] with detailed knowledge of domestic heat pump technology, project economics, electricity networks or technology deployment.

The following sections describe the methodology of the REA in detail.

A5 Search of the Evidence

During each search for information, a record of the date, the database and search terms used, along with the number of hits and any date limits applied were recorded. The details of the individual pieces of relevant evidence were clearly collated in Zotero™, which has been shared with BEIS for transparency.

[16] Zotero is an open-source reference management tool that was used to collect, organise and share research between research team members in different organisations and locations.
[17] Technical experts were used for each question to extract information from the relevant evidence, appraise the evidence, and identify any gaps. Their findings inform this report.

The benefits of using a reference manager such as Zotero ™ are that it contains a well-presented record of added literature with references that can be exported as part of a bibliography. In addition, Zotero ™ offers a custom tagging feature that meant publications could be categorised and filtered. The tool includes the publication name, date, and source location – including a hyperlink, or saved location of the article.

The records of each individual search have been combined to give a full list of the evidence found, less any duplicates. A summary of the initial search parameters are given in Table 2 below.

Table 2: Summary of the scope of the REA agreed with BEIS

Parameter	Definition
Publicly Accessible Information Source (Search Engine, Knowledge Leader, Database, etc.)	Google Scholar (for academic research). Google main search engine (for grey literature – non peer reviewed).
Primary Search Terms (record number of references each search term returns)	"Review of" AND "heat pump" AND (Residential OR Domestic OR Dwellings)
Secondary Search Terms (use to narrow down search results to reasonable number)	Q1: AND ("Business Model" OR "financing models" OR "Heat as a Service") Q2: AND ("Area-Based" OR Cluster OR Mass) AND (Deployment OR Roll-out) AND (Substation OR LV OR Grid OR "Low Voltage" OR Distribution) AND Impact Q3: AND ("Area-Based" OR Cluster OR Mass) AND (Deployment OR Roll-out) AND (Coordinated OR Strategy OR Plan OR "Quick Wins" OR "Easy Wins") Q4a: AND "Performance gap" AND (lessons OR implications OR Understanding) Q4b: AND (Stakeholders OR "Local Council" OR "Local Authority") AND (Plan or Tool)
Other keywords	Tools, Processes, Lending, Payments, credit, leasing, HAAS, "improvement opportunities".

(use to search in document)	
Type of Document	Peer reviewed studies and reports by governments, utility companies and consultants. Not interested in documents focussed on single technology or solution – reviews preferred.
Limits of Search	Geography: UK, Northern Europe, Canada, USA, Japan, New Zealand. Publication Date: 2011 to 2022. Technology: Air source heat pumps, Ground source heat pumps; Exclude: District heating, hybrid heat pump/boilers, non-electrically driven heat pumps (gas-fired), deep geothermal. Application: Single dwelling/multi-occupancy buildings. Exclude: community heat networks.
Search strategy	Scan for recent reviews or each topic using primary & secondary search terms. Upload search results into Zotero TM for collation, screening/prioritising, and review. Limit each search to 100 results, by relevance. (Total max: 500). Collate documents that are immediately accessible via google scholar. Note abstracts of high relevance without documents immediately available. Repeat search in google main search engine – AND .pdf to limit to publications. The researcher will only capture reports by governments, utility companies and consultants. Limit each main engine search to the 50 most relevant reports (Total max: 250 reports).

A6 Screen the Search Results

Once the Review Team completed the initial search for material, a screening session took place to outline the most relevant/reliable sources of information. This was undertaken by following a pre-conceived a set of inclusion/exclusion criteria:

- Geographical references: UK, Northern Europe, Canada, USA, Japan, New Zealand.
- Business models for a wider geographical area were also considered.
- Language restrictions: only evidence published in English.
- Anything that seemed key and was in another language was flagged for potential follow-up/translation in the latter half of project.

Date restrictions: only evidence from after 2011.

This screening followed a two-fold approach:

First phase screening

Read only the title or headline of the evidence found.

Mark the evidence sources as: clearly relevant, not relevant, or unclear relevance.

If the evidence was found to be clearly relevant or unclear relevance at this first stage it was obtained in full.

Second phase screening

Read only the abstract or first paragraph of the clearly relevant or unclear relevance evidence.

Identify those that meet the inclusion/exclusion criteria.

The evidence was marked with a second tag if it was no longer relevant e.g. not relevant 2.

Zotero TM contains details of the outcomes of the first phase and second phase screening and will be retained to provide an audit trail for the evidence review (ER) process.

Only evidence with a tag of clearly relevant was used in the evidence extraction, critical appraisal and synthesis stage of the REA. All other items that did not meet the inclusion/exclusion criteria at both the first and second screening stage have been recorded and will be made available as supplementary information alongside the final REA report.

A7 Extract Evidence that Relates to the REA Questions

Once the evidence was screened the next stage was to extract information relevant to the REA's question in a systematic manner. The method to collate extracted evidence was dependent on the type of evidence found and on the objectives of the REA. The information to be extracted from the articles was defined a priori and was shared with the technical experts.

Information to be extracted included:

- The type of evidence.
- The research design used.
- The population studied.
- The geographical context.
- Details of the intervention applied.
- Outcomes measured.
- Evidence relating to the primary questions.

The technical experts assigned tags from a predetermined list to evidence in Zotero ™ and the results have been used to inform statistical analysis.

A8 Critical Appraisal of Evidence

This activity involved evaluating each piece of evidence to consider both the relevance of the evidence to the REA questions and also the robustness of the methodological quality utilised. The assessments of both these aspects were then combined to provide an overall evaluation for each piece of evidence returned by the review.

The first step of the critical appraisal phase was to evaluate the relevancy of evidence in relation to the REA question. This considered the following:

- The relevancy of the method used to answer BEIS' questions.
- The relevancy of the evidence to the target subject/population of the REA.
- The relevancy of the intervention assessed.
- The relevancy of the outcome measured.

The technical experts recorded the outcome of their consideration of the relevance of each item of evidence tagged as clearly relevant using the categorisation in Table 3.

Table 3: Categories of relevance to the research questions

Class	Description
3	High Relevance: The document contains an analysis of an approach to the medium/large scale deployment of heat pumps and provides a number of generalised learnings for a heat pump innovation programme.

2	Medium Relevance: The document addresses a number of specific aspects of the medium/large scale deployment of heat pumps and provides some generalised learnings for a heat pump innovation programme.
1	Low Relevance: The document addresses some minor aspects of the medium/large scale deployment of heat pumps – but no generalised learnings for a heat pump innovation programme.
0	No relevance: The document has no obvious relevance to BEIS' question.

The technical experts then made an evaluation of the robustness of the evidence returned by the REA, i.e. the accuracy of the evidence and the degree to which bias has been minimised.

To do this it was useful to describe and categorise each piece of evidence included by the REA in terms of study design type and method. Table 4 provides the categorisation which was assigned to the evidence tagged as clearly relevant in this REA.

Table 4: Categories of evidence types

Category	Study Design Type
A	Quantitative experimental e.g. Before-after experiments, randomised control trials, non-randomised control trials.
B	Quantitative observational e.g. before-after observations, case-controls, cohort studies, correlations.
C	Qualitative studies e.g. interviews, expert elicitation.
D	Economic studies e.g. cost-benefit/effectiveness/consequence studies.
E	Reviews e.g. literature reviews, systematic reviews, reviews of randomised control trial.

An assessment of methodological quality was then made for each piece of relevant evidence after considering the following points, which impact on perceived accuracy and bias of the publication:

- Specific research questions are addressed (i.e. the focus of the document is declared).
- Related existing research or theories are acknowledged.
- Sources of funding and vested interests are declared, and any bias is addressed.
- The methodology used is clearly and transparently presented.

- The method is appropriate for the research question and the conclusions reached by the study.
- Assumptions made are outlined.
- The geography and context of the study is clear, with a discussion of how relevant findings are to other contexts.
- The methods used for measurements and analytical techniques have been validated and verified.
- Conclusions are backed up by well presented data and findings.
- Links between descriptions of existing research, and data, analysis and conclusions are clear and logical.
- Limitations and quality have been discussed.

The relevant criteria were used by the technical experts to assess the robustness of the evidence and a class associated with the degree to which bias was mitigated was then assigned, according to the classes in Table 5.

Table 5: Categories of methodological quality

Class	Description
3	High Quality: All or most of the methodological criteria appropriate for the study type have been fulfilled (low risk of bias).
2	Medium Quality: Some of the methodological criteria appropriate for the study type have been fulfilled and those criteria that have not been fulfilled or not adequately described are thought unlikely to alter the conclusions (risk of bias).
1	Low Quality: Only a few or no methodological criteria have been fulfilled. The conclusions of the study are thought likely or very likely to alter (high risk of bias).

To assign an overall grade for each piece of evidence at the critical appraisal stage it was necessary to combine the scores given for relevancy and robustness. This allowed higher scored pieces of evidence to be given greater weight at the synthesis stage. The categories for relevancy and robustness were assigned a score from 1 to 3 (low to high quality) and 0 to 3 (no relevance to high relevance). These were then combined to provide an overall rating for each publication reviewed from 0 (0*1) to 9 (3*3), whereby the most relevant articles with the highest quality methods are weighted the highest, and those with little relevance and poor method are ranked lowest.

A9 Synthesis of the Results

A9.1 Describing What the Evidence Indicates

The research team adopted the use of a narrative synthesis over quantitative synthesis or meta-analysis. This method has proven to be particularly useful when communicating findings for policy and practice.

As a result of this narrative synthesis, statements regarding the consistency and convergence of the evidence have been made. This allowed for one of the following to be allocated as true:

- Consistent evidence = A range of different forms of evidence point to identical, or similar conclusion.
- Contested evidence = One or more study/studies directly refutes or contest the findings of another study or studies.
- Mixed evidence = Studies based on a variety of different designs or methods, applied in a range of contexts, have produced results that contrast with those of another study.

These statements have been supported by data with the appropriate evidence.

A9.2 Implications of the Findings

The final part of the evidence synthesis related the findings of the REA to the policy and/or practice context outlined at the inception meeting. For example, was the evidence supportive of current policy and/or provided a clear route for a heat pump innovation programme to support specific measures or innovations?

A9.3 Suggestions for Further Research

Finally, the synthesis of the evidence includes suggestions for further research based on any gaps identified. The synthesis has been reviewed by a technical expert and any missing key documents highlighted. Suggestions have been made on how to best approach filling these gaps.

A10 Assigning Confidence and the Creation of Evidence Statements

Once the technical experts had created a statement of the evidence collated in respect of each question, an assessment was made of the level of confidence in the findings of the rapid evidence assessment. To assign confidence to these statements, both the robustness (quality), and quantity of the evidence supporting the statement was considered. By combining these elements, categories of confidence were assigned as set out in Table 6.

Table 6: Categorisation of certainty

Class	Description
High	Evidence from many studies classed as 2 and/or 2-3 studies classed as 3.
Medium	Evidence from one or more studies that have been classed as at least 2.
Low	Evidence from a small number of studies or studies classed as 1.
Contested	Evidence that differs in its conclusions (present the class for each study/evidence).

A11 Communicate REA Findings

The REA report summarises the findings of the REA, uses charts and tables to visualise the results and provides recommendations for programme design. The background and policy context of the work has been included with the final outputs of the REA for completeness. In the interest of transparency and confidence of un-bias, this report highlights where any deviances from the methodology occurred.

The REA report also includes a bibliography of the relevant publications and is accompanied by a database of all the evidence found, so that an audit trail of how the REA was conducted can be followed. A Systematic Map of the extracted information from the evidence meeting the inclusion criteria is also provided.

Appendix B: Overview Exercise

B1 Overview

As described above, evidence was collected for each research question and added to Zotero™. Table 7 provides a summary of the number of publications collected for each question, how many of these were considered relevant after screening, how many additional publications were added by the technical experts, and how many the experts then reviewed.

Table 7: Summary of evidence collected as part of the REA

	Evidence added to Zotero™	Evidence tagged clearly relevant	Evidence added by technical experts	Total items reviewed by technical experts
Question 1 – financial innovations	181	26	4	30
Question 2 – low voltage grid issues	229	35	10	45
Question 3 – roll-out facilitation	443	10	12	22
Question 4a – performance improvement	315	11	21	32
Question 4b – deployment tools	376	6	2	8
Totals	1,543	87	49	136

Question 3 (roll-out facilitation) had the highest amount of evidence added to Zotero™ and Question 1 (financial innovations) had the lowest amount of evidence added to Zotero™. Although accounting for the most evidence, Question 3 (roll-out facilitation) had the second lowest amount of evidence deemed relevant. Question 4b (deployment tools) had the lowest amount of evidence deemed relevant and Question 2 (low voltage (LV) grid issues) had the highest amount of evidence deemed relevant.

Question 4a (performance improvement) had the most evidence added by technical experts and Question 1 (financial innovations) the least. The technical expert responsible for Question 2 (LV grid issues) reviewed the most evidence and Question 4b (deployment tools) the least.

B2 Summary of Relevant Evidence

As part of their review, the technical experts extracted information from the relevant evidence and assigned tags in Zotero™ that were defined in a predetermined list.

Table 8 shows that the majority of the relevant evidence reviewed by the technical experts was located in the UK followed by Northern Europe, with none of the relevant evidence being from Japan or New Zealand. It was not possible to assign a location to every piece of relevant evidence and some pieces of relevant evidence has been assigned more than one location.

Table 8: Geographical location of relevant evidence

Geographical References	All Questions
UK	63
Northern Europe	37
USA	8
Canada	2
Japan	0
New Zealand	0

Table 9 shows that the majority of the relevant evidence reviewed by the technical experts was written by academics. Some pieces of relevant evidence may have been assigned more than one author type, if perhaps the evidence was written as a partnership between two or more individuals or organisations.

Table 9: Author of relevant evidence

Author Type	All Questions
Academic	85
Government	26
Consultant	12
Network Operator	12
Local Authority	6
Non-Governmental Organisation/Charity	5
Other	4
Professional Body	4
Technology Provider	4
Trade Association	4
Market Analyst	3

Table 10 shows that not every piece of evidence discussed the deployment of heat pumps. Where the deployment of heat pumps was discussed, it was mostly at a regional scale with few publications discussing street or suburb level deployment.

Table 10: Scale of heat pump deployment discussed in relevant evidence

Scale of Deployment	All Questions
Scale not specified	61
Regional deployment	37
City-wide deployment	15
Small heat pump cluster	10
Suburb level deployment	7
Street level deployment	6

Table 11 shows the number of heat pump installations cited in the relevant evidence that included a heat pump trial or experiment. The majority of these heat pump trials took place on a small scale (between 0 and 100).

Table 11: Number of heat pump installations in trials cited in relevant evidence

Number of Installations	All Questions
Small (0-100)	20
Medium (101-1000)	8
Large (1000+)	9

Table 12 shows the number of relevant publications citing the different heat pumps. The air to water heat pump category includes these heat pumps only and the air source heat pump category was used if no distinction was made between the two. Air source heat pumps were mentioned the most in the relevant evidence, followed ground source heat pumps.

Table 12: Type of heat pump discussed in relevant evidence

Heat pump type	All Questions
Air source heat pump	37
Ground source heat pump	29
Air to water heat pump	18

B3 Relevance and Robustness of Evidence

The technical experts have critically appraised the relevant evidence and consider both its relevance to the REA questions and the robustness of the methodology utilised.

The experts tagged the relevant evidence in Zotero^{TM} with a rating of its relevance to the REA question, from no relevance to high relevance. Table 13 is a summary of the ratings assigned for each question; the results for Q4a (performance improvement) and Q4b (deployment tools) have been combined. The question with the most relevant literature is Question 2 (LV grid issues) and the evidence base for Question 3 (roll-out facilitation) contains the least relevant literature.

Table 13: Relevance rating assigned to relevant evidence

Technical (Policy) Relevance	Question 1 – Financial Innovations	Question 2 – Low Voltage Grid Issues	Question 3 – Roll-Out Facilitation	Question 4 – Performance and Deployment
High Relevance	9	19	7	8
Medium Relevance	11	14	6	8
Low Relevance	4	5	4	11
No Relevance	2	0	1	9

As part of the REA the technical experts were also asked to assess the methodological quality of the relevant evidence (using the criteria defined in the Critical Appraisal of Evidence section of the methodology) and assign a tag with a rating from high to low quality. The following Table 14 shows the ratings assigned for each question, the results for Q4a (performance improvement) and Q4b (deployment tools) have been combined. Question 1 (financial innovations) has the highest number of publications with high quality methodologies and Question 3 (roll-out facilitation) has the least amount of evidence with high quality methodologies.

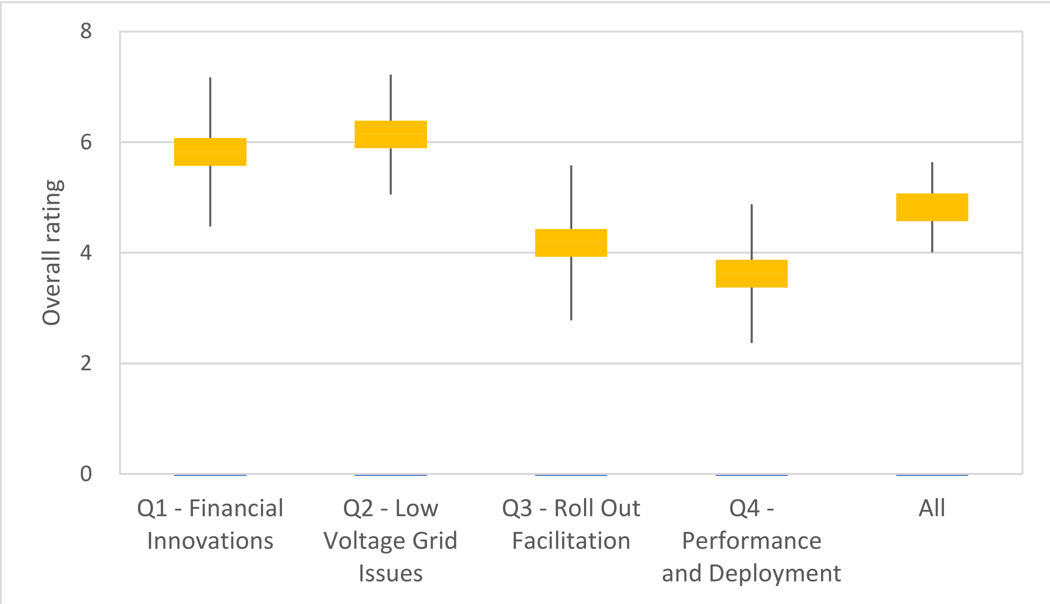
Table 14: Methodological quality rating assign to relevant evidence

Methodological Quality	Question 1 – Financial Innovations	Question 2 – Low Voltage Grid Issues	Question 3 – Roll-out Facilitation	Question 4 – Performance and Deployment
High Quality	23	21	3	17
Medium Quality	3	17	12	17
Low Quality	0	0	3	2

After the technical experts had assigned the relevant evidence with ratings for relevance and methodological quality, each publication was assigned a number from 1-3 (low to high methodological quality) and from 0-3 (no relevance to high relevance). These were then combined to provide an overall rating for each relevant publication from 0 (1*0) to 9 (3*3).

Figure B.1 shows the average overall rating for each question, with the rating for Question 4a and 4b combined. The boxes represent the mean and the vertical lines are error bars. The error bars represent a 95% confidence interval for the mean of the relevant publication ratings, calculated using the standard deviation of the ratings for each question.

Figure 4: Average overall rating for the relevant evidence



The evidence for Question 2 (LV grid issues) has the highest average overall rating and Question 4 (performance and deployment) has the lowest. Question 3 (roll-out facilitation) has the widest error bars or 95% confidence interval and the average rating for all questions has the narrowest 95% confidence interval.

Appendix C: Evidence Statements

C1 Question 1 – Financial Innovations

The evidence base for Question 1 contains 181 publications, 26 of these were identified as being relevant and 4 additional publications were added by technical experts.

The majority of publications in this evidence base were authored by academics (24/30). The publications were predominantly focused on the UK (16/30) and or Northern Europe (11/30). It was not possible to access four of the relevant publications included in the total (30), so these have been excluded from the following analysis. The majority of publications reviewed had high quality methodologies (23/26) and were of medium (11/26) or high (9/26) relevance to the research question.

Table 15 shows the topics mentioned in the relevant publications for Question 1. The most frequently mentioned topic in this evidence base was business models.

Table 15: Topics mentioned in the relevant publications for Question 1

Financial Innovations	Q1- Financial Innovations
Business models e.g. Heat-as-a-Service	20
Financing models e.g. leasing	9
Consumer offers e.g. grants	8
Finance solutions e.g. Community Improvement District Financing	6
Financial products e.g. loan	3

The following section outlines the key learnings captured from the review of evidence for Question 1 – financial innovations. The publications are grouped according to their relevance, from high relevance to no relevance.

C1.1 High Relevance

Business Model Innovation to Support Air Source Heat Pump Retrofits in Metro Vancouver (Nelson, 2019)

- Key barriers to ASHP uptake in Metro Vancouver (Natural Resources Canada, 2017)

  - Affordability: higher cost of electricity and air source heat pumps (ASHPs) relative to natural gas systems.
  - Availability: ASHPs are not readily available and don’t have a strong market presence.
  - Accessibility: the most efficient ASHPs are not accessible in the area or in Canada.
  - Awareness: much less awareness by households and the Heating, Venting and Air Conditioning (HVAC) industry.
  - Acceptance: ASHP systems perceived to be riskier to install, harder to use and less likely to achieve stated performance.
- Tools suggested to overcome barriers to uptake included:
  - Moving away from short-term and upfront costs to long-term and regular expenditures and incentives.
  - Full-service rental agreements circumvent the need for any upfront cost and instead charge a competitive monthly fee for an all-inclusive service.
  - One-Stop-Shop (OSS) models provide a single entity that sources quality ASHPs, contractors, and financing. This reduces the time and resources needed for the retrofit process. An example is Saint John Energy, New Brunswick, which uses a low rental fee, single point of contact, and integrated supply chain to make renting easy and affordable without any government subsidies. The model also attempts to reduce information asymmetry between stakeholders.
  - Efficiency Nova Scotia and Efficiency Maine both utilize Property Assessed Clean Energy (PACE) and on-bill financing (OBF) to cover the capital costs of a heat pump purchase.
  - OBF is an effective tool already being used by the EcoSave programme in Nelson, British Columbia. Half of the participants in the initial pilot programme used OBF, with an average loan of $8,100. OBF financing could prove particularly useful for rental properties as it helps to overcome the Principal-Agent problem where landlords are resistant to retrofit because tenants pay utility bills.
  - Innovative strategies such as Production-Based Incentives and Greenhouse Gas Offsets provide additional long-term incentives that can help mitigate potential energy price differentials between natural gas and electricity.
  - Forging closer relationships between contractors and manufacturers through coordinated marketing, education, training.
- All programs provide financial incentives to customers to induce heat pump adoption, primarily through rebates, ranging from $216 to US $4,500.
- Many of the programs offer free or low-cost home energy assessments.

- There is an emerging group of innovative pay-for-performance (P4P) models where companies are paid based on the actual utility bill savings resulting from energy efficiency upgrades.
- A new heat pump business model for Metro Vancouver would utilise rental agreements or financing models such as PACE plus government funded incentives to increase the affordability and uptake of heat pumps.

Exploring the potential of heat as a service in decarbonization: Evidence needs and research gaps (Britton et al., 2021)

- Novel business model and financing of HaaS (Heat-as-a-Service) with lessons from UK trials and insights from stakeholders. A stakeholder workshop took place, which identified barriers, evidence needs, and research gaps related to behaviour and customer issues:
    - Lack of awareness about HaaS.
    - Low digital literacy with some unable to access a smart phone, which may be required to access HaaS settings.
    - Consumers value short-term contracts (1 to 2 years) and ability to switch provider.
    - Energy use behaviours related to energy use and building performance.
    - Lack of clarity about consumers' willingness for disruption caused by retrofit and to guarantee efficiency.
    - There may be insufficient space to install new equipment.
    - Policy and regulatory barriers associated with: supplier switching regulations, the use of long-term contracts, social equity, lack of clear HaaS specific regulations, and supply Licensing conditions and tariff rules
- The paper concludes with recommendations for policy that could support the uptake of HaaS business models and maximise its potential to decarbonise heat:
    - Uncertainties around consumer preference, building performance, and policy frameworks, limit HaaS uptake.
    - More trials are needed to address consumer concerns and lack of understanding of HaaS.
    - HaaS requires supportive policies for market development and regulation.
    - Open, interoperable and secure data are key to deploying HaaS.
    - Best practice energy services from other countries can inform HaaS development.
    - To facilitate HaaS, opportunities for consumers, experts, and industry to work together should be explored.

Smart Systems & Heat Phase 2: Evaluation Report Smart Systems & Heat Phase 2: Evaluation Report (Holland et al., 2019)

- A 'living lab' of 108 homes was created to understand consumer energy use and preferences and test the concept of HaaS. Market engagement, research and analyses were conducted to explore the business case for consumer-focused delivery of low carbon heating.
- A heat plan allowed consumer to pay for heating for an hour, rather than paying by unit of fuel used. A heat plan sold the homeowner a number of hours per month, at a fixed price, with the ability to purchase additional hours. Three types of plans allowed homeowners to decide whether they wanted a lower cost and fixed number of hours, flexibility at a higher price, or unlimited heating at a higher price.
- Cost certainty appeared to be a clearer benefit than comfort certainty for participants and was the reason most often cited for take-up.
- The trial was not designed to test commercial viability, and therefore further work is required to demonstrate if commercial viability is achievable.
- The report mentions five business models most feasible in enabling innovation to be delivered at the scale required to meet the 2050 target:
    - Building / retrofit and operation. An energy service provider provides services at low / zero upfront costs to new build / retrofit properties to address energy efficiency and create smart-enabled homes. Costs are paid back by the customer over time through energy service bills.
    - Municipal Energy Service Companies (heat and power). Aimed at municipal owned social housing, and providing services for tenants for deep retrofit, with tenants paying back costs over time through energy service contracts.
    - LISCo (both the data and capital-intensive versions). A lifestyle services company, providing energy and wider services through a one-stop shop for all services, including installation of equipment and other home improvements, with no upfront costs and a contract for repayment.
    - Supplier – aggregator. An Energy Service Provider with a service to aggregate and sell consumer flexibility to markets, thus offsetting the customer bill. This is a model that customers will be familiar with, as it is a per kWh offering.
    - Commercial ESCo. A model already mainstream in the commercial sector but yet to be demonstrated for private customers.
- The report recommended that business models align incentives throughout their products and supply chain in order to deliver better consumer experience.
- The report suggested an outcome-based decarbonisation standard or obligation on future retailers or home energy service providers to incentivise the market to deliver.

Emerging Pathways to Upgrade the US Housing Stock: A Review of the Home Energy Upgrade Literature (Walker et al., 2021).

- Highly relevant and recent overview of the US market with regional focus.
- Promising programme design strategies covered in this review include: end-use electrification programs, novel financing approaches (e.g., Pay-As-You-Save and local lender networks), Pay-for-Performance incentive structures, securitization of portfolios of upgraded homes as investment products, and One-Stop Shop programs that integrate financing, project management, design and support services.
- Pay-As-You-Save is a mechanism where a utility company covers the cost of installation, which is recovered on the consumers' monthly utility bill with a charge that is less than the estimated savings. Ownership is transferred to the consumer once the costs have been recovered.
- Local lender networks are networks of lenders that operate in the local area rather than operating nationally.
- Key barriers to scaling home energy upgrades:
    - Emphasise other benefits alongside energy savings such as health, maintenance, resilience, and environmental aspects.
    - The workforce remains inadequate.
    - The cost remains too high with the lowest cost way to save energy likely involving a variety of efficiency measures as opposed to costly envelope upgrades.
    - Economic justifications are possibly inadequate due to low energy costs and failure to appropriately price carbon.
- Guidance for scaling home energy upgrades include:
    - Partner with trusted messengers.
    - The language used to discuss energy improvements is powerful.
    - Make the process of accessing energy efficiency measures easy and fast.
    - Contractors are the ambassadors of programmes.
    - A well-qualified and reliable workforce is essential.
    - Rebates, financing and other incentives are effective at creating demand.
    - Reduce variability to save costs by using a standardised approach to install elements in homes that already have energy efficiency measures.
    - Offer the packages at little or no up-front cost to homeowners and remove the need to shop around for contractors or finance.

Getting on track to net zero: A policy package for a heat pump mass market in the UK (Lowes et al., 2021)

- This paper examines how the policy gap between the governments' target for heat pump installations and existing and planned programmes can be closed.
- At a high level it is necessary to have a strategically governed combination of measures, which includes regulation, restructuring of taxes and levies, financial support, area-based planning and citizen engagement.
- Deployment of heat pumps under the RHI has fallen consistently below expectations, perhaps as it does not provide upfront capital support. Some combination of financial support, shifting to upfront capital support with a regulatory mandate, will likely be needed.
- The green house grant (GHG) proved to be popular among households from the outset, but the performance of the scheme is not meeting expectations. The upcoming Clean Heat Grant represents a fall in funding available compared to the combinable support of GHG and RHI.
- Best practice for the deployment of heat pumps should be formed of the following elements with strong governance: coordinated set a policies and regulations; policy stability; financial support that includes grants and financial penalties for the use of fossil fuels; direct focus on skills and consumer awareness.
- Incentives are required as upfront costs of heat pumps are higher than fossil fuel alternatives and the running costs do not provide clear cost savings.
- Carbon taxes have been a driver of heat pumps in Sweden.
- Suggested financial incentives:
    - Grants to help overcome additional upfront costs that are higher for low-income households.
    - Subsidised loans can remove issues related to accessing capital and reduce the cost of capital.
    - Stamp duty rebates before and after the sale of a house.
    - Tax reductions, such as removing VAT or offering income tax rebates or credits to installers or households, and capital allowances for landlords.
- Policy options to make low carbon heating the cost-effective measure for households:
    - Use carbon or energy taxes to shape the economics of heating away from fossil fuels towards lower carbon alternatives.
    - Assign carbon standards to energy retailers or distributors to encourage them to support the installation of heat pumps.
    - Stamp Duty reflecting energy and carbon performance could be designed to be revenue neutral.
    - Policy could support HaaS.

  - Green mortgages, whereby borrowing against the building, or for a new purchase, could also be used to resolve the issue associated with upfront capital.

- Recommended policy measures include:
  - Financial support through public funding to support switch to heat pumps.
  - Structural incentives by shifting the tax and levy burden to fossil fuels used for heating, e.g. gas.
  - Medium to long-term regulation to enable a market led approach.
- Financial support will be needed in the early years of deployment to offset higher investment costs and support low income households to at least 2030

Business models for residential retrofit in the UK: a critical assessment of five key archetypes (Brown, 2018)

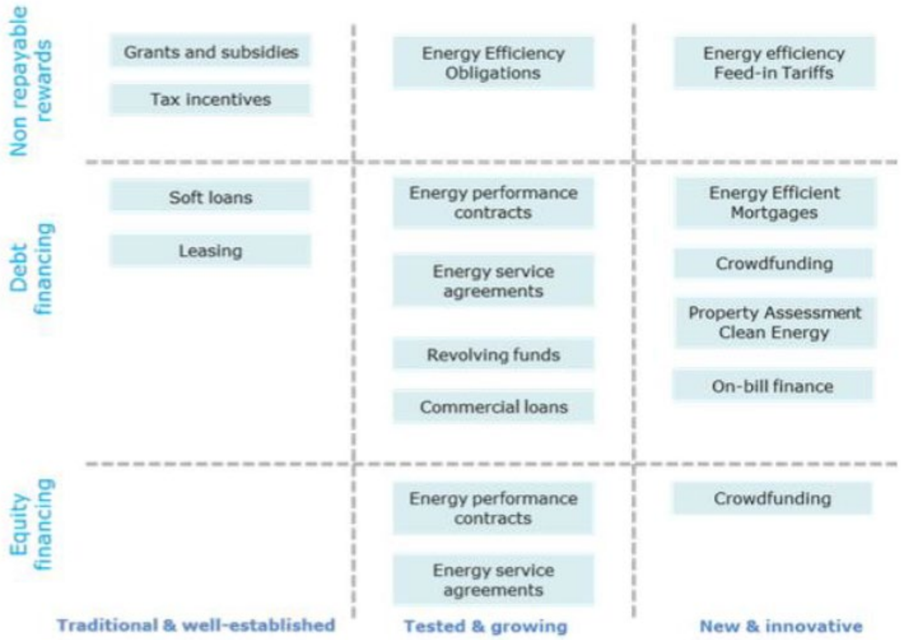
- The paper describes and compares five distinct business model archetypes:
  - the atomised market model: based on estimate energy cost and carbon savings, individual retrofit measures installed by separate contractors.
  - market intermediation model: implementation of government subsidy schemes, focused on single measures, with a basic energy audit, and a simplified consumer journey through an intermediary organisation.
  - one-stop-shop: an integrated supply chain and customer interface that provides a single point of contact for the customer.
  - energy services agreement: building occupants receive an energy performance guarantee for specific energy services, such as temperature or amount of hot water, normally over a period of 15 years or more.
  - managed energy services agreement: similar to an energy services agreement, except the contracting organisation also takes on responsibility for the payment of the energy bill in an energy supply contract upstream of the customer, providing total energy management.
- The paper discusses the importance of supply chain integration in delivering comprehensive retrofit using the one-stop-shop approach, which can improve the reputation of the industry and simplify the consumer journey.
- The paper includes the components that a successful BM should include:
  - A value proposition focussed upon aesthetics, comfort, health and well-being with guaranteed energy performance savings.
  - An integrated supply chain offering a comprehensive whole-house approach.

  - A customer interface with a single expert point of contact.
  - A financial model that includes a low-cost financing mechanism in the offering.
  - Coordinated governance of these parts through a comprehensive business model.
- Conclusions:
  - Low cost of capital is essential for the viability of long-term comprehensive approaches due to the low rates of return.
  - Energy performance guarantees can reduce perceived risk for investors, and thereby lower cost of capital.
  - An integrated financing package provided with the retrofit is also likely to encourage customer demand.

Feasibility study for a financial instrument and a review of existing retrofit loan schemes (Vaze et al., 2020)

- Financing targeted from pension funds and insurance companies is the principal source of capital capable of providing trillions of dollars of investment for energy efficiency measures. Retrofit funded entirely by government has typically been restricted to fuel-poor households or to cover relatively shallow retrofits, and private finance is now being considered for the deep retrofit of existing homes.
- Market Failures include:
  - Lack of savings – hence Grant or subsidy
  - Long pay-back – FiT plus subsidy etc.
- US Property Assessed Clean Energy (PACE): In the case of the US PACE programmes the source of capital are usually Asset-Backed Securities (ABS) issued by the PACE provider. The lender is repaid through a special assessment on the property tax. PACE’s unique debt collection system reduces the cost of collection and credit risk relative to an unsecured loan. The eligibility for finance is based neither on the individual credit assessments nor the homeowner’s income, though the property owner does need to have a level of equity in the home to qualify. The rate of interest is not subsidised and is not determined by the borrowers’ credit score.
- Recommendations for EuroPACE programme:
  - Lower the cost of finance e.g. interest rate charged.
  - Shorten payback period of measures e.g. through energy efficiency grants.
  - Higher subsidy for deep retrofits.

- Closing the knowledge gap to help homeowners select the most suitable energy



efficiency measures through websites or one-stop-shops, connecting homeowners with contractors through an advisor.

- Aggregate customers to increase the savings per unit.
- Split-incentives that target both owner-occupiers, the rental market and social housing providers.
- Reduce the amount of risk borne by the consumer. Protect lenders against credit risk. This has been done by using a lien against a mortgage in the PACE programme in the USA but has not been attempted in Europe.

- Funding options for energy efficiency measures:

Financing zero carbon heat: Turning up the dial on investment (Green Finance Institute, 2020)

- Summaries of existing Financial offers for new homes, off-grid and on-grid houses.
- Case studies of the following business model/finance solutions:
  - Lending Products:
    - Demand Aggregation Financing: establishes a critical mass in demand in an area to lower the cost of low carbon heating with purchases funded through low interest loans.
    - Green Home Salary Sacrifice Scheme: a tax-efficient method for employees to pay for a heat pump via a hire purchase agreement with their employer or a third-party.

        - Mobilising Secured (mortgages) and Unsecured Finance (personal loans, credit cards): use existing secured or unsecured finance to support the installation of low carbon heating.

    - Institutional Investments:

        - Third Party Asset Infrastructure: investors fund an asset, such as heating infrastructure, which is paid back over time by homeowners.

        - Green Real Estate Investment Trust (REIT): embed environmental criteria into the REIT asset class to attract institutional investment into funding energy efficiency buildings with low carbon heating.

    - Skills, Incentives, Enabling Mechanisms:

        - Zero Carbon Investment Guides: one guide to educate lenders, and another to educate manufacturers, suppliers, and installers about finance options.
        - Tax Credits and Incentives for the Private Rented Sector: better understand the roles tax credits and incentives could play in supporting landlords.
        - National Heat Delivery Body: design a centrally-run, locally-led organisation to provide oversight and central coordination for national heat decarbonisation, which could support standardisation.

    - Tenancy Agreements:

        - All-in Rental Agreements: tenants pay rent each month inclusive of heat (and often other items including internet) to provide a landlord with recoup costs in low carbon heating.

    - Energy Service Products:

        - HaaS: homes are upgraded to high energy performance standards with controls accessed through an app. This manages heating preferences and provides opportunities for cheaper energy. The resident pays for the service through a monthly bill or as part of their rent.

- Barriers to investor and consumer confidence: the lack of long-term demand certainty that is critical for investor and business appetite; difficulty in accessing information about finance options and low awareness of technical solutions; high up-front costs, and the perceived ‘hassle factor’ of low carbon heat installations.
- Further steps necessary to increase confidence and achieve greater scale include levelling the playing field between electric heat and gas prices, and consequently improving the economics of low carbon heating solutions.

C1.2 Medium Relevance

Strategic research and innovation agenda for heat pumps: making the technology ready for mass deployment (Auvray et al., 2021)

- Many OSS are being started, or are already running. One example is SuperHomes2030, which tries to scale up its existing deep retrofit services and expand its proven approach to other countries.
- OSS are going to become more widespread, and they should be considered as essential (supported with funds) for the energy transition.
- They offer first-hand examples of the use and integration of heat pumps with other renewable energy measures.
- OSSs enable the manufacturers and service providers of HPs to collaborate more closely and efficiently.
- In order to successfully apply business models that use heat pump flexibility:
  - The connectivity of the heat pump unit is crucial, as well as tailored controls.
  - Strategic partnerships between players in the power sector, as well as heat pump manufacturers and operators should be encouraged.
  - Technical aspects, such as the development of connectivity, data analysis and control algorithms should be enhanced.

Business Models Using the Flexibility of Heat Pumps – A Discourse (Fischer et al. 2017)

- Operating costs of heat pumps and their optimization (using smart technology to be flexible enough to control best market situation) – relatively technical paper.
- Often the transactional / administrative barriers are too burdensome to justify business models based on accessing these revenue streams. However potential revenue from providing flexibility could be in the region of up to approximately 80 €/kWHP for heat pumps.
- Smart integration of heat pumps in energy systems is complex and risky, but additional revenue can be achieved through business models of this kind.
- To facilitate a flexible heat pump business model requires supportive market conditions and the possibility to combine them with reduced grid and concession fees.
- Strategic partnerships will be beneficial for a successful use of heat pump flexibility.

Fundamental Economic Analysis of Ground Source Heat Pump Markets in North America (Tanguay, 2017)

- Subsidy and economic analysis dependant on gas prices.

- This paper analyses the performance of the North American ground source heat pump market using the framework of a theoretical economic model, which is designed to further research in this area.

A Review of domestic Heat Pumps (Staffell et al., 2017)

- An overview of the cost of Heat pumps (capital costs, installed costs, running costs).
- The technical aspects of heat pumps and their installation are discussed, as well as the capital costs and how these can vary, the benefits of reduced running costs, and availability of the Renewable Heat Incentive to reduce the payback period.

Heat purchase agreements could lower barriers to heat pump adoption (Kircher and Zhang, 2021)

- Paper includes an economic simulation comparing a business model centred on a heat purchase agreement between a user and an aggregator (owner) with a consumer ownership business model for a case study using a single home in the USA.
- The literature review covers consumer ownership and innovative ownership business models.
- The findings are more relevant for further research than for informing heat pump deployment.

Supporting sustainable product service systems: a product selling and leasing model (Kuo et al., 2019)

- This study includes a profit and cost analysis of a heat pump leasing model versus a selling model to evaluate a proposed sustainable product-service system.
- The method proposed in this study could be a reference decision making model for different business models based on different decision strategies.
- Life-cycle coverage.

Prosumers in the post subsidy era: an exploration of new prosumer business models in the UK (Brown et al., 2019)

- Mentions Business Model, however article very specific to prosumer business Model, i.e. those who produce and consume energy – are key actors in energy transitions.
- Becomes more relevant if prosumer business models are explored e.g. for heat pump and solar.
- Heat pumps (and would batteries for example) can act as a ‘Flexibility Service Provider’ and hence open a value pool /balance mechanism value. The current feed-in-tariff for UK prosumers offers an export tariff of £0.0372-0.0524/kWh, but when first introduced offered £0.46/kWh for a small rooftop solar installation.
- Benefits offered to those generating power at the distribution level are to be decreased from £47.30 per kW of capacity to £2 per kW to make the benefits of distributed energy solutions for cost-reflective.

What is prosumerism for? Exploring the normative dimensions of decentralised energy transitions (Brown et al., 2020)

- Energy as a service – Bristol Energy trial of HaaS looks at homeowners which are offered a flat rate tariff based on the internal temperature of their home. Through a series of energy monitoring devices, the trial aims to generate data on occupant behaviour and heating system operation, for future refinement of the offering.
- Article not heat pump specific but worth getting more detail about the Bristol City Case as a frontrunner in energy transition.
- Current UK electricity market regulations give consumers the right to switch energy supplier within 28 days. This requirement is a significant risk for business models offering an energy service, where the costs of measures and improvements are paid off gradually over a long-time. Further, current state aid requirements actually prevent Bristol Energy from acting as the preferred energy supplier for government-owned buildings and energy assets in the city. Equally, authorities in the UK face significant restrictions on their ability to borrow for infrastructure projects, hampering their entrepreneurial ambitions.

Emerging Business Models for Energy Storage: Applications to the power, transport and heat sectors (Stucchi et al., 2016)

- This paper evaluates the different emerging business models regarding energy storage systems in three case studies: power, transport, and heat (heat pumps in residential buildings) sectors.
- The main barriers to these kind of arrangements (e,g. solar and heat pump system) is the high costs of installation. The renewable heat incentive was very small compared to the required investment cost. Two further barriers identified are those related to the complexity of the system (due to the combination of two providers for the solar incentive and heat pump incentive) and the lack of certification system for this kind of arrangement.
- The paper cites a lack of incentives for promoting optimal integration systems and there are still regulatory, market, technical and economic issues to resolve.

Enabling Conditions for Consumer-Centric Business Models in the UK Energy Market (Hardy and Mazur, 2020)

- Results of a Workshop:
    - Five key issues that will need to be addressed in the near-term to enable energy business model innovation in the United Kingdom market. These are: 1) Create space to enable business model innovation; 2) Ensure smart devices and data are interoperable and secure; 3) Improve the service standards of energy businesses; 4) Ensure business models work for consumers in all situations; and 5) Implement targeted carbon regulation.

Hot transformations: Governing rapid and deep household heating transitions in China, Denmark, Finland and the United Kingdom (Sovacool and Martiskainen, 2020)

- Equity, or the equal distribution of benefits and/or sharing of costs, seems to play an elemental role in effective heating governance. This plays out through the use of public funds or taxes, cost-sharing, national policy targets, and/or the achievement of positive externalities or co-benefits.
- Denmark - funded their research on Combined Heat and Power (CHP) through taxes so that its costs were spread among all electricity customers. Such taxes were equitable because they were based on the amount of energy consumed and funded just by ratepayers instead of all taxpayers (or externalized to society).
- Finland - Public subsidies for heating system renovations were available for all households during the 2000s, while taxes for fossil fuels continued to rise. These encouraged energy efficiency improvements and a move away particularly from oil-based heating systems. In addition, the heat pump transition has created jobs in manufacturing, installation and maintenance, with the Finnish Heat Pump Association (SULPU) estimating that in 2017 the sector employed 3000 people in Finland
- In Finland various energy grants were available from the government between 2003 and 2013 to make heat pumps more affordable and inclusive to all, including both urban and rural areas. Grants were removed in 2013.
- Finland also harnessed user and peer-to-peer learning, and innovation, alongside national and European policies and incentives

Heat as a Service – Understanding evidence needs and research gaps (Marques et al., 2019)

- HaaS trial in Bristol.
- Workshop participants ideas on HaaS in relation to financing and business:
    - Consumer/ supplier partnerships.
    - Innovative heat fund.
    - Low interest loans tied to home:
    - HaaS offered by 3rd parties.
    - Guarantee that energy bills will not go up as a result of HaaS.
    - Interest free loans from government.
    - Understanding well-established HaaS model outside UK.
    - Buy / build to let with energy included.
    - HaaS demonstrators.
    - Long term capital.
- The conclusions from this report are:

   - More trials are needed to address consumer concerns and lack of understanding of HaaS. Potential solutions include more trials to find out what motivates different consumers, education policies to ensure ongoing behavioural change, trialling HaaS with a retrofit package and introduce a competitive system for saving carbon at various levels, e.g., individual, local, regional, national.

   - HaaS requires supportive policies, especially for market regulation as current regulations are restrictive.

   - Proposed solutions should focus on how to make data open, interoperable and secure, use Internet of Things (IoT) enabling technology for big data generation, deploy large scale trials with data capture, optimisation and alerts.

   - Best practice energy services from other countries can inform HaaS development in the UK. Offered suggestions include interest free loans from government, a heat innovation fund, consumer/supplier partnerships, buy/build to let with energy package included and long-term capital.

   - To facilitate HaaS, opportunities for consumers, experts, and industry to work together should be explored. HaaS stakeholders agreed for the need to connect installers, consumers and experts to facilitate HaaS.

C1.3 Low Relevance

Domestic heat pumps in the UK: user behaviour, satisfaction, and performance (Caird et al., 2012)

- Less about business models and finance - rather surveys on consumer behaviour.

Pathways to high penetration of heat pumps (Frontier Economics, 2013)

- Policy measures.

Hear Pump Retrofit in London (Carbon Trust, 2020)

- Review of potential CO2 savings, capital costs, operating costs and lifetime costs of ownership of heat pump retrofit, through the context of 15 London buildings.
- Paper does not discuss the state of financing models or give examples of solutions being deployed at scale.
- It does present the costs and benefits of heat pump deployment comparing the renewable heat initiative (RHI) and a proposed heat pump grant, finding the cost of heat pump installations to be higher than the gas boiler installations and the grant to fall short of covering the costs of installation and retrofit.

C1.4 No Relevance

Transforming a residential building cluster into electricity prosumers in Sweden: Optimal design of a coupled PV-heat pump-thermal storage-electric vehicle system (Huang et al., 2019)

- Article very specific to prosumer business model, i.e. those who produce and consume renewable energy.
- Aggregating the building energy demand and supply through energy sharing could increase the optimal capacity of PV systems maximising the amount of energy produced and consumed on site. This is because energy sharing makes the PV system more versatile, and thus the whole energy cluster is more efficient at consuming the electricity produced on-site.
- This paper becomes relevant if business models are explored for heat pump with solar for example.
- This paper is a modelling case study rather than a practical installation and is therefore not relevant as per the search criteria defined in the methodology.

Techno-economic review of solar heat pump systems for residential heating applications (Poppi et al., 2018)

- Economic performance of heat pump, and policy with not much provided on actual business models or finance solutions.

C2 Question 2 – Low Voltage Grid Issues

The evidence base for Question 2 contains 229 publications, 35 of these were identified as being relevant and 10 publications were added by technical experts. In total, 45 publications were reviewed by the technical expert for Question 2.

Most publications in this evidence base were authored by academics (32/45). It was not possible to review two of the relevant publications, as they could not be accessed and have therefore been excluded from the following analysis. The majority of publications reviewed had high quality methodologies (21/43) with the remaining having medium quality methodologies. The relevance of the evidence to the research question was similar, with (19/45) publications having high relevance and (14/45) having medium relevance.

Table 16 shows the topics mentioned in the relevant publications for Question 2. The majority of topics covered in the relevant evidence base were centred on grid impact learnings and mitigation, followed by deployment size planning.

Table 16: Topics mentioned in the relevant publications for Question 2

Topics	Q2 - low voltage grid Issues

Grid impact learnings	30
Grid impact mitigation	26
Deployment size planning	21
Demand-side response/demand-side management	19
Time of use tariffs	10

The following section outlines the key learnings captured from the review of the medium and highly relevant evidence for Question 2.

C2.1 High Relevance

Technical Feasibility of Electric Heating in Rural Off-Gas Grid Dwellings (Delta Energy & Environment, 2018)

- This report presents an estimation of the number of rural off-gas grid houses that could have electric heating systems installed, considering technical feasibility at a dwelling level and at the level of the local electricity network.
- The effects of adding additional insulation measures to the dwellings has been explored. They describe an Excel based model with input from real field data.
- Helpful report for deployment size planning as it assesses the number of houses suitable to be electrified, based on current grid constraints and house insulation levels.
- Useful for assessing grid impact caused by installation of heat pumps and for identifying the major barriers to technical feasibility of electric heating.
- It also describes options available to accommodate electric heating: more efficient electric heating, increase heat pump capacity, smart control, integration of thermal and/or electric storage.

A review of flexibility of residential electricity demand as climate solution in four EU countries (Mata et al, 2020)

- A significant reduction of CO2 emissions can be achieved by deploying renewables and various changes in loads including heat pumps.
- The literature identifies substantial economic, technical, and behavioural benefits from implementing flexibility measures.
- The high cost of advances smart metering /energy metering systems is a significant barrier to some flexible business models.
- The current regulatory framework would need to change to facilitate participation in flexibility measures.

- The largest absolute potentials were found in countries that had electricity production with higher carbon intensity such as Germany and the UK.
- If loads were shifted to maximize the use of renewables, carbon emissions from residential electricity could be reduced by up to 22% in the UK.
- Risks identified as a result of flexibility measures include higher peaks and congestion on the LV network in low-price hours.

Air Source Heat Pumps field studies: A systematic literature review (Carroll et al., 2020)

- The review identifies what ASHP data is publicly available to assist other researchers in building, testing and analysing ASHP efficiency models.
- A cost benefit analysis shows that policies can encourage uptake of heat pumps.

Changing Load Profiles (Western Power Distribution, 2018)

- An important factor when assessing network loading is the level of diversity between the same type of demand and the coincidences of different demand types. This principle of diversity is particularly important when looking at some of the new demand types with less predictable behaviour that are starting to connect to the network, such as heat pumps.
- In the analysed Western Power Distribution network, the winter peak demand from a direct electric back up / top up for a heat pump system, created significant network issues, with an additional 5.7kW, due to the 3kW electric back-up. The gas back-up heat pump at winter peak demand can switch to entirely gas.
- The use of flexibility services will be able to defer or remove the need for traditional reinforcements.
- If no smart solutions of flexibility were to be used, loadings could increase by as much as 60%.
- If it was possible to implement the smart solutions described above, only a 19% rise in peak demand would occur, but a 28% increase in the energy requirement.
- The two emerging demand technologies that are forecast to impact the networks the most are EVs and heat pumps. The factors influencing heat pump energy requirements and operation (i.e. ambient temperature) are better understood than EVs, but the type of heat pump and actual uptake is more uncertain.

Coordinated Energy Management for a cluster of buildings through Deep Reinforcement Learning (Pinto et al., 2021)

- The paper explores the opportunity to enhance energy flexibility of a cluster of buildings.
- Results show a reduction of operational costs of about 4%, together with a decrease of peak electrical demand up to 12%. Furthermore, the control strategy allows a reduction of the average daily peak and average peak-to-average ratio by 10 and 6% respectively.

Decarbonising heat with optimal PV and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation (Rinaldi et al, 2021)

- The Swiss energy system is analyzed. Results show that the replacement of current residential heating systems by heat pumps is feasible with additional energy system investments, which are outlined.
- Results suggest that policy makers and utility companies should target first envelope retrofitting to avoid large investment in electricity storage technologies.
- The use of heat pumps alongside PVs and storage increases the flexibility of the system and can help save cost to the occupier and reduces grid impact.
- A shift of heat pump operation from night to midday which increases local PV self-consumption, resulting in larger PV deployment.
- increased deployment of HPs will result in increased deployment of solar PV and storage.

Decarbonizing heat with PV-coupled heat pumps supported by electricity and heat storage: Impacts and trade-offs for prosumers and the grid (Pena-Bello et al., 2021)

- An open-source model to optimize solar photovoltaic (PV)-coupled heat pumps is developed.
- The use of heat storage reduces the levelized cost of meeting the electricity demand between 13–26% compared to the baseline case without storage, in particular when heat pumps are used for both space heating and domestic hot water.
- The quality of the envelope plays a key role and heat pumps can double the power peak demand in poorly insulated houses. Energy retrofitting is very effective (up to 50% smaller peak flow in well insulated buildings) for decreasing the grid impacts of heating electrification.
- The implementation and design of capacity-based tariffs are fundamental to relieve grid impacts from PV, batteries and electric heating with heat pumps.

Domestic demand-side response with heat pumps: controls and tariffs (Sweetnam et al, 2019)

- The results of a trial (involving 31 homes) of a new control system that aims to optimize heat pump operation were shown.
- Pre-heating in advance of high price periods led to overheating and noise which was unacceptable to participants; however, short-term demand reductions could be delivered with minimal impact on internal temperatures.
- Consumption during high price periods was greater than expected and new peaks in demand were created in advance of price increases. The higher than expected peaks were partly due to participant intervention and partly due to the physical nature of the dwelling and heating systems.
- Future control systems could overcome some of the issues identified through more effective zoning, using temperature caps or installing dedicated heat storage, but these may either limit the available flexibility or be challenging to achieve.

- Aspects of the ease of use of the control system were shown to be important in determining participants' attitudes towards using it.

Heat pump and PV impact on residential low-voltage distribution grids as a function of building and district properties (Protopapadaki et al, 2017)

- This paper aims to assess and quantify in a probabilistic way the impact of PV and heat pumps on the low-voltage distribution grid, as a function of building and district properties in Belgium.
- Air-source heat pumps have a greater impact on the studied feeders than PV, in terms of loading and voltage magnitude.
- Rural feeders are more prone to overloading and under-voltage problems than urban ones. For large rural feeders, cable overloading can be expected already from 30% heat pump penetration, depending on the cable, while voltage problems start usually at slightly higher percentages.
- Building characteristics show high correlations with the examined grid performance indicators.
- Electrification of heating would require different network design due to higher load simultaneity, in particular, with presence of electric auxiliary elements for the heat pump.

Heat pumps and our low-carbon future: A comprehensive review (Singh Gaur et al., 2021)

- Many studies conclude that ground source heat pumps are better options than air source heat pumps in colder regions.
- Water source heat pumps are the most efficient in comparison to ASHPs and ground source heat pumps (GSHPs). However, the requirement of a waterbody or storage tank and other environmental concerns limit their widespread uptake rate.
- Heat pumps in conjunction with thermal energy storage provide system wide flexibility services such as load shifting, peak shaving, and demand side management, thereby ensuring increased utilisation of excess renewable energy during off-peak periods.
- Heat pumps can efficiently replace conventional heating systems in old dwellings only if they are well-insulated, thereby increasing the overall cost of retrofitting.

IEA HPT Programme Annex 42: Heat Pumps in Smart Grids (Delta Energy and Environment, 2018)

- In the UK, demand side response (DSR) with heat pumps is possible in many of today's buildings, whether positive or negative balancing energy is required or a flexible hourly tariff is to be followed.
- The length of time of such DSR events during which no violation of the comfort standards occurs, is very dependent on the thermal characteristics of the building.
- In the harsher conditions of a 1-in-20 winter, significant improvements of both the thermal mass and the insulation are likely to be required in many UK buildings in order to achieve sufficient levels of flexibility.

- The aggregation of heat pumps can be done successfully in order to provide DSR. Pools of heat pumps can be managed in a way that ensures that a minimum DSR capacity is provided and that no grid congestion occurs.
- The required metering infrastructure (smart meters) for billing hourly or half-hourly consumption needs to be deployed.
- The paper identifies research gaps and the need for ongoing support on both academic and commercial research and development into the building stock's suitability for DSR, smart heat pump control technologies, heat storage solutions suitable for the UK market and the requirements and behaviours of end-customers.
- An important question that remains to be answered for the UK is the occurrence of conflicting DSR requests from the balancing responsible party (National Grid) and the distribution network operators and their impact on the availability of DSR.

Impact of low voltage – connected low carbon technologies on network utilisation (Bilton et al, 2014)

- An example network which forms part of UK Power Networks' London network was used as a test case. For an average outdoor temperature of -4ºC and a penetration level of 20% of households owning heat pumps, the peak daily load increased by 72% above baseline.
- Additional transformer headroom is required to account for cold conditions in which diversity is much reduced and the Coefficient of Performance (COP) of the heat pumps collapses, even at lower level of 5% uptake amongst domestic customers.
- In particularly cold conditions, the maximum demand for a typical home with heat pump technology can reach 4.5kW after diversity, with 3.6kW from the heat pump operating steady state.
- Further research is recommended including "modelling the impact of Heat Pumps on the network with different levels of insulation; neutral voltage rise modelling and individual feeder analyses.

Low Carbon Heat: Heat Pumps in London (Greater London Authority, 2018)

- Heat pumps can provide the greatest energy efficiency and carbon saving benefits when the overall heating / hot water system is designed around the characteristics of heat pumps.
- Building fabric energy efficiency is a robust strategy to reduce peak demand on the electricity grid caused by heat pumps.
- For relatively inefficient traditional buildings there is little potential for demand side management of heat pumps, as the rates of heat loss are so high that it is not possible to effectively reduce the power consumption of heat pumps during periods of peak demand without an impact on the comfort of occupants.
- For new buildings, significantly reduced rates of heat loss could enable demand side management of heat pumps, even during very cold periods.

- The most robust route to decarbonise heating while mitigating impacts on the electricity grid for new developments is likely to be through excellent levels of building fabric efficiency combined with moderate thermal mass and smart heating controls.

Probabilistic Impact Assessment of Low Carbon Technologies in LV Distribution Systems (Navarro-Espinosa, Ochoa, 2016)

- The paper considers the impact on the UK grid at various levels of penetration of low carbon technologies (LCTs), such as heat pumps and solar PVs. The methodology is applied to 128 real UK LV feeders.
- If the Distribution Network Operator (DNO) does not accept any potential problem, then the issues start at 20% of penetration level (percentage of houses with the LCT).
- If the DNO is able to accept a certain level of potential problems (e.g. 0.12% probability of having more than 1% of customers with voltage problems), then the problems can be considered to start at 30% of penetration level.
- If the DNO is not able to accept that congestion happens with a probability higher than 0.05, problems start at a penetration of 30%.
- A ranking analysis carried out to determine the LCT that produces problems at the earliest penetrations revealed that both electric heat pumps and solar PV systems are in the top place: 60% of the feeders with problems will see early issues due to electric heat pumps whilst for 40% it will be due to solar PV systems.
- Key finding is that each feeder is unique with regards how it is loaded, with some feeders handling 100% heat pump penetration while others result is become heavily overloaded.
- They found feeders with fewer customers (<25) had much fewer issues than feeders with more customers.
- This paper also seems to have graphs that will allow you to calculate an actual number of customers that will cause an impact.

Reduction of heat pump induced peak electricity use and required generation capacity through thermal energy storage and demand response (Baeten, et al., 2017) – Abstract only.

- Demand response of heat pump systems could aid in reducing peak loads on the electricity grid.
- Extra flexibility can be added in the form of a thermal energy storage tank.
- Results indicate that the proposed demand response strategy reduces the required peak load capacity substantially with only a small increase in costs for the consumer.
- When adding a large hot water storage tank, the required additional capacity is nearly eliminated. Increasing the storage tank size increases the amount of energy that is shifted.
- If demand response is desired by the grid operator, heat pump owners should be encouraged to participate by remunerating them for their additional expenses.

Review of control strategies for improving the energy flexibility provided by heat pump systems in buildings (Péan, et al., 2019)

- Two supervisory control strategies for activating energy flexibility with heat pumps have been reviewed and classified between: Rule-based controls (RBC) and Model Predictive Control (MPC). RBC are simple heuristic methods which generally have the form “if (condition is verified), then (action is triggered)”. RBC usually rely on the monitoring of a specific “trigger” parameter (PV power, room temperature for example) on which a threshold value has been fixed. When the threshold is reached, the operation of the heat pump is changed, according to the predefined strategy. On the other hand, Model Predictive Control is a more complex strategy, which relies on a model of the building to project its behaviour in the future. MPC is an optimization problem, therefore it intends to find the best solution for the management of the heat pump operation, over a certain time horizon and within certain constraints.
- The strength of RBC strategies resides in their simplicity of implementation, and they already achieve satisfactory performance, though not optimal.
- MPC is more complex and costly to integrate but yields substantially better results.
- A great majority of the studied literature relies on simulations rather than implementations in real contexts, therefore more experimental work is needed.
- For activating the energy flexibility of buildings, a thermal storage is necessary.

UK smart grid development: An expert assessment of the benefits, pitfalls and functions (Xenias, et al, 2015)

- This research provides a systematic in-depth exploration of private-, public- and third sector stakeholder views on Smart Grid (SG) development in the UK.
- Experts agree on the need to make electrical delivery smarter and highlight a range of potential benefits resulting from SGs, including efficiencies, cost reductions, and network balancing.
- The importance of policy stability to promote investment and reduce industry inertia, and the necessity of developing smart metering and data exchange standards, communication protocols and active network management were highlighted.
- Expert participants expected SGs to deliver significant cost reductions via deferred investment, efficiency savings.
- Data protection and privacy were clearly identified as a problematic aspect, inherent to smarter girds, where much greater transparency on how, where and when energy is used will be essential.
- Allowing integration of active loads such as heat pumps is one of the key SG functions.
- There is a need for clear rules on connection charges, and for incentive programmes (with variable pricing) to support management of active loads.
- Consumer engagement, DSR, and monitoring of the low voltage network are significantly important to facilitate the roll-out of active loads.

Unbalanced voltage compensation in low voltage residential AC grids (Trintis et al, 2016)

- The control performance of an active front end converter in field operation in a residential grid situated in Bornholm, Denmark was investigated for four different use cases.
- Active front end converter loads can have a positive influence on the low voltage residential grids. A power converter supplying a heat pump can balance the grid voltages over a whole feeder up to the transformer station, having a rated power of just 10% compared to the feeder's maximum load.
- It is however required a careful design of the controllers and the converter hardware and software to ensure that the converter actions are positive and not negative.
- It is necessary for mass deployment of such technology to be tested with multiple converters in the grid, to ensure the interaction between them.
- Coordinated references given by the DSOs can minimise the power flow to the medium voltage network to increase the overall system efficiency.

C2.2 Medium Relevance

Heating with wind: Economics of heat pumps and variable renewables (Ruhnau, et al., 2020)

- Heat pumps will only be cost-efficient if their load cost plus investment (running cost plus initial outlay) outperform the total cost of alternative heating technologies.
- Flexible heat pump operation with thermal storage could mitigate this rise in load cost and hence support the competitiveness of heat pumps.
- Adequate price signals are essential for the economically optimal deployment of heat pumps, including different heat pump technologies and thermal storage. Heat pumps should turn away from collective standard load profiles towards individual settlement with smart meters that considers variable wholesale prices.

Improving energy self-sufficiency of a renovated residential neighbourhood with heat pumps by analysing smart meter data (Walker et al., 2021)

- The implementation of a neighbourhood-level energy management system (NEMS) and clustering similar demand patterns significantly reduce the data burden for prediction and computational time required while increasing the prediction accuracy.
- To accommodate all-electric heating systems, it is important to increase the self-sufficiency of buildings. This study showed that with the involvement of data-driven prediction and control algorithms this target can be achieved during the spring/summer months.

Possible effects of future domestic heat pump installations on the UK energy supply (Gupta, Irving, 2014)

- Estimates of embedded carbon showed a substantial reduction - about 32% - from heat pump systems compared with gas boilers.

- Estimates of carbon emissions from operation showed that the UK target of 80% reduction is approachable under the 2050 scenario of about 15.6 million heat pump installations but is dependent on the parallel decarbonisation of the UK electricity supply.

Heat Pumps and Their Role in Decarbonising Heating Sector: A Comprehensive Review (Gaur et al., 2019)

- Paper focuses mainly on the pros and cons of the different types of heat pumps with various renewable technologies and operational strategies. It also discusses the cost savings and the impact on the electricity market. Various modelling frameworks are used to study these impacts.
- The paper assists with point 1 of the question however, point 2 and 3 are not entirely covered.
- The paper proposes potential flexibility services to be provided by heat pumps. It assesses the impact on the grid and the barriers to heat pumps deployment.

A critical evaluation of grid stability and codes, energy storage and smart loads in power systems with wind generation (DlzarAl kez et al., 2020)

- Impacts of large scale renewable power generation on power system dynamics are identified.
- Technological and operational changes are required to the power system when new modern smart technologies such as heat pumps and electric vehicles are introduced.

An area-based modelling approach for planning heating electrification (Calderon et al., 2019)

- An area-based modelling of heat electrification for dwellings in Newcastle is described.
- The impact of domestic electrical heating options on the electrical grid infrastructure and the additional electricity demand on the system are identified.

Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data (Salom et al., 2014)

- It has been shown that curtailment of exported energy during a limited amount of time (1–5%) during the year has a significant impact on the energy actually exported from the building to the grid.
- In order to evaluate the flexibility potential from the owner/user perspective, cost and user acceptance must be considered in future research.

Comparison of load shifting incentives for low-energy buildings with heat pumps to attain grid flexibility benefits (Patteeuw, et al., 2016)

- Multiple scenarios for load shifting application are studied, inspired by time-of-use pricing and direct-load control.

- The study shows reductions in operational costs of the electricity generation system between 0.9% and 5.5%, depending on the number of participating buildings and the share of Renewable Energy Sources (RES) in the electricity generation.
- The authors suggest that a practical implementation of this load shifting approach may be performed centrally, namely by performing the day-ahead optimization of the operation of the electricity generation system and an aggregated formulation of the building portfolio with heat pumps.

Electrification of residential space heating considering coincidental weather events and building thermal inertia: A system-wide planning analysis (Heinen, et al., 2017)

- This paper has demonstrated how a lumped-parameter building sub-model based on an resistor–capacitor circuit analogy can be integrated into a least-cost planning model.
- The planning impact on electricity system adequacy of different weather variables as well as coincidental weather events can be studied.
- The benefits of utilising the thermal inertia of buildings to optimise system-wide performance can be assessed.
- If heat is electrified, the temperature sensitivity of electricity demand increases.
- The increased weather-sensitivity to investment cost also means that reliability metrics and weather test years should be developed to ensure cost-efficient infrastructure development.
- Utilising building thermal inertia enables electricity and heat demand to be partially decoupled through flexible heater operation and building pre-heating while also maintaining the occupants' thermal comfort.

Virtual Inertia Control of Variable Speed Heat Pumps for the Provision of Frequency Support (Ibrahim et al., 2020)

- A variable speed heat pump can provide frequency response with virtual inertia control by changing its power consumption and also providing power during regenerative braking.
- The level of virtual inertia obtained from the heat pumps was quite significant, but dependant on ambient temperatures and the amount of penetration of the demand response controllers.

Experimental testing of variable speed heat pump control strategies for enhancing energy flexibility in buildings (Péan, et al., 2019)

- MPC strategies to control heat pump systems can be implemented with the goals to minimise either the delivered thermal energy to the building, the operational costs of the heat pump, or the CO2 emissions related to the heat pump use.
- The MPC controller is able to perform load-shifting by charging the thermal energy storages at favourable times. The satisfactory performance of the control strategies was

analysed in terms of different indicators, such as costs, comfort, carbon footprint, and energy flexibility.

- The MPC strategy aiming to minimise the operational costs of the heat pump managed to reduce them by 1 to 7% and the one minimizing the marginal CO2 emissions managed to reduce them by 3 to 17%, despite an increase of the actual energy use in most cases.

Heuristic optimization of clusters of heat pumps: A simulation and case study of residential frequency reserve (Romero Rodríguez, et al., 2019)

- Heat pumps can be controlled by a cluster manager and equipped with both electrical and thermal storage systems for flexibility when providing Frequency Restoration Reserve (FRR) to the grid.
- The Demand Response (DR) potential is significant, but for profits to be achieved, particular attention needs to be given to the number of activation times, and most importantly to their duration. Otherwise, it is very difficult for such a framework to be economically viable.
- To successfully implement DR programmes, further control system algorithms at the cluster and aggregator levels need to be studied and applied to effectively manage and coordinate the availability of individual systems in and across households.

DNO tools and systems learning (UK Power Networks, 2014)

- There is increasing needs for integration between systems, particularly more interfacing between information technology and operation technology systems; and an integrated network topology model with connectivity from Grid Supply Points (GSPs) down to customer premises that can be shared between a number of applications.
- The most significant area in which new IT systems will be required is for handling the smart meter data that will become available through the national rollout.
- Messaging gateways to DSR aggregators/owners, and a basic DSR settlement system for validating and authorising payment of their invoices, will also be needed.
- In the forthcoming period, much more data will need to be collected and stored, including secondary supervisory control and data acquisition measurements and data collected from LCTs or consumer premises.

Low Voltage Network Solutions: A First Tier Low Carbon Networks Fund Project (Electricity North West, 2014)

- Probabilistic impact assessment studies were carried out on 128 feeders considering the effects of residential solar PV, electric heat pumps (EHP), electric vehicles (EV) and micro combined heat and power units.
- 45% of the feeders have the first problem due to thermal issues in the EHP case.
- Fitting a transformer with an On Load Tap Changer (OLTC) can improve the hosting capacity of the network.

- Considering the current cost of deploying OLTC-fitted transformers, the traditional cable-based reinforcement remains a cost -effective option to tackle medium penetration levels of LCT (up to 50%).

Numerical study of the electrical load shift capability of a ground source heat pump system with phase change thermal storage (Teamah, Lightstone, 2019)

- The benefits of storage incorporation in a GSHP system on the electrical load shift potential are assessed.
- Thermal energy storage can offset peak demand periods to off-peak hours. The larger the storage volume, the higher the predicted load shift.

On heat pumps in smart grids: A review (Fischer, Madani, 2017)

- Heat pumps, when controlled in an appropriate manner, can help easing the transition to a decentralized energy system accompanied by a higher share of active loads and renewable energy sources.
- Predictive controls are successfully used in the majority of studies, often assuming idealized conditions.
- Topics for future research have been identified including: a transfer of control approaches from simulation to the field, a detailed techno-economic analysis of heat pump systems under smart grid operation, and the design of heat pump systems in order to increase flexibility.

Optimal real-time residential thermal energy management for peak-load shifting with experimental verification (Baniasadi et al., 2018)

- The operation of a GSHP can be managed to produce the desired amount of thermal energy by controlling the volume and temperature of the stored water in the water storage tank while optimizing the operation of the heat distributors to control indoor temperature.
- Simulation and experimental results demonstrate that the proposed thermal energy management system has significant potential for real-time peak-load shifting.

The potential for peak shaving on low voltage distribution networks using electricity storage (Pimm, et al., 2018)

- Battery storage in residential areas can help to alleviate the impacts of heat pumps.
- Small scale electricity storage of the size that is currently being installed within households (e.g. 2 kWh and upwards) has the potential to significantly reduce peak power flows in low voltage networks.
- 2 kWh of battery storage per household could potentially reduce the current peak demand at a low voltage substation in the UK by over 50%.
- Battery storage of 3 kWh per household proved sufficient to keep peak demands at current levels when 100% of space and domestic hot water heating was provided from heat pumps.

Getting on track to net zero: A policy package for a heat pump mass market in the UK. (Lowes et al., 2021)

- A supportive guide to policymakers in the UK.
- It provides comments on actual and forecast uptake if heat pumps, based on existing or forecast data from other sources (e.g. BEIS).
- Predictions are based on confirmed and planned government policy.
- It also provides comments on approaches that have worked elsewhere.
- The objective is to explain the potential options available to policymakers and propose a package of measures for use by policymakers to support UK goals for heat decarbonisation, in terms of financial, structural and regulatory measures.

C3 Question 3 – Roll-Out Facilitation

The evidence base for Question 3 contains 443 publications, only 10 of these were identified as being relevant and 12 additional publications were added by technical experts. In total, 22 publications were reviewed by the technical expert for Question 3.

The majority of publications in this evidence base were authored by academics (13/22) and were based in the UK (18/22). One of the publications couldn't be accessed, so has been excluded from the following analysis. The majority of publications had methodologies of medium quality (12/20) and were of medium (7/20) or low (6/20) relevance to the research question.

Table 17 shows the topics mentioned in the relevant publications for Question 3. The most commonly cited topic in the evidence base was examples of coordination followed by stakeholder coordination.

Table 17: Topics mentioned in the relevant publications for Question 3

Topics	Q3 - roll-out Facilitation
Coordination examples	12
Stakeholder coordination	10
Coordination tools	6

The section below details key learnings from the relevant publications for Question 3 and their reference.

C3.1 High Relevance

Heat Strategy Proposal: A consultation to deliver a fair transition to decarbonised heat (Scottish & Southern Electricity Networks, 2021)

- This company policy document sets out the draft SSE policy for decarbonising heat.
- This identifies some key examples and learning to be taken forward, and some coordination between different stakeholders and communities to accelerate the net zero transition.
- Regional network challenges and opportunities must be considered.
- Develop geographical roadmaps for heat pump uptake. Locally led plans can inform geographical targeting and to specific groups that would benefit from extra support in this transition.
- Support local communities having sufficient resource and capacity to deliver net zero plans. Local Area Energy Plans (LAEPs), Local Heat Energy Efficiency Strategies (LHEES), and Local Network Plans (LNP).
- The importance of partnerships with trusted third-party intermediaries, and the availability of free impartial advice is highlighted.
- Motivations for switching to low-carbon alternatives are varied, and the cost incentive can at times be less effective than other approaches to stakeholder engagement. Trusted community members have a critical and influential role in driving these changes.
- Safeguarding must be built into strategies in order to protect vulnerable customers.
- Providing a single point of contact for all utilities has helped target support, and has made accessing this easier for customers.
- Engagement with customers needs to be clear and targeted to ensure that there is broad awareness of support available and that this is easily accessed.

Domestic Heat Pumps A Best Practise Guide (Microgeneration Certification Scheme Service Company Limited, 2018)

- The guide gives examples of failed installations due to insufficient appreciation of the contractual processes involved (N.B. this is regarding single installations only, there is no evidence for a wide-scale roll-out). This necessitates the need for a sound legal framework to be established before roll-out.
- Comments on 'benchmarking' of installation, commissioning, operating and future maintenance advice. The guide also necessitates the installer to understand and express to the end-user such additional considerations as fuel tariffs and smart control systems. This implies the need for coordination between (amongst others) the technically and financially orientated stakeholders, in order to develop tariffs and smart control systems that are well suited to the various heat pump based domestic heating

systems, that will form part of a large-scale rollout. (No direct evidence has been provided on this regard, however).

Taking the Temperature: A review of energy efficiency and fuel poverty schemes in Scotland (Maiden et al., 2016)

- Author speaks in detail about the inaccuracy of current modelling techniques (disconnect between theoretical performance and post-occupancy performance). Also discusses the effect that 'non-standard homes' tend to show the greatest level of discrepancy between modelled and tested consumption. As such, more research is required to develop more accurate and accountable modelling tools for assessing current state of housing stock, and what specific measures would best be implemented in each area. This needs to be able to account for the most fuel poor, as well as 'hard-to-treat' properties.
- Author claims that relatively few studies have been performed at city-scale, when looking at actual energy consumption. Hence, greater levels of post-occupancy evaluation and modelling needs to be developed to reduce the performance gap and assist in future schemes / trials.
- This paper (like others) discusses the need for a place-based approach to energy efficiency measures as a whole (noting that this would include heat pumps).
- It is suggested that major marketing and communications campaigns need to be rolled out to promote the need, use and personal benefits (health, finance, etc.) of energy efficiency measures (and in this context, heat pumps as a specific measure).

Smart Systems and Heat programme: Phase 2 Summary of key insights and emerging capabilities (Energy Systems Catapult, 2019)

- This paper aims to address the challenge of low-carbon heating by focussing on consumer needs, e.g.
    - Insights into consumer focused 'smart energy services' – digital controls etc.
    - Creating capabilities to support and accelerate uptake of low carbon heating
- Looks at the above in relation to consumer trials of smart energy propositions, local area energy planning and market transformations (new business models etc.)
- Trail showed how a digital platform for home energy services could be successful
    - Proof of concept home energy services gateway (HESG)
    - This shows the importance of establishing genuine interoperability between devices, controls and service providers via open standards and protocols with consideration always aimed towards the consumer (consumer-centric).
- Usage data can reveal consumers preference and aid in system design improvements, to create consumer pull
- Pilot studies like this are highly useful for moving forward – large scale trial environments in consumers' homes will be a major national asset, for innovators,

businesses involved in the UK supply chain and to inform future decarbonisation strategy.

- Area-based analysis and solution deemed necessary for successful future rollouts, informed by key modelling results – need to equip local council with the correct modelling and data collection tools. This data, and outlined planning processes can aid in local engagement processes to ensure the correct local partnerships are founded
- Further work required to consolidate evidence and establish these decision making frameworks, funding streams, and planning processes

Regarding market transformations, firstly, digitalisation is key, for: greater system flexibility, better peak energy management and cost-effectiveness, amongst others. Secondly, smart energy service business models help to align incentives throughout energy product and service supply chain and help to create consumer demand. Thirdly, interoperability between controls is deemed necessary, the author suggests industry standards or regulations the unleash full potential

C3.2 Medium Relevance

Case study 7: Greenhouse Gas Emissions Reductions in France: The Agriculture Sector (ClimateXChange, 2017)

- A series of reviews of relevant national Climate Change and Energy strategies, plans and policies from elsewhere in Europe - with three case studies on heat.
- There is a summary of the Swedish uptake of Heat Pumps. Notably:
  - Investment in the technology at a national level made a marked different from other Northern European countries and has looks to have assisted in improved technologies relevant to Swedish use.
  - Trust in Swedish manufacturers seems to aid uptake.

Reducing carbon, tackling fuel poverty: adoption and performance of air-source heat pumps in East Yorkshire, UK (Owen, et al, 2013)

- Technology attributes, i.e. heat pump functionality, are deemed to be the fundamental driver for adoption, or lack thereof, for a potential ASHP user.
- The importance of area-based analysis is stressed, under the justification that technology selection and hence implementation is heavily influenced by the place characteristic of the area under investigation. It is suggested that place and technology considerations are brought together in order to achieve social policy goals.

DNO tools and systems learning – Report D2 (UK Power Networks, 2014)

- This is a report by UKPN that looks at the data gathered through smart meters and smart grid IT systems can assist in predicting the future grid requirements and network planning.

- Data collection and management will facilitate the implementation of ToU tariffs.

Retrofit for All Toolkit (Kaur Kellay, 2021)

- A toolkit that was developed to be centred around the tenant (experiencing energy vulnerability) as opposed to funder orientated (existing supply chain). Outlining the overlap between client-side requirements (healthy home, low fuel costs, etc.) with scheme manager outputs (reducing fuel poverty and carbon emissions, maintaining economic viability, etc.).
    - Scheme managers in this instance are noted as local authority, housing associations, energy companies, charity, community sector, etc.
- Resident-client defines the resident tenant as the client, alongside the commissioning organisation.
- Desk-based research and ten interviews across 3 stakeholder groups - small sample size and qualitative outputs only, but good basis for further development. Also, the principle behind the study is well centred and represents an important way of looking at the various stakeholders, their inputs and desired outputs.
- 5 stage process outlined as:
    - Initial contact and sign up.
    - Survey.
    - Design.
    - Onsite / Installation.
    - Post-works.
- Provides scheme design considerations and hence a scheme manager checklist required to provide a resident-client orientated approach to an energy efficiency scheme throughout the entire cycle.
- Suggestions seem relevant and actionable, no direct link to a large-scale roll-out but the processes should be easily scalable.

Europe towards positive energy districts (Gollner, 2020)

- A review with stakeholder input of 'positive energy district' projects across Europe - examples of cities and districts where sustainable systems have been implemented including heat pump systems.
- The review references 'Innovation', 'Success Factors' and 'Challenges/Barriers' for each scheme, highlighted by the stakeholders, which forms a useful note of reference of where innovation may result in improved outcomes.
- The Fleuriaye West site at Carqufou (Nantes) in France looked to develop a site with a neutral impact with regards both energy and environment, whilst also implementing a transposable economic model limiting the use of public funding.

  - Innovative stakeholder engagement included a special collaboration with the Distribution Grid Manager in order to optimise electrical infrastructure.
  - Success factors included a collaborative approach to stakeholder engagement
  - Challenges/Barriers listed included legal and tax challenges, the raising the competency of the building companies, and making the construction of Passive buildings more economical and replicable.
- Innovative collaboration with communities, local governments, electrical utility providers and funding groups is a repeated theme in the success of schemes, but also listed as barriers where this has been less successful
- This is not heat pump focused, so the learning may be more related to barriers at the macro level, and transferable strategies that could be considered for the roll-out of heat pumps.

C3.3 Low Relevance

Technology, users and everyday lives: the installation and use of heating systems and energy efficient technologies in UK households (Brown & Swan, 2012)

- One of the main concluding remarks is regarding the technology itself. Tenants found these retrofit technologies confusing and lacking intuitive design
- The authors postulate that this confusion arises from the technology being developed in isolation, i.e. disconnected from the actions of the end-user.
- It is concluded that there needs to be a greater degree of connectivity in stakeholder engagement, from supply to use, to ensure the technology is well received, is used effectively, and as such is operated efficiently.

Adoption of Renewable Home Heating Systems: An Agent-Based Model of Heat Pump Systems in Ireland (Meles & Ryan, 2020)

- This paper looks the outcomes of a computational method (based on actual survey data in 2018) that simulates what changes to various differing barriers to uptake may have on heat pump roll-out in Ireland.
- The findings highlight that policy interventions that increase the levels of awareness about the availability of the technology and its features, the associated benefits, the availability of home grants and insurance to curtail the uncertainty regarding the technology could be important to facilitate the adoption process.
- While this is theory focused, it does use real survey data, and offers reasonable method for interrogating the data to assist in defining what policy may assist the roll-out of heat pumps.

Heat Pumps and Their Role in Decarbonising Heating Sector: A Comprehensive Review (Singh Gaur et al., 2019)

- This is a literature review of different types of heat pumps and some of their barriers to uptake. While some barriers are highlighted, these are technical, and not related to the roll out of the technology.
- Some useful references and discussion about the use with thermal stores and solar thermal systems used in conjunction with heat pumps.

Will domestic consumers take up the renewable heat incentive? An analysis of the barriers to heat pump adoption using agent-based modelling (Snape, Boait, Rylatt, 2015)

- Modelling of adoption rate of Renewable Heat Incentive (RHI) uptake for heat pumps, for the demographic of people studied herein, suggests that adoption rate is sensitive to non-economic factors, despite the presence of a robust economic incentive. A so called end-user ‘Hassle Factor’ involved in the installation and operational stages of heat pump deployment.
- The author suggests that the use of installer package deals, designed to satisfy all requirements detailed in an RHI program, would provide the predictability and speed of install that consumes desire.
- There is a need for further, more directed policy change in order to address the concerns of end-users.

C3.4 No Relevance

2021 Guide on Heat Pumps and DNO Engagement with Local Authorities or Building Owners (Western Power Distribution, 2021)

- The guide speaks about the need to understand the fabric of the building, the occupancy pattern, the required internal climate, etc. No direct examples of how this would be managed, and more specifically, how this would dictate design decisions. However, the guide validates the necessity to do so and as such opens the question of how and which stakeholders can manage the collection and flow of this (and other relevant) data.

Domestic energy mapping to enable area-based whole house retrofits - single solution paper (Gupta & Gregg, 2020) – Abstract only

- This paper analyses the use of heat mapping tools for quickly assessing the requirements for energy efficient house retrofits in Oxford.
- This is a relevant innovation that will help identify clusters of homes that may or may not be appropriate.

C4 Question 4 – Heat Pump Performance and Deployment

The evidence base for Question 4 contains 691 publications, 17 of these were identified as being relevant and 23 additional publications were added by technical experts.

The majority of publications in this evidence base were authored by academics (20/40) and or by government (15/40). The publications were predominantly based in the UK (18/36) and or Northern Europe (20/40). Two of the publications couldn't be accessed, so have been excluded from the following analysis. The majority of publications had methodologies of high (17/38) or medium quality (17/38), and their relevance to the research question was weighted towards low relevance (11/38) and no relevance (9/38).

Table 18 shows the topics mentioned in the relevant publications for Question 4. The most commonly cited topic in the evidence base was package structure with little mention of deployment tools.

Table 18: Topics mentioned in the relevant publications for Question 4

Topics	Q4 - performance and deployment
Package structure	12
Performance improvements	8
Deployment tools	1

The section details findings from the relevant publications for Question 4.

C4.1 High Relevance

Superhomes 2.0: Best Practice Guide for ASHP Retrofit (O'Reilly et al., 2019)

- This guide refers to 20 homes in Ireland that were monitored for this project.
- Preliminary research found factors such as above average compressor modulation and compressor cycling have a negative effect on ASHP performance.
- Heat pump performance is optimised when interruptions in its cycle are minimised.
- To achieve the performance stated by the manufacturers, realistic performance and COP targets need to be set and referred to in the design, installation and commissioning of the ASHP and the following factors well managed:
    - Correct flow temperature range.
    - Reduction in excessive compressor modulation.
    - Avoidance of compressor cycling.
    - Realistic time and set-back temperature control.

    - The location of thermostats, particularly where one thermostat is used to control a zone. Wireless thermostats which can be moved around to find the most representative location.
- The output required for space heating exceeds that required for domestic hot water, so it is not necessary to add a factor to the design capacity of the heat pump.
- The data showed energy consumption for defrost cycles should be around 1% of total annual energy consumed for a well-design and installed heat pump system, even after considering variations in external temperatures.

Strategic research and innovation agenda for heat pumps: making the technology ready for mass deployment (Auvray et al., 2021)

- Not a research paper based on trial data but outlines possible future technology improvements as topics for future research and innovation.
- Suggests a System of Systems perspective – innovations could be on each sub system as well as on the system as a whole.
- The research and innovation agenda should connect heat pumps to the other parts of the system to meet the ultimate goal of a whole. As heat pumps couple heating, cooling, and electricity sectors, inter- and trans-disciplinary.
- Design:
    - Modularity:
        - Boost modularity of heat pump systems by establishing standards and guidance.
        - Benefits operation by ensuring spare parts being interchangeable and industrial scale production of modular units.
        - Increases the ease of replacing or upgrading of modules.
        - Potential innovation in modular system approaches.
    - Circularity:
        - HP ability to recover and re-use waste heat for heating or cooling.
        - Heat pumps specifically designed for easy re-use of parts and for maintenance.
    - Hyper Efficiency:
        - Increase efficiency by optimising source and sink systems.
        - Increase the efficiency of the source and sink systems such as by minimising energy consumption of pumps or fans.
        - Improve temperature in source or sink systems to increase overall heat pump system efficiency.
        - Easily connect to other technologies and storage media.
- Manufacturing:

  - Advanced computer modelling & simulation to improve system efficiency and solve problems.
  - Mass production and 3d printing, such as of heat exchangers. This could increase efficiency, reduce costs or improve reliability.
  - Integrated connectivity to improve UI.
  - Standardisation of components and connectors.
  - Improve supply chain resilience.
  - Upgrade the skills of manufacturing personnel.
- Installation:
  - Development of plug and play software and hardware.
  - Increase ease of installation – such needing using fewer components.
  - Pre-commissioning tools to simplify planning of the suitable heat pump system.
- Maintenance and Operation:
  - Easy to use and understand user interface.
  - Internet of things (IoT) data gathering and connectivity.
  - AI algorithms for optimisation.
  - Software updates, remote diagnostics & Predictive maintenance.

Monitoring of Non-Domestic Renewable Heat Incentive Ground-Source & Water-Source Heat Pumps: Final Report (Hughes, 2018)

- Results from monitoring a sample of 28 ground- and water-source non-domestic Renewable Heat Incentive (RHI) heat pump installations, with a combined capacity of 1600 kWTH.
- 21 sites were monitored from mid-2014 to June 2016 with an additional 7 sites monitored from March 2015 to June 2016.
- Out of the 19 heat pumps with performance results, 15 had performance better than SPFH2 (SPF in heating mode) ≥2.5. Six heat pumps achieved an SPFH2 ≥3.0, while four demonstrated an SPFH2 <2.5.
- There is not one overriding factor that affects heat pump performance, but more careful design, installation, commissioning, and operation are all required to ensure a high-performance system. It is always important to:
  - Maximise the source temperature at the heat pump evaporator inlet.
  - Minimise the temperature at the heat pump condenser outlet.
  - Minimise the energy used by secondary equipment.
  - Avoid unnecessary heat losses and use the correct configuration of controls.

- Each heat pump installation will be different and therefore each system needs to be designed and optimised for that application.
- Heat metering set ups on eight installations were not of sufficient standard for performance analysis due to a range of errors.
- Heat pump systems with underfloor heating were not found to have significantly higher performance than those using radiators.
- The hours of operations (e.g. weekday office hours to 24/7) were not found to significantly influence performance.
- No significant difference in performance between heat pumps from different manufacturers.

Detailed analysis from the first phase of the Energy Saving Trust's heat pump field trial (Dunbabin and Wickins, 2012)

- The Energy Saving Trust monitored 83 residential heat pump installations across Great Britain from April 2009 to April 2010.
- Findings from Phase I of the project were published in, "Getting warmer: a field trial of heat pumps", in September 2010.
- Fifteen different manufacturers heat pumps were included in the trial.
- Several factors contribute to under-performance. Results from the trial and approximate calculations were used to establish the impact of certain factors on system efficiency. The following table presents the factors in two categories: design and installation or commissioning:

Category	Factor	Estimated potential loss of performance as measured by system efficiency
Design	Under-sizing of heat pump	Up to 1.5
	Under-sizing of borehole/ground loop	Up to 0.7
	Insufficient insulation of pipework and hot water cylinders	0.3–0.6
	Under-sizing of hot water cylinder	Up to 0.4
	Too many circulation pumps	0.1–0.3
	Over-sizing/control strategy results in over-use of back-up heating	<0.1
Installation/ commissioning	Central heating flow temperature too high: radiators	0.2–0.4
	Central heating flow temperature too high: under-floor heating	
	Circulation pumps always on	0.1–0.3

Final report on analysis of heat pump data from the renewable heat premium payment (RHPP) scheme (Lowe et al., 2017)

- Report on the same trial covered in the publication from Gleeson et al. (2016).
- For heat pumps with good part load performance, it is possible, in principle, to move between intermittent and continuous heating, simultaneously increasing annual heat demand, and reducing electricity consumption and CO2 emissions.

- The headline results from an analysis of sub samples of the data are:
    - A wide distribution of seasonal performance factors (SPF), due to metering errors and differences in efficiency, because of, for example, differences in control, and the use of other sources of heating (e.g. immersion heaters).
    - The statistical analysis showed that although GSHPs performed better than ASHPs, and ASHP sites with underfloor heating performed better than those without, it was not clear how this differed from owner occupied to social landlord tenant properties; there are multiple factors which impact on SPF.
    - The results below were produced from a study of factors that influence performance, e.g. flow temperature, cycle length and domestic hot water immersion:
        - No single factor accounted for good or poor performance.
        - Many ASHPs have 10 minute on-to-on cycling patterns and the median for GSHPs was longer at 18 minutes. This study did not show a correlation between median on-to-on cycle length and monthly coefficient of performance (COP), but this may have been influenced by heat metering error.
        - Average winter space heating flow temperatures in the study were generally low (<45°C); such temperatures are a sign of good design and should result in good efficiencies.
        - During winter, on average, underfloor heating temperatures were lower than those for systems using radiators. There are several technical factors that influence these temperatures.
        - Above average use of electric immersion for heating domestic hot water, was shown to have a negative effect on the SPF. On average, immersion heater electricity consumption formed 12% of the total, but over half of the sites with an SPF<2 had immersion heating responsible for > 20% of the total.

Low Carbon Heat: Heat Pumps in London (Greater London Authority, 2018)

- The factor that most affect efficiency is the difference between the heat source temperature and the hot water being produced. The closer these temperatures are, the higher the heat pump efficiency. These temperatures are influenced by the heat pump design, installation and operation and must be understood if the system is to operate efficiently.
- If the temperatures are not addressed, there is a significant risk of a performance gap, and the heat pump systems won’t deliver the optimum carbon and cost savings.
- Heat pumps work best when this temperature difference does not exceed 30-40ºC. The temperature difference associated with generating domestic hot water is usually higher than this optimal range in the UK climate.

- The consultancy was commissioned by the Greater London Authority to carry out the following tasks: a review of the heat pump market; an impact assessment of heat pump deployment in new buildings; an assessment of the risks of heat pump deployment.
- Consumer concerns on heat pumps (from Etude project experience and literature review) include: high energy costs if the wrong heat pump system has been installed; the high complexity of some systems; problems with maintenance due to low number of capable companies.
- The authors believe there are too many measures of efficiency that are not comparable.
- A lack of consumer understanding often leads to excessive use of secondary direct electric e.g. back-up electric immersion heater and therefore increased running costs.
- The consensus is consumers need to be provided with greater education on the control and operations of heat pumps. User related control errors can be detrimental to a heat pump's efficiency.

Monitoring Air Source Heat Pumps in Domestic Properties (National Energy, 2013)

- This project evaluated the social impact of 16 ASHPs in two off-gas grid communities.
- They compared the performance of the heat pump systems with the properties previous systems and monitored their social acceptability.
- Findings from the study included:
    - The systems and controls were not fully understood by the tenants and resulted in over and under heating, or tenants resorting to "manually control" their systems.
    - Tenants did not understand the role or the existence of different electric tariffs.
    - Tenants did not understand the need for or the benefits of the new systems and had not been involved in deciding where controls or tanks would be placed.
- Based on the conclusions the authors have the following recommendations:
    - More training on how to use the controls that are easy to understand.
    - More support from energy advisors on selecting and moving to the appropriate energy tariff when a new heating system is installed.
    - Tenants should be involved in design and installation decisions from the start, where it will affect their living space.
    - Energy usage should be logged automatically to increase data confidence and detail.
    - Systems should be designed and installed according to strict standards.

Detailed analysis from the second phase of the Energy Saving Trust's heat pump field trial (Dunbabin, Charlick and Green, 2013)

- This report presents the results from monitoring 38 heat pumps with interventions to improve their performance. Interventions included:
  - Major (exchanging an ill-sized heat pump).
  - Medium (upgrading radiators, installing a buffer tank, replacing circulating pumps with variable speed direct current (DC) pumps).
  - Minor (altering controls, refilling the ground loop, adding insulation).
- 6 new heat pump systems were added to the sample and were monitored from April 2011 to March 2012.
- Major interventions increased the system SPF at nine of the twelve sites (by more than 0.5 at three sites and between ~0.2 and ~0.47 at an additional five sites).
- During the phase II study both heat pumps were replaced, an exhaust heat immersion was switched off, and circulation pumps were replaced with low energy DC pumps. This resulted in the Coefficient of Performance (COP) increasing from 1.63 to 2.70.
- Nine heat pumps were replaced, and another was moved closer to the house, reducing considerable heat loss from the pipes.
- Some heat pumps (5) were also replaced with smaller heat pumps due to oversizing.

Detailed analysis of data from heat pumps installed via the Renewable Heat Premium Payment Scheme (Gleeson et al., 2016)

- A report on the second heat pump field trial established by the Department of Energy and Climate Change (DECC) in conjunction with the Renewable Heat Premium Payment (RHPP) grant scheme.
- The trial included several types of ground-source HP systems (GSHPs) and air source HP systems (ASHPs), located in domestic properties across Great Britain not supplied with natural gas.
- 700 sites were monitored as the basis for an evaluation of their performance.
- 328 properties were Registered Social Housing and the remainder were owner-occupied properties. The sample covered a range of dwelling construction types, sizes, ages and households.
- The results showed that on average heat pump systems were above the seasonal performance factor (SPF) = 2.5 limit required to be classed as a renewable energy source (mean SPF for ASHP of 2.56 and 2.92 for GSHPs).
- However, a large proportion of ASHPs (45%) and just over 20% of GSHPs had an SPF below the 2.5 limit and were therefore not operating with enough efficiency to be classed as a renewable energy source.

Annex 49 Field monitoring in nZEB with heat pump – Part 2 Report (Heat Pump Centre, 2020)

- Contributions from participating countries with more than 15 projects in different types of Net Zero energy buildings with heat pumps.

- In numerous projects SPF values around 5 and higher were achieved, which is above the industry average. This was in part due to the high performance of the building envelope.
- The projects saw a good operation of the heat pump systems in monitoring periods spanning several years and recognised that monitoring provides the opportunity for optimisation, particularly in the year following installation.
- Many of the residential systems had good performance and high SPF of the heat pump, between 4 and 5 and above. Optimisation options were identified for systems with lower SPFs, so their performance can be expected to improve in the future.

C4.2 Medium Relevance

New tools to support the designing of efficient and reliable ground source heat exchangers: the Cheap-GSHPs databases and maps (Galgaro et al., 2019)

- This paper briefly introduces the content of the databases behind an online Decision Support System (DSS) that was developed to support the design of new closed loop geo-exchange systems.
- The DSS contains several databases and tools that collect and build on the preliminary data and information that are necessary during the sizing phase of a GSHP project, such as the geological and drilling aspects as well as the heating and cooling building demand.
- This project aimed to reduce the total installation cost of closed-loop shallow geothermal systems.
- It appears this tool is no longer available.

Domestic heat pumps in the UK: User behaviour, satisfaction and performance (Caird, Roy and Potter, 2012)

- The study discussed in this paper is covered by other papers but results from a survey of user experience are worth considering.
- The relatively high satisfaction levels of heat pump systems compared to previous heating systems suggest users experienced few problems using their heat pump system.
- However, a significant minority of users experienced one or more problems.
- The reasons for the underperformance of many UK field trials is not known, but likely reasons revealed in this user study include a lack of understanding among UK consumers of heat pumps and their operation, and the multiple contractors involved during installation works, which sometimes led to poor quality installations.
- One action suggested is to reduce the noise levels of heat pumps, especially ASHPs in small homes and social housing, where the unit may be situated nearby the living areas.

Implementation Report for Smart Community Demonstration Project in Greater Manchester, UK (Greater Manchester Combined Authority, 2017)

- Installed 550 heat pumps in properties in Manchester as part of a trial into heat pumps and demand response.
- Study stated that there is a need for a quick assessment of network reinforcement requirements would be required for any future large-scale HP rollout programme.
- A key finding of the project is that the take up of new technologies needs to be supported with user friendly interface.
- The study does not provide information on the performance of the heat pumps themselves but focuses on demand response aspects which are out of scope for this study.
- A number of properties were found to be unsuitable for heat pumps for a range of reasons, including lack of space, lack of sufficient insulation, asbestos issues with existing properties and tenants dropping out due to the level of disruption required.
- The study also found that by relaying on the thermal inertia of the building fabric, demand in most cases could be comfortably shifted by 1 hour.

Appendix D: Further Research

Question 1 (financial innovations) would benefit from further research on the suitability of different financial models for different consumer profiles, as this discussion was missing from the evidence base. It would also be beneficial to research the implications of other economic factors that may become relevant, such as carbon taxes, on financial and business models.

Several recommendations for further research have arisen from the evidence assessment for Question 2 (low voltage grid issues), because of limited data on the concentrated deployment of heat pumps. Suggestions for further research are:

- Better understanding of consumer energy use after heat pump installation.
- An assessment of the future climate and how this will affect the use of heat pumps.
- A better understanding of the impact and benefits of grid flexibility/DSR on the end user.
- What technical changes are required to prepare the grid for the largescale deployment of heat pumps and what are their costs.
- Bottom-up modelling of aggregated heat pump demand going up the voltage level, ideally informed by measured data / trial data.
- Further research will likely involve modelling, and as such the approaches to modelling should be standardised to ensure results can be compared across studies.

The recommendations for further research for Question 3 (roll-out facilitation) are also informed by the large number of gaps in the evidence base, they include:

- Finding examples of coordination efforts between the stakeholders required for the large-scale roll-out of heat pumps, as the evidence was limited in this area.
- Taking learnings from live or completed heat pump trials in the UK, as well as recommendations for targeted innovation to improve large-scale roll-out.
- “Europe towards positive energy districts” provides high-level stakeholder input from 'positive energy district' projects across Europe where sustainable systems have been implemented (including heat pump systems), it would be beneficial to gather further research on these projects to learn from the stakeholder coordination effort.
- Models will support the large-scale roll-out of heat pumps and it would be beneficial to increase the accuracy of modelling and, as mentioned for Question 2, standardise the process where possible.
- Further research and perhaps a review of stakeholder tools to facilitate heat pump deployment, as the evidence included individual papers on consumer tools, heat mapping tools and distribution network operator tools (e.g. smart meters), but this doesn’t cover all stakeholders.

Further research for Question 4 (Heat Pump Performance and Deployment) should explore whether better guidance or heat pump monitoring and optimisation is required to address prevalent performance issues. Different approaches to optimisation were used in the small-scale heat pump trials, if larger-scale trials were to take place it would be beneficial to learn what solutions are most effective in solving performance issues. The evidence base found that the on-going monitoring of heat pumps is essential, so further research should identify the potential improvements from on-going monitoring and optimisation. Another recommendation for further research is to review tools for heat pump system improvement, as this represents a gap in the literature.

Overall, the evidence base did not uncover extensive research from heat pump trials worldwide. Recommendations for further research include seeking learnings from trials and heat pump deployment in New Zealand, where their Heat Smart Programme has improved insulation in 230,000 homes and heat pumps are becoming the low carbon heating technology of choice. It would also be beneficial to seek learnings from the deployment of heat pumps in Japan, where heat pumps are widely deployed (c.4m units by 2012) to provide both heating and cooling and were an integral part of early smart grid trials.

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