HEAT PUMP READY | Department for Energy Security & Net Zero

Part of the Net Zero Innovation Portfolio

Innovation in heat pump technology and manufacturing

Learnings from the Heat Pump Ready programme

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1. Introduction

1.1. About Heat Pump Ready

Heat Pump Ready is part of the UK Government's £1 billion Net Zero Innovation Portfolio which provided funding for low-carbon technologies and systems and aimed to decrease the costs of decarbonisation, helping enable the UK to end its contribution to climate change.

Heat Pump Ready, led by the Department for Energy Security and Net Zero (DESNZ), aimed to accelerate heat pump adoption in the UK. The programme supported the development of new tools, technologies and business models to:

1. Improve the survey, design and installation process for heat pumps
2. Improve the customer journey for heat pump adoption
3. Develop smart and flexible home energy systems utilising heat pumps
4. Create new business models to finance heat pump installations and maintenance
5. Reduce the lifetime costs of heat pumps through innovations in technology and manufacturing
6. Develop new approaches to heat pump deployment at high-density

1.2. Report objectives and audience

This report summarises key learnings from Heat Pump Ready projects focused on innovation in heat pump technology and manufacturing. Learnings are structured according to specific innovation needs identified under this theme. Short summaries of the individual projects funded under this theme are located in Appendix A.

The purpose of this report is to share insights into the innovations supported by the Heat Pump Ready programme with the wider heat pump sector. The primary audience is organisations and workers involved in the design, development, delivery, financing, installation and maintenance of heat pump technology.

Similar reports on the lessons learned against the other Heat Pump Ready themes, more detailed case studies on individual projects and programme evaluation reports can be found on the Heat Pump Ready website.

1.3. Relevant projects – Innovation in heat pump technology and manufacturing

Table 1: Summary of Heat Pump Ready projects focused on innovation in heat pump technology

Project name	Objectives	Summary
Clear Blue Energy The Flexible Heat Pump	Increase the efficiency of heat pump units Utilise thermal storage to improve efficiency and flexibility	Developed a high-efficiency prototype heat pump that integrates a thermal storage unit into the refrigeration cycle to recover and reuse heat, boosting SCOP by up to 20% and enabling more efficient defrost cycles.
FeTu NATURALHEAT	Increase the efficiency of heat pump units Develop heat pumps suitable for a wider range of homes	Designed a sustainable heat pump using natural refrigerants and recyclable materials to achieve high seasonal efficiency, compact size, and low noise output.
ICAX Heat Pump Manufacturing Automation	Reduce costs and improve quality in heat pump manufacturing	Designed and tested elements of an automated robotic manufacturing system and adapted heat pump designs to be compatible with this system.
Kensa Highly Flexible Storage Heat Pump	Utilise thermal storage to improve efficiency and flexibility; Develop smart control technologies to improve efficiency in operation	Created a heat pump integrated with Phase Change Material (PCM) thermal storage and smart controls to reduce grid impact, enhance efficiency, and lower customer costs through load shifting.
Mixergy Making Efficient Systems around	Develop smart controls to improve efficiency in operation	Integrated advanced thermal storage and smart controls to improve system performance, reduce installation time, and enhance real-world heat pump efficiency.

Heat Pumps (MESH)	Develop modular and pre-fabricated designs for quicker installation Consolidate the central heating buffer vessel and hot water cylinder into one tank.	
NUSKU Packaged Heat Pump for Distress Purchases	Develop heat pumps suitable for a wider range of homes Develop smart control technologies to improve efficiency in operation	Developed an all-in-one, externally sited heat pump with an integrated controller designed for quick installation and compatibility with time-of-use tariffs to achieve comfort-cost parity with gas boilers.
Thermo-electric Conversion Systems (TCS) Two-Stage Thermoelectric Heat Pump	Develop heat pumps suitable for a wider range of homes Increase the efficiency of heat pump units	Designed a compact solid-state thermoelectric heat pump that, achieves high efficiency and complete modulation that is suitable for constrained spaces and a range of other situations where vapour compression heat pumps may not be.
Vital Energi Therma Hub	Develop modular and prefabricated designs for quicker installation Utilise thermal storage to improve efficiency and flexibility	Developed a modular heat pump unit for mid and high-rise buildings that integrates high-temperature thermal storage Phase Change Material (PCM) to deliver heat affordably and flexibly through a Heat as a Service model.
Ventive Modular Heat Pumps for Microfactory Assembly	Develop modular and prefabricated designs for quicker installation Reduce costs and improve quality in heat pump manufacturing Utilise thermal storage to improve efficiency and flexibility	Created a modular exhaust air heat pump system with Phase Change Material (PCM) storage and a semi-automated cell-based manufacturing process to reduce costs and enhance flexibility for retrofits and new builds.

1.4. Key learnings - Innovation in heat pump technology and manufacturing

Heat Pump Ready Stream 2 projects trialled a variety of innovations in heat pump technology and manufacturing that can be grouped under six core objectives:

1. Increasing the efficiency of the heat pump unit

Projects explored several approaches to improving heat pump efficiency. Clear Blue Energy integrated technology to capture waste heat from the vapour compression cycle, with early-stage lab tests identifying potential SCOP gains of up to 20%. TCS developed a novel thermoelectric, solid-state heat pump offering 100% modulation and CoPs of up to 4.9. Kensa and Mixergy focused on system design and control improvements to reduce short cycling, while Nusku developed a closed-loop controller that cut heat pump cycling by 25%. These innovations show promising routes to delivering higher efficiency heat pumps, although it should be noted that most results remain confined to lab or pilot testing at this stage.

2. Using thermal storage to improve heat pump system efficiency and flexibility

Several projects looked at integrating thermal storage into heat pump system design to enhance system flexibility and reduce peak demand. Kensa incorporated Phase Change Material (PCM) modules into the heat pump unit, achieving a 21% increase in domestic hot water efficiency. Mixergy's Aggregated Thermal Inertia (ATI) cylinder acts as both buffer and DHW store, enabling the optimisation of system efficiency, particularly when used flexibly with time-of-use tariffs. Clear Blue Energy used an integrated storage vessel to recover and reuse waste heat from the compression cycle, including for defrost cycles. These innovations demonstrate that thermal storage can support more efficient and more flexible operation of heat pump systems. The project findings highlight that there are challenges in integrating Phase Change Material effectively into heat pump systems and that advanced controls are of critical importance to optimising flexible system performance.

3. Developing smart controls to improve efficiency in operation

Three projects demonstrated the value of smart controls in real-world performance. Kensa developed controls to manage its Phase Change Material system in response to variable tariffs. Mixergy deployed AI based controls to manage the Aggregated Thermal Inertia (ATI) system and scheduling of the heat pump operation in response to time of use tariffs.

Initial testing on 20 homes showed a 15-40% improvement in energy efficiency compared to conventional systems. Nusku's closed-loop controller optimised performance and cost under time-of-use pricing. These results confirm that intelligent control strategies are essential to unlock efficiency.

4. Developing modular and pre-fabricated heat pumps for quicker installation

Several projects explored the potential for modular and prefabricated heat pump system designs to streamline deployment. Ventive developed modular units aimed to reduce installation time on-site. Vital Energi’s Therma Hub offers a prefabricated solution for communally heated, mid and high-rise blocks of flats, minimising on-site works. Mixergy aimed to streamline installation by removing the need for separate hydraulic components such as buffers, low loss headers and hot water cylinders, thereby reducing installation complexity. The project's findings highlight the potential for prefabricated systems to expedite and enhance the quality of heat pump installations, although validation of these outcomes in real-world settings is limited.

5. Developing heat pumps suitable for a wider range of homes and situations

Several projects addressed well-known barriers to retrofitting heat pumps into existing homes. Nusku developed a high-temperature, all-in-one, externally sited unit for rapid boiler replacement where internal space for a cylinder is limited. TCS tested a compact, low-noise thermoelectric design that is significantly smaller than traditional heat pumps and can offer 100% modulation for situations where heat demand may be highly variable. Vital Energi targeted multi-occupancy buildings with an external, modular system that can be installed within a small footprint outside the building. These projects demonstrate great potential for increasing the suitability of heat pumps for difficult-to-decarbonise homes.

6. Reducing costs and improving quality in heat pump manufacturing

Several projects focused on manufacturing innovation to support cost reduction and scalability. ICAX developed and tested automated assembly of key components including the utilisation of an autonomous guided vehicle (AGV) as well as the use of robotics in braising. Ventive designed a cell-based micro-factory for modular EAHP units, though progress was disrupted by a partner's insolvency. Mixergy reduced part count and installation time through component integration, estimating a 30% cost saving. These approaches show potential for cost-effective scale-up, though development timelines proved challenging.

2. Detailed project learnings

1.5. Increasing the efficiency of heat pump systems

A number of projects funded under Stream 2 of the Heat Pump Ready programme set out to increase the seasonal efficiency of heat pump systems. While most of these initiatives remain in the prototyping or early testing stages, they collectively highlight a range of promising technical strategies for boosting efficiency.

- **The Flexible Heat Pump (Clear Blue Energy)** aimed to increase seasonal efficiency by integrating a compact thermal storage device within the vapour compression cycle. The core innovation involves recovering heat from the high-temperature liquid refrigerant after it exits the condenser, storing it in a buffer, and reintroducing it into the heating circuit. This approach aims to reduce compressor load and enables defrosting without interrupting heat delivery. Clear Blue has developed the concept through 5kW and 12kW prototypes using an R290 refrigerant. Early-stage lab tests suggest a potential SCOP improvement of up to 20% over conventional systems is possible, although these results have not yet been independently validated.

- **NATURALHEAT (FeTu)** targeted a SCOP of 4.0 or greater through the use of natural refrigerants and over 95% recyclable materials. The project also sought to reduce noise, maintenance demands, and the overall physical footprint of the heat pump. The proposed system combines sustainability with performance by using components with a long design life and simplified mechanical structures. At the time of reporting, the system design has been refined and a test rig has been established, but empirical performance data has not yet been published.

- **Two-Stage Thermoelectric Heat Pump (TCS)** explored an alternative thermoelectric heat pump architecture based on the Peltier effect, using both air and greywater as thermal sources. The system comprises a two-stage configuration integrating an accumulator thermal store and advanced control algorithms. Multiple prototypes were developed and tested, with one water-source unit reportedly achieving thermal output exceeding 20kW. Coefficient of Performance (CoP) values were observed to improve from 4.5 to 4.9 during testing. While these results exceed expectations, it is important to note that the system remains in the prototype phase and commercial-scale verification is still pending.

- **Highly Flexible Storage Heat Pump (Kensa)** focused on increasing efficiency through the integration of phase change material (PCM) thermal storage into the refrigeration circuit. By recovering and storing superheat during the compression cycle, the heat pump can subsequently deliver space heating and domestic hot water using stored energy. The internal variant of the unit reached prototype stage and demonstrated efficiency gains of approximately 7% for space heating and 21% for hot water provision in lab simulations. However, these figures are based on internal testing and have not been independently corroborated.
- **MESH (Mixergy)** addressed efficiency losses associated with short cycling by integrating thermal storage and buffer functions into a single component using its Aggregated Thermal Inertia (ATI) technology. By combining hardware and software innovations, the system reduces the frequency of compressor start-stop cycles, which are known to degrade performance. Lab and early field testing indicated energy efficiency gains of 15% to 40%, depending on configuration and user behaviour. These improvements were attributed to both better thermal management and optimised operation scheduling through AI-based controls.
- **Packaged Heat Pump (Nusku)** sought to improve real-world performance and user cost outcomes by developing a closed-loop controller tailored to its high-temperature packaged heat pump unit. The system is designed to maintain comfort parity with gas boilers, particularly in retrofit or distress purchase scenarios. Thermal modelling suggests a 20% reduction in space heating costs when paired with a time-of-use tariff and pre-heating strategy. A key innovation is the controller's ability to reduce compressor power cycling by over 25%, thereby improving reliability and lifetime performance. These outcomes are based on testing at the Salford Energy House and simulation studies.

1.6. Using thermal storage to improve efficiency and flexibility

Several projects under Stream 2 explored integrating thermal storage technologies to improve heat pump systems' efficiency, operational flexibility, and grid responsiveness. The primary innovations in this area involved using phase change materials (PCMs), thermal buffering within the refrigeration cycle, and control strategies to optimise charging and discharging cycles. These approaches aimed to enable load shifting, reduce peak demand, and enhance overall system efficiency. While commercial deployment has not yet been realised, the results of lab testing and early-stage simulations provide insights into the potential of these technologies.

- The **Highly Flexible Storage Heat Pump** project **(Kensa)** integrated PCM-based thermal stores directly into the heat pump unit, with the goal of improving both efficiency and flexibility. The PCM units store thermal energy recovered during periods of excess compressor output and release it during high-demand periods or when electricity is more expensive. Two variants of the HFSHP were designed, internal and external, using Sunamp's 58°C PCM modules. Simulation studies and controlled testing showed improved energy utilisation, with estimated efficiency gains of 7% for space heating and 21% for domestic hot water. Kensa undertook annual energy forecast simulations for various household types which showed that the optimised control strategy could reduce annual space heating costs by 20% under certain time-of-use tariffs, with the greatest saving achieved by smaller and better-insulated properties.

- **MESH (Mixergy)** used its ATI system to provide thermal buffering by combining the functions of a buffer vessel and a hot water cylinder into a single integrated unit. The thermal store is managed via software that models the thermal inertia of the home and schedules heat pump operation to align with off-peak electricity tariffs. Field trial data from 20 homes (10 ATI, 10 control) showed efficiency improvements of 15–40%, attributed in part to the system's ability to shift heat generation outside of peak periods. While the control strategy is a key enabler of these savings, the thermal storage component is critical to ensuring user comfort is maintained despite variations in heat pump output.

- The **Flexible Heat Pump** project **(Clear Blue Energy)** incorporated a compact thermal store into the refrigeration cycle itself, enabling the recovery and reuse of heat from the refrigerant stream. This internal heat storage mechanism allows for continued heat delivery during the defrost cycle—a period when traditional heat pumps typically suspend heating output. This innovation has the potential to reduce defrost-related performance losses and increase seasonal efficiency. Prototypes using this system have been constructed and tested in laboratory settings, with results indicating operational viability, though full integration with wider control systems remains in development.

- **Two-Stage Thermoelectric Heat Pump (TCS)** included a thermal accumulator as part of its integrated two-stage system. The accumulator works in tandem with thermoelectric modules to buffer energy during periods of low demand and release it during peak times. This should enable smoother operation of the thermoelectric modules and reduces the requirement for real-time thermal generation.

- **Ventive Modular Heat Pump** integrated PCM modules into an exhaust air heat pump system. The PCM provided a store of thermal energy that could be used to supplement peak demand periods and improve the responsiveness of the system. Initial testing revealed challenges in achieving consistent melting of the PCM at low temperatures, which led to modifications in the refrigeration cycle including a change of compressor and refrigerant. Although this resulted in a lower coefficient of performance (COP ≈ 3), it demonstrated the technical feasibility of incorporating thermal storage into compact systems. Further work is needed to improve efficiency and consistency in PCM operation.

- **Therma Hub (Vital Energi)** utilised both hot water storage and composite phase change material (CPCM) as integrated thermal stores in a modular heat pump designed for multi-occupancy buildings. The system stores energy during periods of low grid demand and discharges it to meet heat demand peaks or provide flexibility services. Although full CPCM performance testing is still underway, early testing suggests that both heat pump output and CPCM thermal store energy density exceeded design expectations, indicating strong potential to buffer and shift significant thermal loads.

1.7. Reducing costs and improving quality through innovation in heat pump manufacturing

A subset of Stream 2 projects specifically addressed the challenge of reducing capital and operational costs associated with heat pump manufacturing. These efforts included the adoption of advanced manufacturing techniques such as robotic automation, modular design, and integrated system simplification. The primary goal was to enhance consistency, reduce labour input, and scale production capabilities, all while maintaining or improving product quality. The initiatives remain in development and have not yet reached full-scale commercial deployment, though early-stage results suggest clear potential for cost savings and manufacturing improvements.

- **Heat Pump Manufacturing Automation (ICAX)** focused on considering where the heat pump manufacturing process could be automated through robotic assembly. The project’s key innovations included adapting heat pump designs to be compatible with automation. ICAX partially constructed and tested a robotic cell which considered the role for robotics in undertaking braising processes.

- **Modular Heat Pumps for Cell-Based Microfactory Assembly (Ventive)** aimed to reduce manufacturing costs by developing a modular product architecture and a semi-automated, cell-based production process. The technical innovation involved designing modular components, such as heat exchangers and PCM thermal storage units, that could be assembled in parallel using standardised interfaces. Ventive set up a prototype micro-factory, incorporating robotic cells, mobile trolleys, and an end-of-line (EOL) test station. Although one key partner exited the project midstream, the team successfully relocated and resumed development. Early results indicated that modularity helped reduce part complexity and simplified assembly procedures. However, due to system redesigns required by PCM performance issues, the full efficiency gains of modular manufacturing are still to be validated.

- **MESH (Mixergy)** addressed cost reduction through system integration rather than automation. The project's ATI design replaced multiple hydraulic components—such as buffer tanks, low-loss headers, and circulation pumps—with a single integrated unit combining domestic hot water storage and space heating functionality. This simplification reduces part count, installation time, and required training for installers. Mixergy projected that scaling the ATI system could reduce the cost of hydraulic components by 30% relative to conventional systems, although this figure excludes the potential cost premium of a smart controller. Initial installations confirmed the system was straightforward to install using standard heat pump training.

1.8. Develop smart controls to improve efficiency in operation

Several Stream 2 projects developed advanced control strategies to improve heat pump system efficiency and operational flexibility. These smart controls aim to optimise system performance under varying environmental and user conditions by enabling demand forecasting, dynamic scheduling, and integration with tariff signals. The control technologies remain largely in prototype or field-trial stages, but results indicate significant potential to reduce energy use and improve cost-effectiveness, particularly when paired with thermal storage or system integration.

- **Highly Flexible Storage Heat Pump (Kensa)** designed a control system capable of managing the interaction between a PCM thermal store and household heating demand. A thermal block model simulated heat transfer through system components and the building envelope, enabling the controller to determine the optimal charge and discharge strategy under different heating schedules and tariff profiles. Smart controls also allowed the heat pump to shift operation to off-peak hours, reduce strain on the electricity grid, and respond to user comfort preferences. Forecast simulations indicated potential space heating cost reductions of up to 20%.

- **MESH (Mixergy)** integrated both device-level controls (within the heat pump and thermal store) and cloud-based controls (at the server level), enabling the system to respond to tariff signals, forecast demand, and optimise performance remotely. This layered approach improves efficiency and supports demand-side response by coordinating operations across multiple homes or systems. Using machine learning algorithms and a digital twin of the household, the control system dynamically scheduled heating operation to align with user demand patterns and real-time energy pricing. It also reduced short cycling by predicting heat loss and recovery rates. Early field trials showed improvements in energy efficiency ranging from 15% to 40% depending on the scenario. The higher end of these savings (around 40%) was observed under optimal conditions that maximise the benefits of both the ATI cylinder and flexible operation strategies, i.e. households on time-of-use tariffs that can enable scheduling of heat pump operation during off-peak periods.

- **Packaged Heat Pump (Nusku)** developed a closed-loop controller that manages heat pump operation based on temperature feedback and user-defined comfort levels. The controller was designed to optimise performance under fixed and time-of-use tariffs. During testing at Salford Energy House and in simulations, the system achieved cost parity with gas boilers under favourable conditions. The control logic significantly reduced power cycling—by over 25%.

1.9. Developing modular and pre-fabricated heat pumps for quicker installation

Projects in this category addressed the need to simplify and accelerate the deployment of heat pumps through modularity and prefabrication. These innovations aimed to reduce installation time, decrease the required skill level of installers, and improve the repeatability and consistency of installations. Modular design also has implications for manufacturing and servicing, potentially lowering lifecycle costs and enabling product standardisation.

- **Therma Hub (Vital Energi)** developed a prefabricated unit incorporating a high-temperature heat pump, hot water store, and CPCM thermal storage, all packaged for external siting in dense housing contexts. Designed for deployment in mid- and high-rise buildings, the Therma Hub is intended to be sited externally to overcome space constraints and allow for factory-based quality control. The system remains under testing, but initial deployment suggests the concept is viable for high-density applications.

- **MESH (Mixergy)** demonstrated modularity through functional integration. By combining hot water and buffer storage into a single unit, the project aimed to enable installation of the system within a single day. Installer feedback confirmed that the system could be installed without requiring additional upskilling beyond standard heat pump training, offering potential for large-scale deployment by the existing installer base.

- **Ventive's Modular Heat Pump** was based on a flexible, modular EAHP platform featuring swappable components such as PCM thermal storage and custom heat exchangers. Modules were designed for ease of assembly and minimal site-based integration. Early testing uncovered challenges with PCM integration, requiring refrigeration cycle redesign and further validation.

n.b. The UK Government has confirmed its intention to introduce a 'smart heat mandate' as part of the Energy Smart Appliance (ESA) Regulations requiring all new domestic-scale heat pumps placed on the market to meet minimum smart functionality requirements from 2027. This mandate will ensure that heat pumps are smart-enabled and can respond to external signals such as time-of-use electricity tariffs or consumer-led flexibility events. The innovations trialled in Heat Pump Ready projects demonstrate advanced capabilities that will benefit from the ESA Regulations . Features such as predictive control, dynamic thermal storage management, and real-time optimisation for cost and comfort go beyond basic compliance with the smart mandate.

1.10. Develop heat pumps suitable for a wider range of homes and situations

Recognising the diversity of the UK's housing stock, several projects focused on developing systems capable of operating effectively in homes with limited internal space, high heat loss, or other retrofit challenges. Solutions focused on compact packaging, high flow temperatures, ease of installation, and suitability for both planned and distress purchase contexts.

- **Packaged Heat Pump (Nusku)** addressed the ‘distress purchase’ segment with a compact, all-in-one external unit that combines the heat pump, hot water cylinder, and control system. Capable of 65°C output, the system avoids the need for radiator upgrades and internal plant rooms. Salford Energy House testing demonstrated that the system could be installed within one day and deliver comparable comfort and cost to gas boilers under certain tariffs. For example, the Nusku heat pump system was shown to achieve comfort and cost parity with a gas boiler during average winter conditions (4.5°C outdoor temperature) when operated on a single-rate tariff. In modelling of a full heating season, the system delivered up to 33% lower operating costs than a gas boiler when used with the OVO Heat Pump Plus tariff.
- **NATURALHEAT (FeTu)** developed a compact, recyclable unit using natural refrigerants and designed for low-noise, low-maintenance operation. The unit was designed with constrained spaces in mind, offering potential for urban applications or small dwellings. Final performance data are not yet available, but component design and initial rig testing have been completed.
- **Two-Stage Thermoelectric Heat Pump (TCS)** proposed a novel thermoelectric solid state heat pump system. Compact and modular by design, the unit is intended for homes with installation constraints or higher temperature demands. While still at a developmental stage, the thermoelectric modules provide a potential pathway for quiet, scalable heat pump solutions.
- **Therma Hub (Vital Energi)** offered a solution for high-density residential buildings, integrating high-temperature delivery and external siting to support heat-as-a-service models and communal heating infrastructure. Early deployment indicates that the unit can be installed without major internal retrofits.