Flexitanker final project report

LoDES Stream 2

January 2026

Acknowledgements

With special thanks to the Department of Energy Security & Net Zero for making this work possible, to our project monitoring officer Andrew, and to all of the Keep Energy Systems team present and past for their outstanding efforts and commitment.

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Executive summary

As part of the Longer Duration Energy Storage competition, Keep Energy Systems (KES) has progressed its modular compressed air energy storage technology with the support of the Department for Energy Security and Net Zero (DESNZ), as part of the Net Zero Innovation Portfolio (NZIP). The technology is designed to support commercial and industrial customers that need five to twenty hours of energy storage capacity and makes use of proven industrial hardware such as repurposed truck engines as compressor-expanders and compressed natural gas pressure vessels for high pressure air storage.

Over the course of the project, three main work streams have been delivered. The first was the first full-scale prototype of the KES technology. This was designed, procured, assembled and tested at a site in Nottingham, within the Boots industrial campus. Testing showed strong performance, with representative power output close to design specifications as well as opportunities for improvement around engine valve sealing and controllability.

The project initially planned to deploy multiple pilot units to a customer site in Colchester as the second work stream, unlocking a new mixed-use development that faces significant grid constraints. Unfortunately, the progress of the new development slowed materially and the site remains unoccupied at time of writing. This led the KES team to rescope the second work stream in late 2024 to instead focus on deploying a second-generation system at the Nottingham site, known as Demonstrator. This allowed for greater technical innovation, pushing up the power rating and energy capacity of the system alongside higher round trip efficiency, while also reducing the total project spend by over £2.5m.

The change was approved in January 2025 and the Demonstrator system was designed, manufactured and commissioned within 12 months. The testing of the system was ongoing at the time of writing, and consequently the Demonstrator findings provided within the report are simulation data at this point. The simulations show that the system is able to deliver the upgraded 200 kW and 1 MWh specification, with the potential to reach 52% round trip efficiency in due course, exceeding the 50% target set on the performance roadmap.

In the third workstream, commercial engagement with major customers like Shell, Amazon and a major mining player in Western Australia, key stakeholders such as Northern Powergrid and supply chain partners Siemens, Volvo Penta and Tharsus have helped to shape the technology rapidly towards its full production specification.

Abbreviations

BDC	Bottom Dead Centre
CAES	Compressed Air Energy Storage
CAS	Compressed Air Store
DESNZ	Department for Energy Security and Net Zero
ECS	Electrical Control System (overall system controller)
EMS	Engine Management System
EVCU	Electronic Valve Control Unit
GUI	Graphical User Interface
HMI	Human/Machine Interface
HP	High Pressure
IHE	Intermediate- and High-Pressure Engine
IP	Intermediate Pressure
IPS	Isobaric Pressure Store
KES	Keep Energy Systems
LoDES	Longer Duration Energy Storage
LP	Low Pressure
LPE	Low- Pressure Engine
P&ID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
SC	Supercharger
TDC	Top Dead Centre
VSD	Variable Speed Drive

Glossary

Table 1: Definitions

Term	Definition
Charge (engine)	Engine valve operating mode. When charge mode is selected, the cold-side valve opens during the piston downstroke to draw in air from the cold plenum then closes at BDC. The air is compressed during the upstroke and the hot valve is opened when the cylinder pressure approximates the hot plenum pressure. The compressed air is discharged into the hot plenum until the hot valve closes at TDC. This consumes mechanical power (supplied by one of the electric motors) and produces hot compressed air.
Charge (system)	System operating state wherein the engine subsystems are in engine charge (compression) mode and in communication with the thermal store and air store subsystems. Electrical power is consumed by the engines, and the heat and compressed air produced are stored in the thermal and air stores.
Demonstrator	Second generation KES energy storage system, developed with learnings from the Prototype system but with higher power rating and energy storage capacity.
Discharge (engine)	Engine valve operating mode. When discharge mode is selected, the hot-side valve opens at TDC then closes during the piston downstroke. The inducted air is then expanded until it reaches approximately the pressure of the cold plenum, at which point the cold valve opens. The air is discharged through the cold valve during the upstroke and the cold valve closes shortly before TDC, such that enough air remains to reach hot plenum pressure at TDC. This consumes hot compressed air and produces mechanical power (which may be converted to electric power by the electric motor-generator).

Discharge (system)	System operating state wherein the engine subsystems are in engine discharge (expansion) mode and in communication with the thermal store and air store subsystems. The heat and compressed air stored in the thermal and air stores are used by the engines and converted to electrical power.
Engine	The reciprocating expander/compressor component of the LPE and IHE. The term engine is used for brevity regardless of the current function. The engine interfaces to the raft, to either of the motors at its flywheel and to the two plenums.
Engine valves	The two valves located in the cylinder head of each engine cylinder. Engine valves are differentiated from the valves elsewhere as they are controlled by the EVCU rather than by the system ECS. The “hot” valve is the higher-pressure side of the engine in all cases (operating as the outlet in charge mode and the inlet in discharge mode), and vice-versa for the “cold” valve.
ECS	The overall controller for the system.
EMS	The controller for each engine, which comprises 12-off valve actuator controllers (one per engine valve, which control the motion of the valves) and one or two EVCUs that command the drivers to open or close according to user instructions and the engine’s current state.
EVCU	The EVCU controls timing of the engine valves based on the position of the engine's crankshaft. Based on the operating mode and the plenum pressures, the EVCU calculates the crank angle at which to trigger each engine valve to open and close, and transmits this signal to the actuator drive.
Idle mode	Engine valve operating mode as set by the EVCU. This allows the engine to rotate freely (there is no net torque exerted by pressure) without the need to actuate valves.
IHE	The IHE subsystem, comprising the engine, raft, motor, etc.
LPE	The LPE subsystem, comprising the engine, raft, motor plenums etc.

Plenums	Pulsation bottles and manifolds connecting the engines to the wider pipework system, connecting multiple engine cylinders into one pipe interface and damping out pulsations.
Thermal store	Combined thermal store/heat exchanger subsystem.
System valve	Any manual or actuated valves located in the system pipework. (Cf engine valves.)

Project context

Background

The UK's transition to a net-zero energy system will require much greater flexibility to integrate renewables, with storage, demand side response and interconnection together expected to deliver £6–12bn of system savings by 2050[1] and support up to 10,000 domestic jobs[2].

Energy storage enables higher utilisation of intermittent generation, provides essential balancing, stability and congestion management services, and can defer network reinforcement, contributing to a lower-cost and more secure system as renewables continue to scale.

Longer duration storage could reduce reliance on fossil back-up and renewable curtailment, which reached over 3.6 TWh of wind in 2020 (75% of days)[3]. Alongside mature technologies such as the 2.8 GW of pumped hydro already deployed[4], new technologies will help meet the UK's full system needs.

Programme overview

The Longer Duration Energy Storage (LoDES) funding competition is a UK government innovation programme under the Net Zero Innovation Portfolio run by the Department for Energy Security and Net Zero (DESNZ). It seeks to accelerate the commercialisation and demonstration of innovative longer-duration energy storage technologies (beyond lithium-ion and pumped hydro) that can store energy for four or more hours and provide grid flexibility as renewables grow. The competition has supported projects from feasibility to full demonstration, with winners receiving grants to scale prototypes and enhance UK energy system capabilities.

> **'The aim of the Competition is to further accelerate commercialisation of innovative energy storage technologies. It will do this by focusing on technologies that provide longer duration storage capability and can provide novel services/system benefits.'**
>
> LoDES Stream 2 guidance, July 2021

[1] BEIS, Modelling 2050: Electricity System Analysis (2020), https://www.gov.uk/government/publications/modelling-2050-electricity-system-analysis
[2] BEIS, Energy Innovation Needs Assessment (2019), https://www.gov.uk/government/publications/energy-innovation-needs-assessments
[3] Lane, Clark and Peacock, "Is battery storage a good investment opportunity?" (2020), https://www.lcp.uk.com/energy/publications/is-battery-storage-a-good-investment-opportunity/
[4] British Hydropower Association, Pumped Storage Hydropower (2025), https://british-hydro.org/wp-content/uploads/2025/05/Pumped-Storage-Brochure-May25.pdf

Company introduction

Keep Energy Systems is a Nottingham-based clean energy technology company developing longer-duration energy storage solutions, targeting grid resilience and renewable integration. It was formerly known as Cheesecake Energy and rebranded in 2025 to reflect its focus on dependable, resilient energy storage. Building on research developed at the University of Nottingham over more than a decade, Keep Energy Systems aims to lower storage costs and accelerate the clean energy transition.

Objectives

The DESNZ LoDES Competition objectives were to:

- Explore the potential for cost reductions of longer duration storage technologies;
- De-risk effective non-conventional storage technologies and therefore
- Secure buy-in from commercial investors;
- Demonstrate capability, securing data to inform policy formulation;
- Build a pipeline of storage technologies in the UK, supporting expertise and export opportunities.

The specific Flexitanker project aims were to:

- Deliver a strong multi-unit demonstrator for Keep Energy Systems' technology
- Engage at meaningful volumes with a scalable supply chain
- Validate the technology and cost roadmaps to production units
- Build customer feedback into technology development

Technology overview

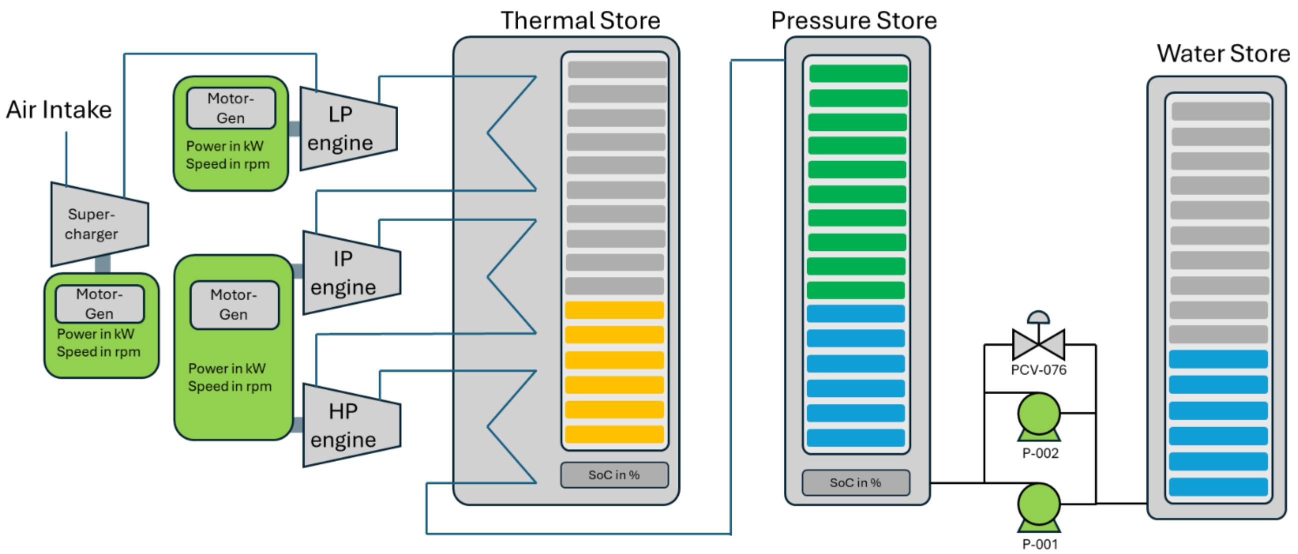
Keep Energy Systems has developed a modular compressed air energy storage solution for longer-duration daily cycling applications. The technology aims to deliver low-cost and reliable energy storage in a modular, containerised package, and provides durable medium-duration energy storage designed for discharge durations of between 5 and 20 hours for power outputs from 200 kW up to 50 MW. The final production system is designed to be simple, robust, and straightforward to operate, with an operational lifetime of up to 25 years, and a target round trip efficiency of 65%. The prototype of this technology has been developed and tested, and a more advanced demonstrator system has also been built and installed, both representing key steps on the technology development journey towards this production system.

How the system works

Electricity from renewables or the local grid is used to charge the system. In charge mode the system takes in air from the local atmosphere and then uses electrical power to compress it to around 230 bar(g). This compression is achieved in three stages (the first of which is supercharged), using electric motors that drive reciprocating-piston machines that are based on modified automotive diesel engines (with fuel systems removed). Each compression stage raises the air temperature, and the air is then passed through a stage of the thermal store to deposit heat prior to the next compression stage. The extracted heat is stored in the form of a bed of magnetite (iron ore), and the compressed air in pressure vessels.

A schematic of the system is shown in Figure 1.

Figure 1: Schematic of KES energy storage system.



In discharge mode the process is reversed to generate electricity. The compressed air is released from the air store, heated using the stored heat in the thermal store and allowed to expand in the cylinders of the same engines which have been used for the compression process. This is repeated for each of the three thermal store and piston machine stages. The expanding air drives the pistons to turn the engine crankshaft, which in turn drives the motors as generators.

The KES team consider there to be four key innovative aspects of the technology. These enable the system to deliver its aims and differentiate it from alternatives. These innovations are summarised below.

1. The KES system has been designed to store the pressurised air at a constant pressure (isobaric conditions). This uses water to balance the pressures in the pressure vessels at all times. The isobaric storage has the advantage of allowing:
    - the compression / expansion machines to always operate at the same condition,
    - the complete charge of air to be removed from the tank during a discharge cycle,
    - tank wall stresses to remain constant, which removes fatigue limits and enables longer lifetimes for the vessels,
    - ‘water testing’ of the tanks at regular intervals – improving safety.
2. The system re-tasks ex-service diesel truck engines to provide affordable reversible compressor-expander machines compatible with hot compression-expansion, and giving the performance required. The past years of testing have developed very significant Intellectual Property in the design of the modification packs for these engines.
3. The system will ultimately incorporate synchronous AC generators directly connected to the grid. These deliver inertia services, reduce harmonic distortion, and provide fault current services in addition to the energy storage services.
4. The compressor-expander machines rely on an active valve actuation system invented and patented by KES.

It is this fourth aspect which allows the reuse of truck engines as efficient and reversible compressor-expander units. The key to achieving the reversible operation of these, and allowing the same units to be used for both compression and expansion, was developing a way to actively control the poppet-valves. It is entirely possible to operate a compressor with passive one-way valves, and if the system were only operating in a compression mode, this would be the simplest solution. But by pioneering a way of flexibly controlling rapid transits of the poppet-valves from one extreme to the other, the same power train can be used for both charging and discharging. This significantly reduces the amount of installed equipment required.

Benefits and challenges

Independent power and energy storage capacity

In the KES system these are scaled independently of one another, allowing commercial and industrial customers to install exactly what is needed for their application, reducing unnecessary CAPEX.

System degradation and asset life

The KES system is designed to be cycled >20,000 times with negligible degradation of the energy storage capacity, giving an asset life of >25 years. This is especially helpful for applications needing a specific energy delivery each day, for example to charge electric vehicles, as it means the system does not need to be oversized to allow for reducing capacity over time.

Synchronous electrical machines

In common with conventional fossil-fired power plants, the KES system is designed to make use of synchronous electrical machines, which deliver a range of grid stability benefits through real inertia, voltage support, short circuit level and fault tolerance. For testing, the Prototype and Demonstrator plants have been developed using variable speed machines ahead of the switch to fixed speed.

Operational environment

The KES technology can operate in a wide range of operating environments, from -20 °C to +50 °C, without the need for air conditioning. This helps to eliminate a source of self-discharge. Analysis has shown that operating at an average ambient temperature of 40 °C results in a roughly 6% derating of maximum power output, and up to 9% derating of maximum energy capacity versus an average ambient temperature of 20 °C. For severe day-night temperature swings of 20 °C or more, the water level in the isobaric air store is managed to avoid over-pressurising the air, for example where the air in an air store filled during cool temperatures overnight starts to expand due to daytime solar heating.

At low ambient temperatures, e.g. 0 °C, the maximum power rating and energy capacity increase by 6% and 8% respectively. A minimal level of oil pre-heating is advised for a -20 °C start but this remains within typical engine testing certifications. Glycol may be added to the water to prevent freezing.

Integration with renewables

The KES system can be developed to charge and discharge with DC power or AC power with no inverters or rectifiers. For certain applications requiring inverters, such as solar farms, this can improve efficiency and lower CAPEX and O&M costs.

Technology maturity, construction and manufacture

As a technology only just breaking through into commercialisation, the KES CAES supply chain is still in the early stages of development but is being designed to take advantage of capable existing supply chains from other industries such as genset manufacturing and Compressed Natural Gas. Manufacturing of the KES system will ultimately be highly outsourced to supply chain partners with only KES's proprietary valve actuation technology and control software being produced in house. The design of the rest of the system is being developed to offer maximum supply chain choice by using well established manufacturing technology that is widely available from established suppliers.

Raw materials price volatility

The markets for the materials the KES system is made from are large and liquid with low price volatility.

Raw material environmental impacts

The KES system is produced using environmentally benign materials.

Maintenance (parts and skills)

The KES system will require replacement of low-cost consumable parts such as filters and oils during planned maintenance. The skills required for the planned maintenance activities on the KES system are widely available in the automotive/genset and process industries. KES also plans to establish a service and training network for customers. The common availability of the necessary maintenance skills is particularly relevant in less economically developed countries where the required specialist battery commissioning, operation, maintenance and decommissioning skills are more nascent.

Operational risks

Although the thermal store holds high-temperature air and magnetite, there is no combustible material or fuel anywhere in the system beyond a small amount of lubrication oil. The fire risk from the system is minimal, and there are no other chemical-related health risks arising. The primary hazard is high-pressure air: this is managed using extremely well-established pressure vessel and pipework codes and protective devices such as relief valves. Electrical hazards are akin to those in all low voltage systems, noting that unlike a battery it is possible to physically decouple the entire electrical system from the stored energy source for maintenance.

Operational impacts

During normal operation when charging and generating the mechanical components of the system will emit noise. The design of the system will ensure that this does not cause nuisance to anyone in proximity, but this does necessitate enclosures. The standard production system is expected to emit less than 65 dB of noise, and this can be reduced further with additional soundproofing technologies commonly used in diesel generator applications. The air release from relief valves will also cause noise, but this is in exceptional circumstances only.

End of life

Due to being modular, all the main KES subsystems can be reconditioned or fully recycled at the end of their operational life, reducing end of life risks, be they economic, legislative, safety or environmental.

System configuration and installation

The KES system is a containerised solution. It is possible to stack some of the KES system's containers, e.g. with a double or triple-height thermal store. However, the footprint remains larger than battery alternatives and may limit the use of the systems within tightly space-constrained environments.

Project overview

Project summary and evolution

Over the course of the project, the Keep Energy Systems team designed and built two iterations of its energy storage system: starting with the Prototype and then advancing the design and concept to deliver the Demonstrator system. Alongside the technical developments required to design, manufacture, assemble and test these units, a parallel commercial workstream drove engagement with potential customers and partners, leading to multiple signed memoranda of understanding with key partners and in-depth customer engagement with major blue-chip companies including Amazon, Shell and Northern Powergrid.

The project was designed from the start to have two stages of technology development: a first stage in which a prototype of the technology was tested at a local site, and a second in which more mature systems were deployed, building on learnings from the prototype. The prototype was designed, procured, assembled and tested at a site in Nottingham, located within the Boots industrial campus. Some supply chain issues were identified along the way, including the supplier of the engine enclosure going into administration unexpectedly.

The second work stream was originally intended to deploy multiple pilot units at a customer site in Colchester, supporting a new mixed-use development that faces significant grid constraints. However, progress on the development slowed substantially following the departure of key personnel at Colchester City Council, and the site remains unoccupied as of early 2026. As a result, following detailed discussions with the DESNZ team, KES revised the scope of the second work stream in late 2024 to focus instead on deploying a second-generation system at the Nottingham site, referred to as the Demonstrator. This approach enabled additional technical development, increasing both the power rating and energy capacity of the system while improving round-trip efficiency. It also reduced overall project expenditure by more than £2.5m and significantly reduced key project risks.

The revised approach was approved in January 2025, after which the Demonstrator system was designed, manufactured and commissioned within a 12-month period, though further challenges included the subsidiary of a different supplier entering administration, though KES had identified this possibility in advance from its observations of quality issues and delays from that subsidiary and was able to work quickly to mitigate the impacts. Testing of the Demonstrator system is currently ongoing.

The following timeline summarises key developments over the project in more detail.

31/03/23 Project kick-off

The project was launched with three main workstreams, namely:

- Development of Prototype system;
- Development of pilots;

- Commercials and dissemination.

The Prototype system workstream was to install and commission a prototype energy storage system at KES's own site for comprehensive offline testing, helping to de-risk the technology and validate its performance.

The pilots were to be deployed to support a large new mixed-use development in Colchester known as the Colchester Northern Gateway. Being in a highly grid-constrained part of the UK, Colchester City Council received costs for the required grid connection of up to £15m, representing a major programme of reinforcement works. In order to mitigate this, the site was to be run as a microgrid with onsite solar and KES energy storage to turn this into around-the-clock power.

Commercial and dissemination activities intended to build awareness of the technology and develop a customer pipeline were carried out in parallel.

08/12/23 KES overcomes engine enclosure supplier entering administration

The order for the Prototype system engine enclosure was placed with a well-established enclosure supplier. Following completion of the design, in September of 2023 that supplier was put into administration. A major procurement effort by the KES team was launched, resulting in a new supplier being spooled up at short notice and delivering a suitable engine enclosure just weeks after the original delivery date.

04/01/24 Commissioned to carry out engineering study by a major mining player in Western Australia

The KES team secured an order for a paid engineering study for a set of systems for deployment at a site in the Pilbara, Western Australia. The work unlocked a set of key customer understandings that have since shaped the product development and commercial strategy very directly, and established a strong working relationship that continues today. The feasibility study was extremely well-received with glowing reviews.

04/04/24 Technoeconomic analysis by Cornwall Insight

The study, by respected industry consultants Cornwall Insight, showed higher returns for production KES systems versus lithium-ion systems of the same size at a discharge duration of five hours. This was an unexpected but welcome finding, as it had previously been anticipated that the lower round trip efficiency of the KES system would drive lower economic returns. However, the modelling by Cornwall Insight takes into account the economic cost of degradation of the battery, which attaches a cost to high cycling and therefore makes it unattractive to carry out trades below a certain return threshold. For the KES system, while the lower efficiency means it also has a returns threshold, this is much less restrictive and the KES system undertakes significantly more cycles, generating more revenue as a result.

30/04/24 Selected for Amazon Sustainability Accelerator

KES (trading as Cheesecake Energy at the time) was selected to join the Amazon Sustainability Accelerator, a four-week intensive programme supporting sustainable innovation across Europe. KES was successful in securing entry to Amazon's follow-on pilot programme and was invited to join a tendering process for energy storage deployments at Amazon's European distribution centres. While the technology showed a strong business case and the commercial proposal was well-received, Amazon ultimately selected a different technology to procure.

25/10/24 Colchester City Council delay

In October of 2024, following the departure of key personnel working on the Northern Gateway development, Colchester City Council confirmed a serious delay to the project in order to complete an estates review. The choice to suspend the project for several months while undertaking this review and the associated uncertainty in the intervening time was not compatible with the project timelines, and KES was forced to evaluate alternative approaches to delivering strong value from the LoDES project opportunity.

07/01/25 Change request approved

An intensive period of replanning and options assessment led to a revised work plan that rescoped the project to instead invest time and effort to deliver a more innovative Demonstrator system at the Boots site in Nottingham, at significantly lower cost than the original Colchester deployment. The project budget was revised down from £9.4m to £7.2m in recognition of the smaller number of systems being deployed, while the level of performance for the Demonstrator was increased through a number of major upgrades. Subsequent negotiation with suppliers to cancel and refund spend on existing orders for Colchester allowed the project budget to be further reduced to £6.8m without reducing scope.

The decision to approve this rescoping in January unlocked a rapid design and procurement campaign that led to the Demonstrator system being developed, manufactured, assembled and commissioned in under 12 months.

27/03/25 Memoranda of Understanding signed

Memoranda of understanding were signed with both Volvo Penta and Siemens, the former providing the truck engines that form the basis of the compressor-expanders in the KES system, and the latter providing the control system hardware and much of the instrumentation.

28/03/25 Prototype system test report delivered

Alongside the Demonstrator design and procurement exercise, the KES team carried out extensive testing of the Prototype system, leading to a detailed test report characterising the prototype system.

28/10/25 Key supplier enters administration

The manufacturing arm of a major pressure vessel and heat exchanger supplier went into administration abruptly prior to completing orders for the thermal store and plenums for the Demonstrator system. KES had had a successful track record of procuring pressure equipment from this company in the past, and the company was in a strong financial position. The manufacturing subsidiary was created to bring together an existing manufacturing site with a recently acquired new facility and the KES order was allocated to this subsidiary. Unfortunately, the new facility proved to have numerous quality issues, leading to delays, manufacturing flaws and degraded performance expectations for the thermal store and repeat work on the plenums. Both facilities were ultimately closed and the subsidiary was put into administration after the delivery of the thermal stores but before delivery of the plenums, and with all quality documentation still outstanding.

08/12/25 Plenums delivered and installed

Through swift and sustained engagement with the administrators, KES was able to agree a route forward to release the plenums and avoid what could have been a very protracted delay. With agreement from the administrators and the parent company, the plenums were delivered and installed by early December, just over a month after the administration was announced and quality documentation was being assembled.

28/01/25 Project closeout meeting

KES hosted a visit from the DESNZ team and project monitoring officer to tour the Demonstrator site and explore findings and lessons learned from the project. KES is continuing to progress Demonstrator testing and commercialisation of the technology and is now well-placed to seek pilot opportunities and investment to continue its development.

Design and development of the system

Previous design history

Between 2020 and 2023 initial lab-scale prototype testing and development of the system was carried out in the University of Nottingham’s Research Acceleration and Demonstration facilities. The innovative valve actuators and associated engine control system were further developed. A full-scale LP compressor-expander was assembled, coupled with 1 MWh of heat storage and 10m^3 compressed air storage at a pressure of 230 bar. Through this the concept of the system and the interoperability of all the sub-systems was proven. The highest priority areas of focus to improve efficiency and reduce system complexity were identified. An example of this is the switch made for the thermal store from being a packed gravel bed with a dedicated air circulation system and heat exchangers, to a packed sand bed with the hot compressed air piping embedded in it, which entirely removed the need for a separate sub-system.

Technology development pathway

In March 2023, KES commenced the DESNZ LoDES project which supported the construction of a full-scale prototype plant at the Boots Site in Beeston, Nottingham. The Prototype had a design output of 150 kW coupled with 2 hours of energy storage, resulting in a 300 kWh CAES system operating at 230 bar and a peak design temperature of around 400 °C. Construction and installation of this system was completed in 2023, with final testing and commissioning from January to March of 2024. This was the first full-scale modular compressed air system to be demonstrated in the UK.

The system has been extended further into a Demonstrator plant, with additional capacity (1 MWh) and power (200 kW), providing a showcase for upgraded capabilities of the system and more closely approximating the production system design.

Looking forward, continued use of both lab-scale systems and the Demonstrator plant is a key part of the KES research and development strategy. These will provide the platforms to rapidly test, monitor, evaluate, learn, develop and prove the ideas and innovations that are in the technology development pipeline, and will continue to be identified.

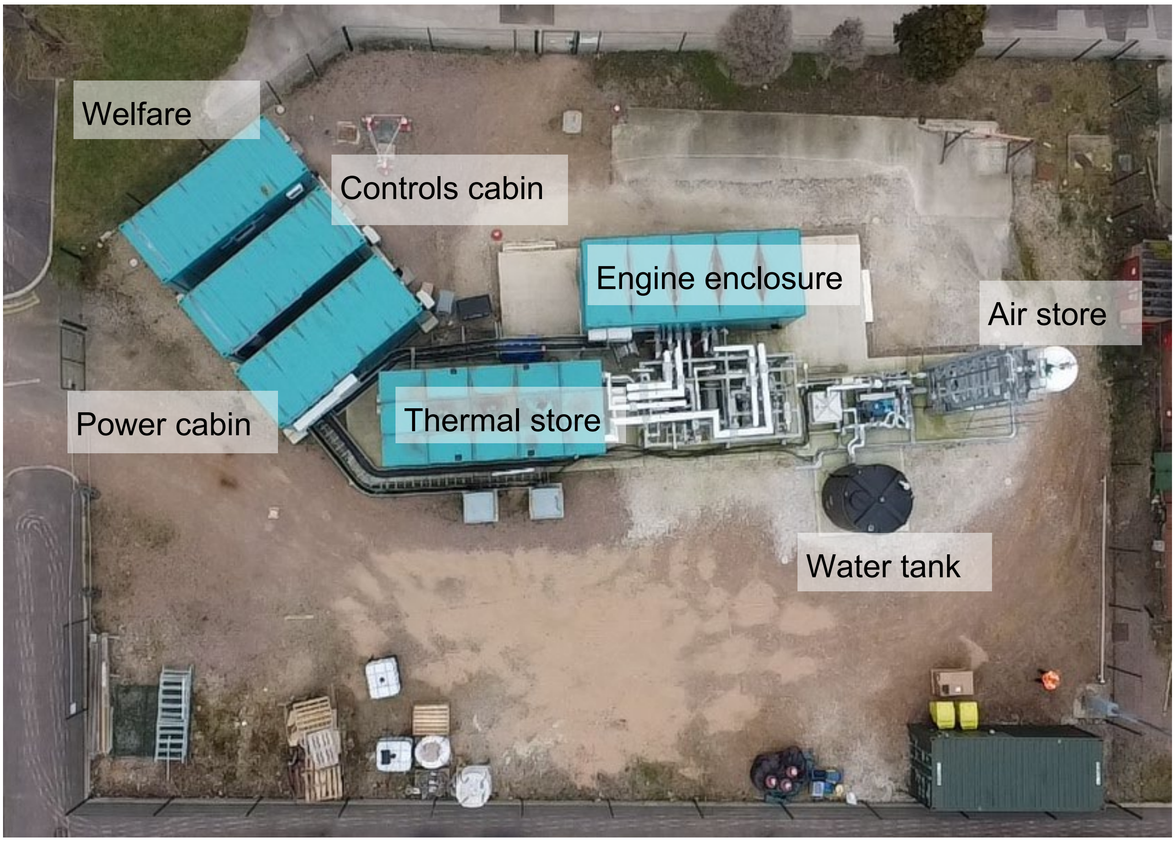
The Demonstrator installation at Nottingham is targeting an ultimate RTE of at least 50%, on route to the target of 55% for pilot systems and 60-65% for production systems. Five initial developments have been identified to improve the system RTE by circa 15%, and a plan developed for how these will be progressively implemented on the Demonstrator to verify their effectiveness, prior to more widespread rollout on pilot systems and inclusion in the standard production system design going forward.

Overall design and layout

Prototype

The physical arrangement of the Prototype site is shown below in Figure 2.

Figure 2: Aerial view of the Prototype energy storage system in Nottingham

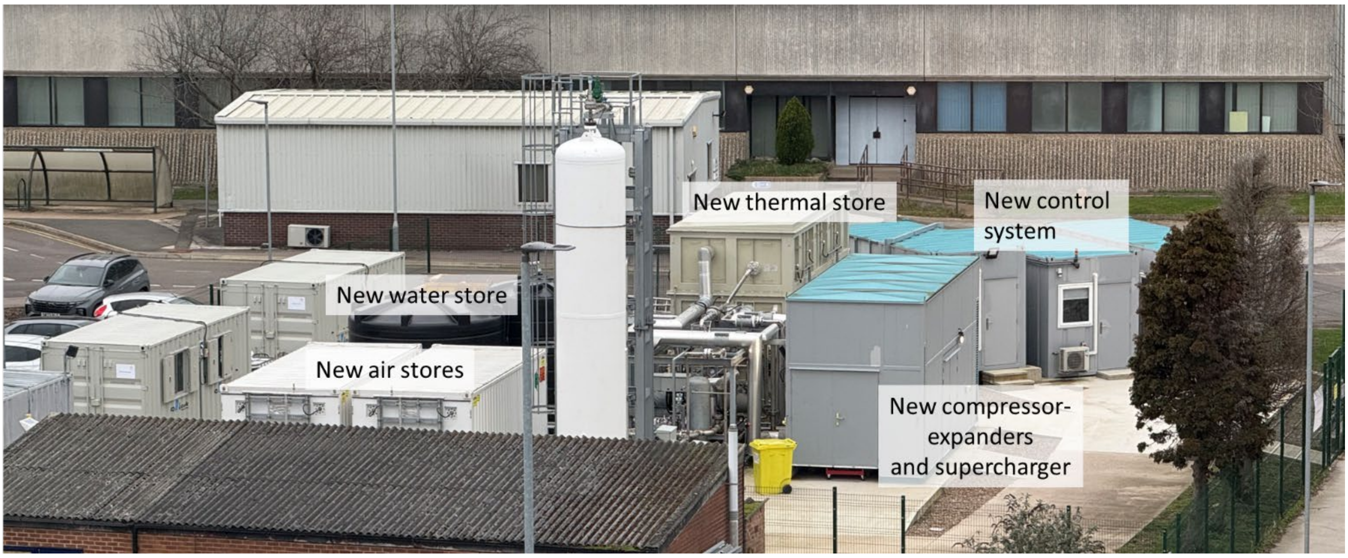


It comprises a high-pressure air storage vessel, a water pump and tank to maintain pressure within the air vessel by hydraulic displacement, a combined thermal store/heat exchanger unit that stores heat in a large volume of sand, three engine stages (which are mechanically arranged as two physical units), plus piping and a control system that interconnect the above. The Prototype and Demonstrator systems are deliberately spread out for ease of access and reconfiguration – production systems will have a more compact footprint.

Evolution to Demonstrator

While the Demonstrator system has been constructed on the same site as the Prototype system, every major subsystem has been upgraded to deliver higher power, larger energy capacity and greater round trip efficiency. Figure 3 shows the upgraded system.

Figure 3: View of the Demonstrator system. The existing engine enclosure and site cabins have been painted grey for extended planning permission reasons.



New containerised air stores

Two new 20-foot shipping containers (Figure 4) filled with glass-fibre composite cylinders have boosted the air store capacity and are much closer to the production air store design. The array of uniform cylinders and containerised approach allows for much faster manufacture and deployment of the store, while the composite cylinders also remove a corrosion risk that is managed using corrosion inhibitor for steel vessels.

Figure 4: Containerised air stores

New thermal stores

Switching from sand to much denser magnetite (a type of readily available iron ore) as the thermal storage medium has delivered a four-times increase in thermal capacity in approximately the same footprint. The thermal stores in Figure 5 have been fabricated in much the same way as a conventional shell and tube heat exchanger, making use of seamless tube and tubesheets with D-shaped headers. This eliminates the extensive branched connection welding of the previous thermal store and reduces the manufacturing time, unlocking greater automation of the process. The move to tubesheets made it possible to greatly increase the number of tubes passing through the thermal storage medium, and transverse aluminium fins further increase the surface area to conduct heat into the store, unlocking higher heat transfer rates as well as the higher storage capacity.

Figure 5: Views of the thermal store from the side and from above

New actuators

A new generation of actuators with larger valves, higher lifts and higher speed capability has been developed, drawing on experience from assembly and test of the Prototype actuators. The actuators are an area where KES has extensive expertise and intellectual property and has filed multiple patents over the course of the project. As well as allowing each piston machine to be switched between compressor and expander for charge and discharge depending on the software-commanded valve timings, the actuators also allow balancing of flows between stages and part-load power flows, while delivering rich telemetry data.

Improved cylinder heads and extensions

The shape of the cylinder head flow passages has been improved for smoother flow. This leads to reduced turbulence and lower pressure drops during intake and exhaust. Reducing swirl and mixing also helps to reduce heat transfer losses, which can reduce thermal stressing challenges as well as losses.

Supercharger

When operating with a supercharger, the LP piston engine operates with a smaller pressure ratio and larger mass flow rate. When supercharged, the configuration of the IP and HP stages is unchanged, although also operating at a higher mass flow rate, and with correspondingly larger bores. Including the supercharger in the system is predicted to reduce the round trip efficiency by up to 3% but boost the rated system power by 25%. Figure 6 shows the two units, with the supercharger assembly on the left and the LP engine on the right.

Figure 6: The low pressure engine and supercharger assembly

New control system

A major recontrol exercise has switched the entire system over to the latest Siemens control hardware, which allows for live feedback from actuators and much stronger cyber security. Production systems will operate entirely autonomously at customer sites, and establishing strong security foundations for remote operations is crucial to unlocking that capability, against known cyber threats to infrastructure and businesses. The Siemens ecosystem offers one of the leading industrial cloud and communications setups, designed to support compliance to key security standards such as the Network and Information Security Directive 2.

Subsystems

The following sections describe the current (Demonstrator) design for each subsystem.

Thermal store

The combined thermal store/heat exchanger comprises a number of steel pipes in contact with transverse aluminium plates to aid thermal transfer. These pipes and fins are immersed in magnetite, such that heat carried in air flowing through the pipes is transferred to the magnetite if the air is hotter or vice versa if the magnetite is hotter.

There are three exchanger units stacked into the assembly, for the low-, intermediate- and high-pressure stages of the system.

Engines

Each engine is arranged in a similar manner to a diesel generator, i.e., a base skid or raft, with an electrical machine and coupled reciprocating-piston heat engine. The electrical machines are motors with variable speed, regenerative drives and the reciprocating machines are modified diesel engines, optimised for adiabatic operation and serving as compressors and expanders depending on whether the system is charging or discharging respectively. The LPE has a single pressure stage and the IHE has two (IP and HP stages).

Each engine has a dedicated, bespoke electronic management system which operates its cylinder valves.

Air storage

Compressed air is stored using two containerised arrays of glass-fibre composite vessels totalling 33 m^3 and an 8 m^3 carbon steel vessel. These are connected to a pair of ambient pressure water tanks via two electrically driven reciprocating pumps and a pressure regulator, which operate in order to maintain a constant pressure of up to 230 barg inside the vessels.

Control

The plant is controlled by a high-integrity Siemens safety PLC which also provides supervisory control and data acquisition functions. For initial testing, this controller is used to operate the plant in a primarily manual condition, whereby single control setpoints or positions are adjusted in sequence. The system will have the capability to operate fully autonomously once testing has been completed.

The PLC’s safety functions are fully operational in all cases to immediately shut the system down should a hazardous condition occur.

Test results

Prototype system operation

Purpose of testing

To demonstrate operation of all equipment in the system, both separately and operating in coordination, thus confirming:

- Mechanical integrity;
- Air tightness;
- Efficiency;
- Engine valve train reliability;
- Isobaric control of the compressed air store; and
- Discharge operations.

System testing also involves incrementally bringing the system up to operational conditions of pressure and temperature, and a final key output is a functional demonstration of the system storing and releasing energy.

Measurements

Data was recorded throughout each operation from the following instruments.

- Thermal store temperatures
- Air store pressures and levels
- Engine (plenum) pressures and temperatures
- Engine oil pressures and temperatures
- Electrical power input/output – (AC and DC input, and DC output)
- LPE VSD
- IHE VSD
- P-001 VSD
- System airflow

Data was logged at a rate of at least one reading every 10 seconds and all instruments were calibrated where applicable.

Test results and discussion

SY-C-02A

In this charge test, air is compressed from ambient to 24 barg using all three stages: LPE, IPE, and HPE. Three cylinders are used—one for LPE, one for IPE, and one for HPE. The compressed air exiting the HPE is stored in the CAS. The system starts in idle mode until 9:30, after which it enters charge mode. Air is compressed from ambient to 2 barg across LPE, from 2 barg to 8 barg across IPE, and finally to 24 barg across HPE. LPE speed is set to 500 RPM, and IHE speed to 750 RPM. As seen in Figure 7, the pressure gradually ramps up to 24 barg before stabilising at a steady 24 barg at a timestamp of around 10:10.

Figure 8 shows the air temperature profile across the engine during the charge test. At the end of the compression period, temperatures reach 100°C for LPE, about 102°C for IPE, and around 85°C for HPE. Figure 9 shows the thermal store temperatures: the hot inlet at the LP thermal store reaches 80°C, the IP thermal store reaches 75°C, and the HP thermal store reaches 20°C. Notably, the gradient of the thermal store temperature profiles is lower than that of the engine hot side temperatures. This is due to heat transfer to the pipework between the engine and thermal store, as well as thermal losses, which reduce the air temperature entering the thermal store.

The mass flow rate of air, based on level readings in the CAS, is approximately 0.169 kg/s, with the volumetric efficiency of the HPE calculated at about 53%. A significant leak was identified in the HPE hot valve due to valve wear, which contributed to the lower volumetric efficiency. This issue was resolved for subsequent tests.

Figure 7: Cold and hot side pressure profiles for LPE (1st), IPE (2nd) and HPE (3rd). The pressure axis scaling differs between plots.

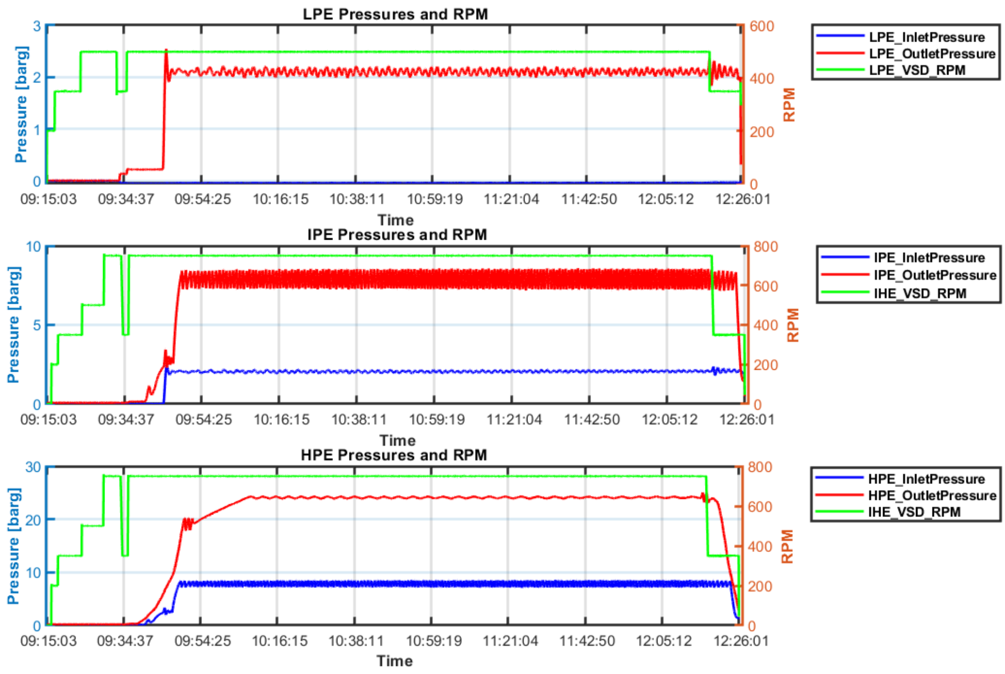


Figure 8: Cold and hot side temperature profiles for LPE (1st), IPE (2nd) and HPE (3rd)

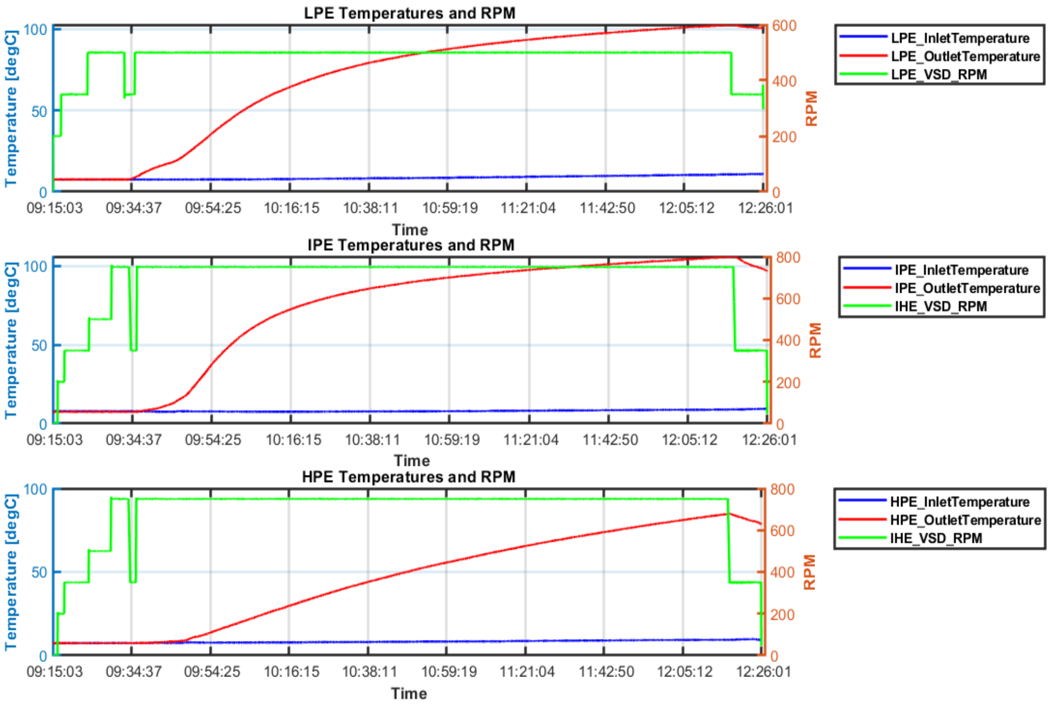


Figure 9: Low pressure (1st), Intermediate pressure (2nd) and High pressure (3rd) thermal store temperature profiles. The temperature axis scaling differs between plots.

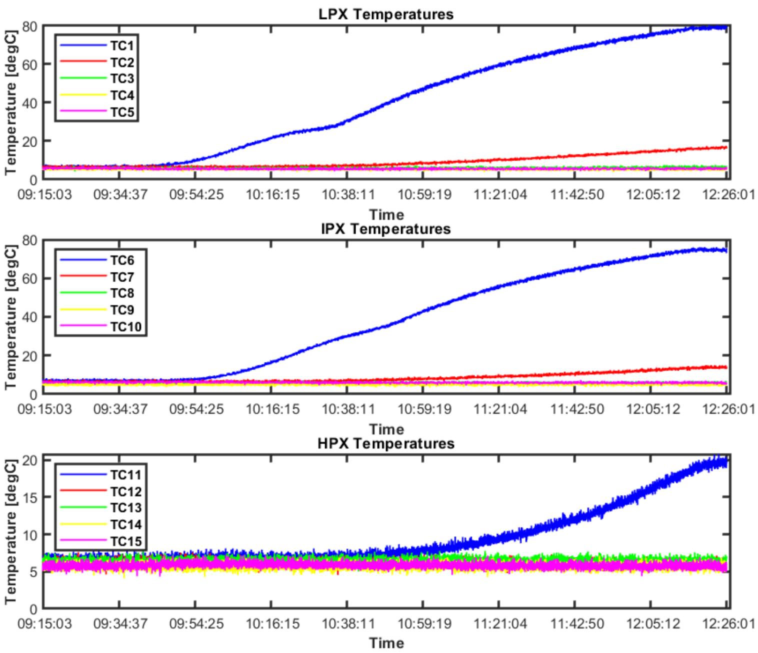
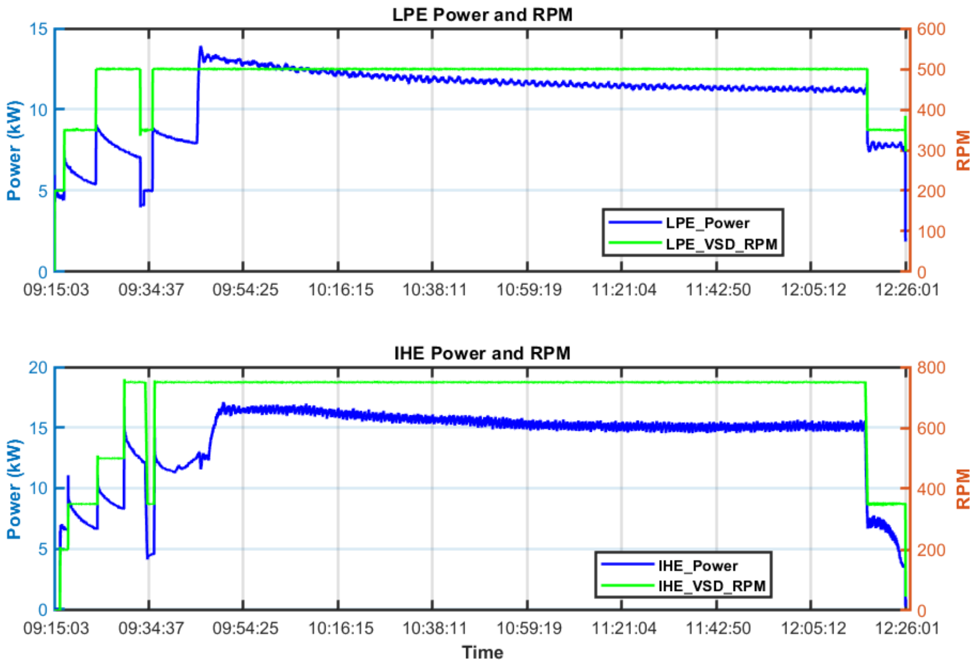


Figure 10 shows the power consumption of each compressor-expander. During the idle period, power gradually decreases at a constant RPM as the oil warms up, reducing friction losses. During compression, the LPE power drops from around 14 kW to 11 kW, while the IHE power remains relatively constant at approximately 15 kW.

Figure 10: LPE (top) and IHE (bottom) power profiles with LPE_VSD and IHE_VSD speed respectively. The y-axis scaling differs between plots.



SY-C-03B

In this discharge test, air expands from 24 barg to ambient using all three stages, supplied from the compressed air store, as shown in Figure 11. The system uses three cylinders in LPE, one in IPE, and two in HPE to balance flow rates and enhance system resilience. The system remains in idle mode until 15:37 to warm up the engines. It then enters charge mode to pressurise the system and heat the pipework, preventing heat losses during discharge. If the pipework is cold, heat from the air would be lost to warming it up, while warmer pipework helps stabilise air temperature before expansion.

During charge mode, the pressures are set to 24 barg for HPE, initially 11 barg for IPE (later increased to 15 barg), and about 3.5 barg for LPE. Oscillatory behaviour is observed in LPE and IPE due to PID-controlled pressure valves, which require further tuning to improve stability.

The dotted black line marks the start of discharge, which lasts approximately six minutes before the system is fully depressurised. Each stage transitions to discharge at different times, with HPE starting first, followed by IPE and LPE, ensuring system stability and control. The test was stopped earlier than planned due to instability in LPE pressure control, as seen in Figure 11, where pressure fluctuates significantly. A system hardware troubleshooting study was conducted, and the team worked on fine-tuning the pressure control loop for improved stability.

Figure 11: Cold and hot side pressure profiles for LPE (1st), IPE (2nd) and HPE (3rd). The pressure axis scaling differs between plots.

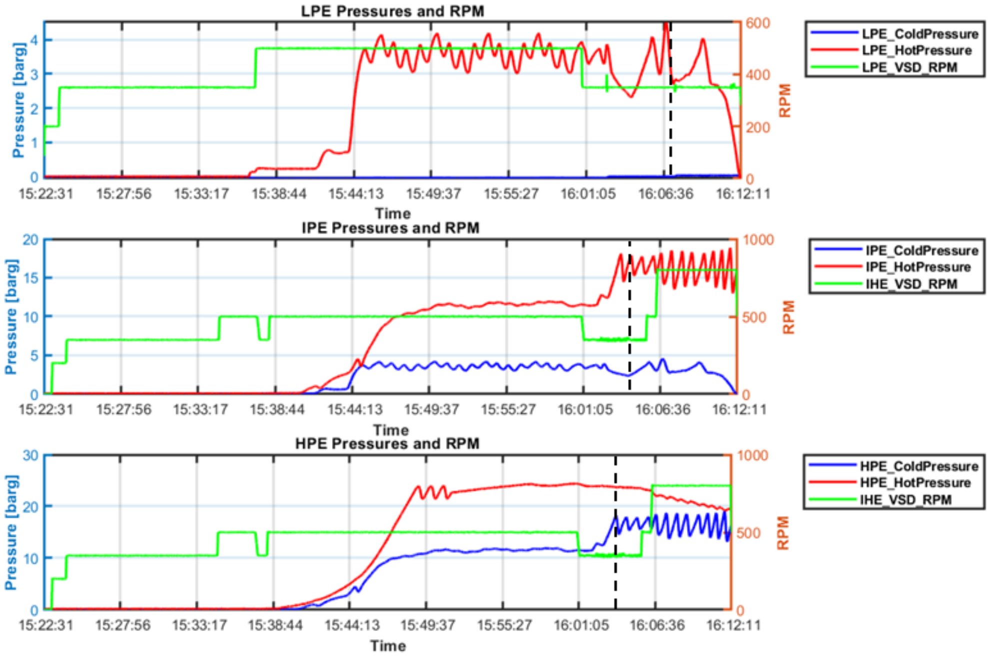


Figure 12 presents the temperature profiles during the system test. As air is compressed, the exit temperature increases before transitioning to discharge. During expansion, the hot-side temperature decreases as heat dissipates into the pipework, while the cold-side temperature drops due to the expansion process.

Figure 12: Cold and hot side temperature profiles for LPE (1st), IPE (2nd) and HPE (3rd). The y-axis scaling differs between plots.

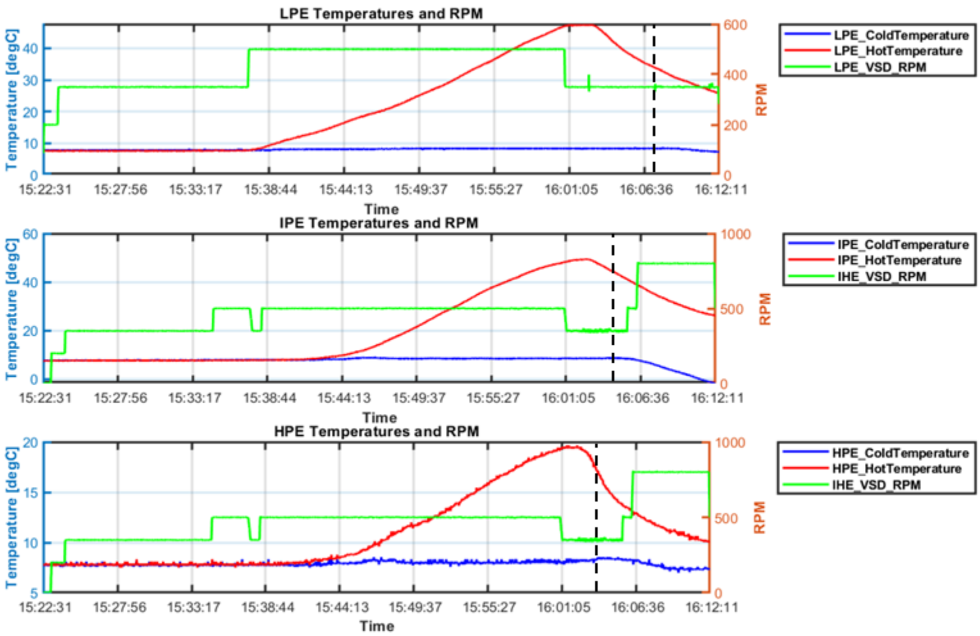
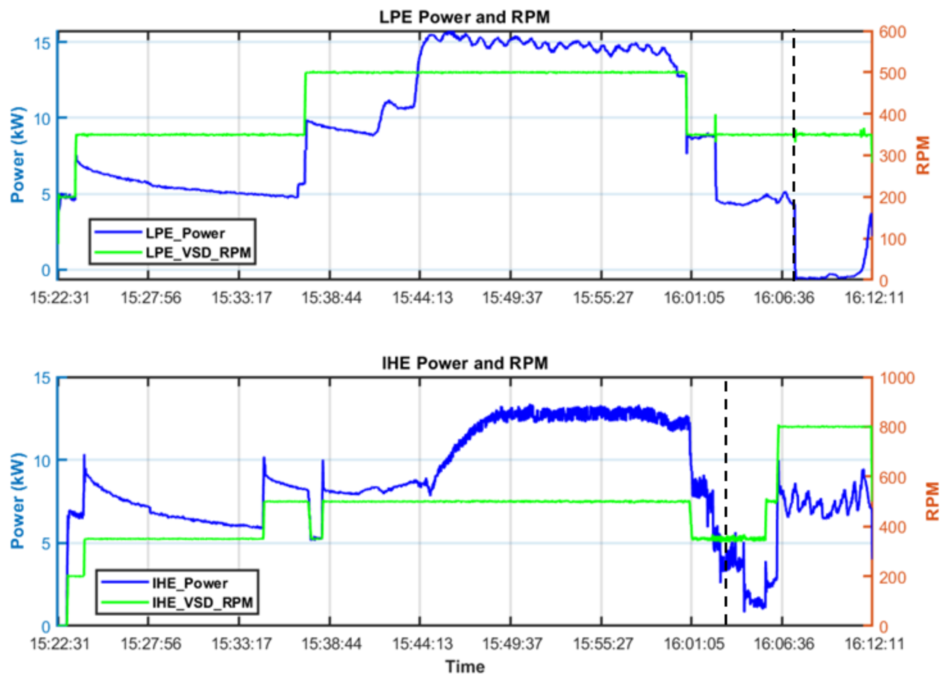


Figure 13 shows that, during the transition from charge to discharge, LPE and IHE power consumption suddenly drop, reversing to approximately 1 kW output power. Given that the friction power for LPE at 350 RPM is around 6 kW, the power contribution from air is estimated at 7 kW. In full operation, all six LPE cylinders are utilised at 1500 RPM with a higher expansion pressure ratio—nearly twice that of the current test. Consequently, friction power is expected to scale up significantly, exceeding double the current value. Based on these factors, the anticipated power generation from air in the full prototype system was projected to be around 100 kW, prior to improvements in the Demonstrator programme.

Based on the analysis, the isentropic efficiency of the IPE is approximately 60%. However, this figure is expected to increase once the leakage issues are addressed.

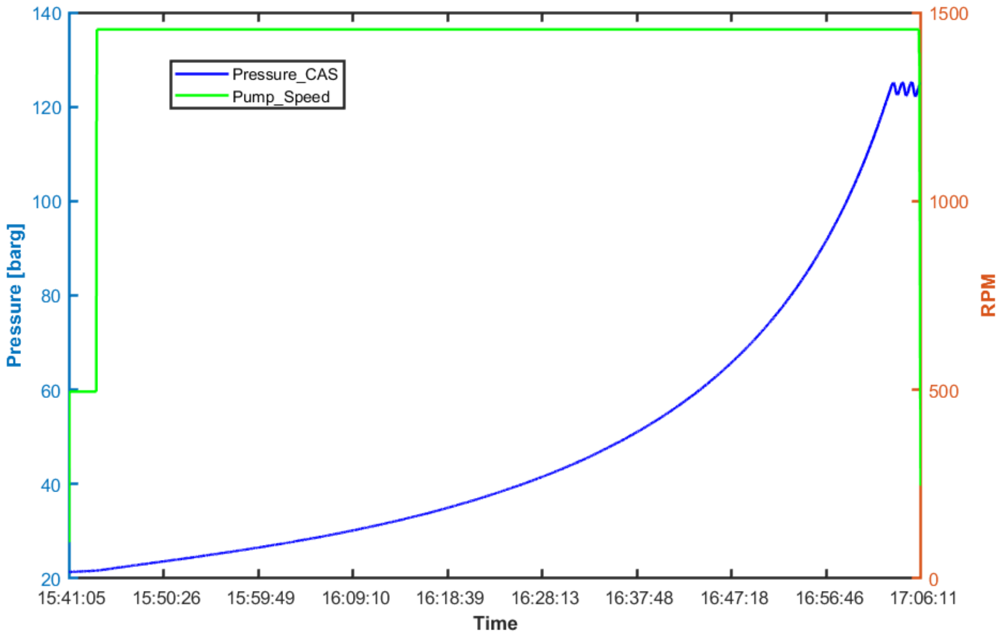
Figure 13: LPE (top) and IHE (bottom) power profiles with LPE_VSD and IHE_VSD speed respectively



SY-D-01

This pump test pressurises the compressed air store (CAS) to 124 barg by pumping water into it. The pump initially operates at 500 RPM before ramping up to approximately 1450 RPM. Figure 14 illustrates the non-linear increase in air pressure until it reaches 124 barg, at which point the pump is stopped. This process is carried out to prepare for charge test SY-D-02, ensuring the CAS is pre-pressurised to 124 barg before introducing compressed air at the same pressure.

Figure 14: Pressure in the compressed air store and pump speed profile



SY-D-02

This charge test compresses air from ambient to 124 barg using three compression stages, with three cylinders in LPE, one in IPE, and two in HPE. The system remains in idle mode until 08:33, after which the speed reference is set to 600 RPM for LPE and 750 RPM for IHE under charge mode to build pressure. The pressurised air exiting HPE is stored in the compressed air store. LPE compresses the air to approximately 4.5 barg, IPE to 17 barg and 24 barg towards the end of the test, and HPE to 124 barg.

Figure 15 shows a pressure ramp as the air pressurises the pipework. The system uses pressure control valves, resulting in oscillatory behaviour, though the pressure profile is more stable than in the previous test due to improved control tuning.

Figure 16 presents the temperature profiles for air on the hot and cold sides of the compression stages. At the start of the operation (idle state), the hot-side air temperature is around 50°C due to residual heat from a previous charge test conducted during system troubleshooting. As the system transitions to charge mode, temperatures rise, reaching approximately 140°C for LPE, 147°C for IPE, and 152°C for HPE.

Figure 17 further illustrates the increase in thermal store inlet temperature, which reaches 65°C for LP, 95°C for IP, and 45°C for HP.

Figure 18 presents the power profile, showing that engine oil remains warm from a prior charge test, preventing a power drop during the idle state. These values correspond to friction power. When the system switches to charge mode, LPE power increases to 16 kW, while IHE power reaches approximately 27 kW. As the pressure ratio in IPE rises from 17 barg to 24 barg, IHE power further increases to around 30 kW.

Figure 15: Cold and hot side pressure profiles for LPE (1st), IPE (2nd) and HPE (3rd). The pressure axis scaling differs between plots.

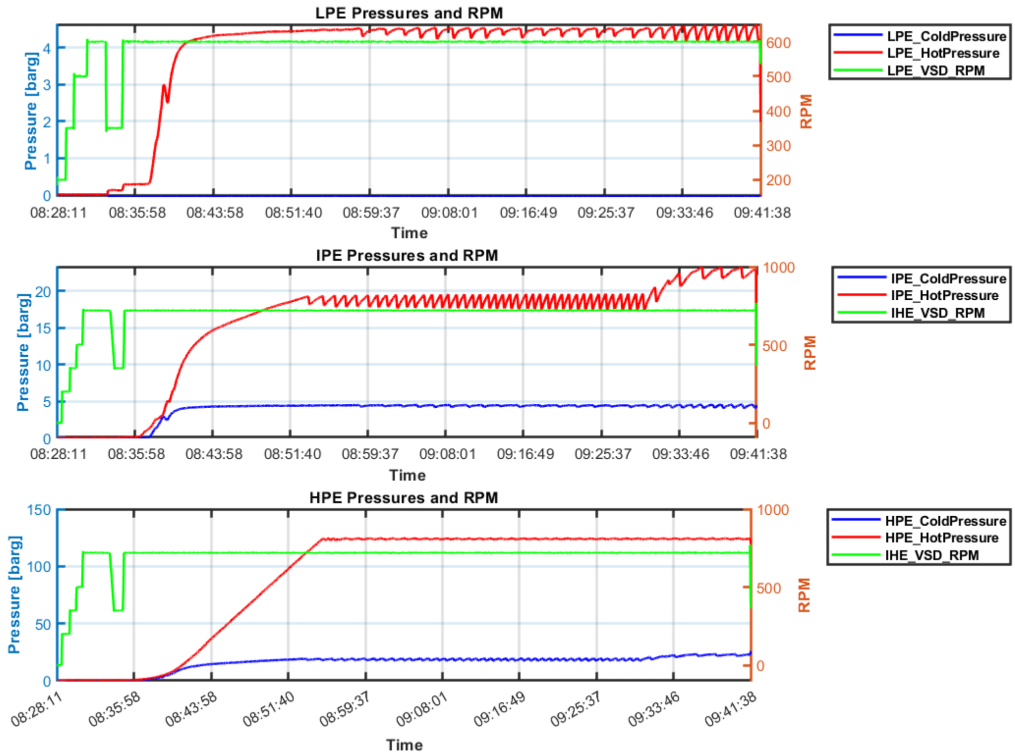


Figure 16: Cold and hot side temperature profiles for LPE (1st), IPE (2nd) and HPE (3rd)

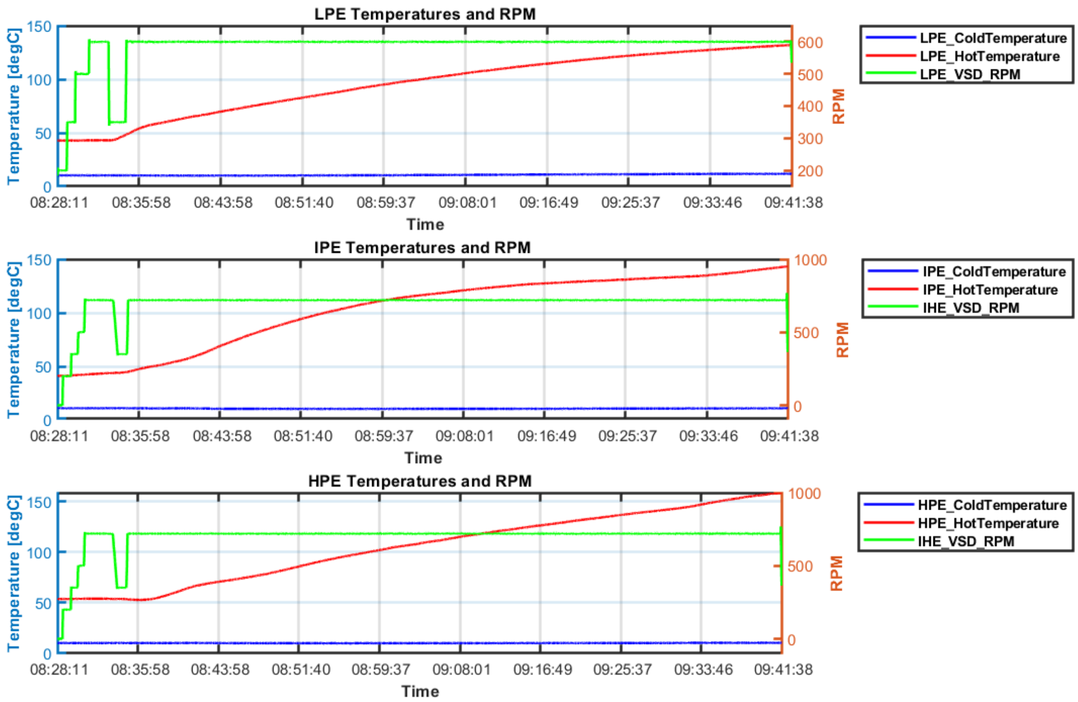


Figure 17: Low pressure (1st), Intermediate pressure (2nd) and High pressure (3rd) thermal store temperature profiles. The temperature axis scaling differs between plots.

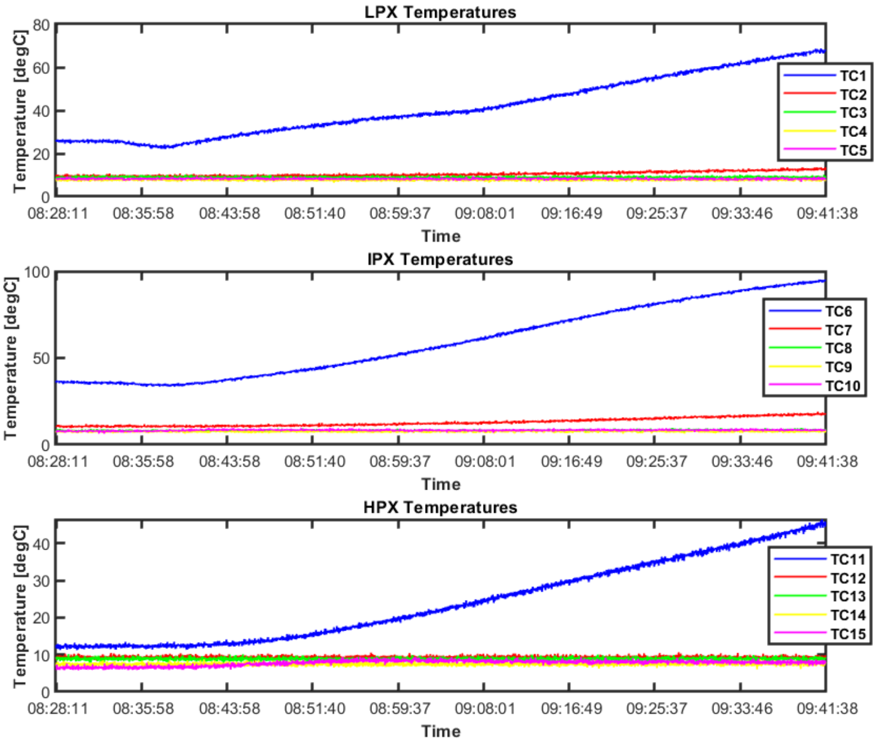
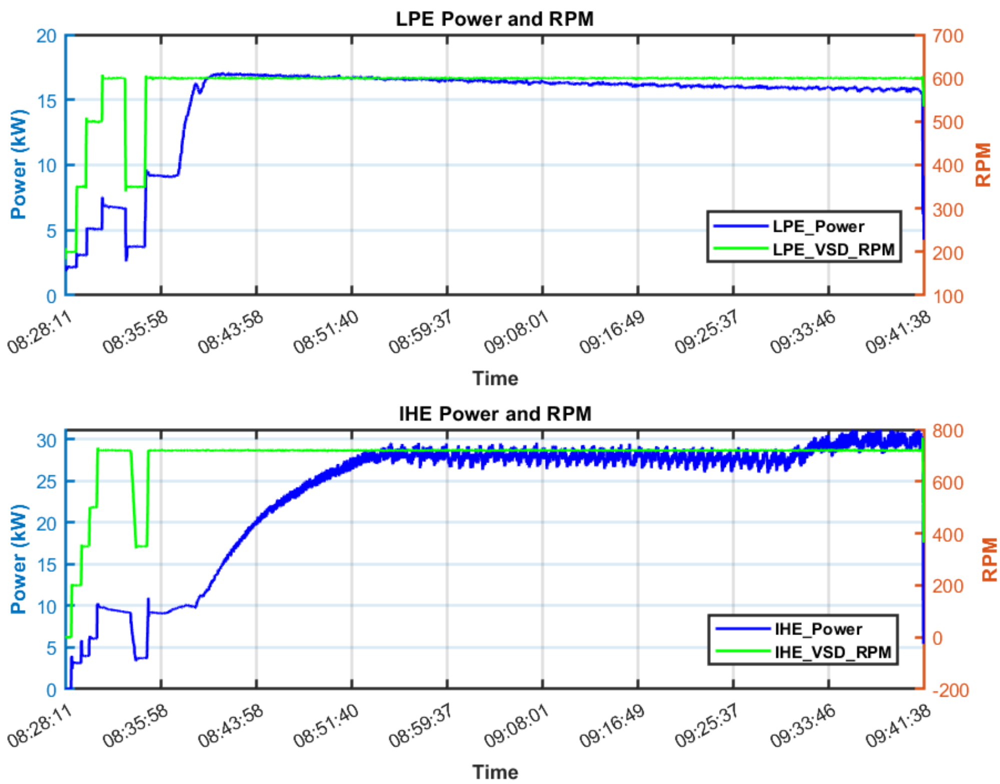


Figure 18: LPE (top) and IHE (bottom) power profiles with LPE_VSD and IHE_VSD speed respectively. The y-axis scaling differs between plots.



Prototype system testing summary

The Prototype system has demonstrated sound basic operation, as evidenced by the results from the various tests conducted. The compression, expansion, and heat dynamics are validated through pressure and temperature profiles, confirming the system's effective performance. At the subsystem level, tests were performed to assess the controls and structural integrity of each individual compression stage. As expected, the air temperature in the thermal store increases during the compression tests, which validates both the principle and design of the thermal store.

The test plan was designed to systematically evaluate the system, checking controls at different pressure limits. In later compression tests, the air was directed into the compressed air store, which tested the pressure control and water level sensing capabilities of the store. For high-pressure compression and expansion tests, the system operated under a 3-1-1 or 3-1-2 configuration, using fewer cylinders and lower speeds. This setup resulted in lower temperatures, flow rates, friction, power consumption, and power generation during expansion. Based on the test results, the anticipated power generation from air in the full Prototype system is projected to be around 100 kW.

Despite these positive outcomes, challenges such as leaking engine valves, which reduced volumetric efficiency, and oscillatory control on pressure control valves were encountered. These have informed design efforts on the Demonstrator system.

Demonstrator test plan and simulations

Time constraints and supply chain challenges have meant that completion of the Demonstrator testing phase has not been possible within the duration of the project; instead the following section outlines the test plan that has been developed and the detailed simulations that have been carried out in accordance with the test plan. The test plan will be carried out from February 2026 onwards and results fed back to DESNZ once available.

The test plan is designed to sequentially characterise different parts of the system, building from low speed and pressure up to full design conditions. The staged approach allows data to be gathered and potential issues to be addressed with a clear baseline for comparison, such that new findings can be attributed to the incremental changes in each test.

Table 2: Summary of tests and which subsystems are active (marked with X if active)

Test	SC	LP	IP	HP	Mode	Purpose
DEM-S-01	X	X			Compression (1.2 barg)	Assess basic SC (supercharger) operation and controllability of SC pressure versus speed
DEM-C-01	X	X			Compression (5.2 barg)	Assess basic operation and compression performance of SC+LPE together
DEM-C-02	X	X	X		Compression (32.4 barg)	Assess basic operation and compression performance of SC+LPE+IPE together
DEM-C-03	X	X	X	X	Compression (200 barg)	Assess basic operation and compression performance of SC+LPE+IPE+HPE together
DEM-SD-01			X	X	Expansion (28 barg)	Assess expansion performance of IHE
DEM-SD-02		X	X	X	Expansion (28 barg)	Assess expansion performance of IHE + LPE
DEM-SC-01	X	X	X	X	Compression (125 barg)	Test compression via all pressure stages, and storing pressurised air in the air store to understand hydrostatic pressure dynamics
DEM-SD-03	X	X	X	X	Expansion (125 barg)	Assess expansion performance of all pressure stages and thermal store degradation
DEM-SC-02	X	X	X	X	Compression (200 barg)	Test compression at higher engine speeds via all pressure stages, and storing pressurised air in the air store to understand hydrostatic pressure dynamics
DEM-SD-04	X	X	X	X	Expansion (200 barg)	Assess expansion performance with higher air store pressure and higher engine speeds
DEM-CC-01	X	X	X	X	Compression (230 barg)	Assess full system cyclic operation at design point
DEM-CD-01	X	X	X	X	Expansion (230 barg)	Assess full system cyclic operation at design point

The test plan includes dedicated motor speed tests for the LPE, IPE, and HPE, as well as blower-only tests intended to assess engine oil temperature and pressure, in addition to engine vibration and friction characteristics.

Test plan simulation results

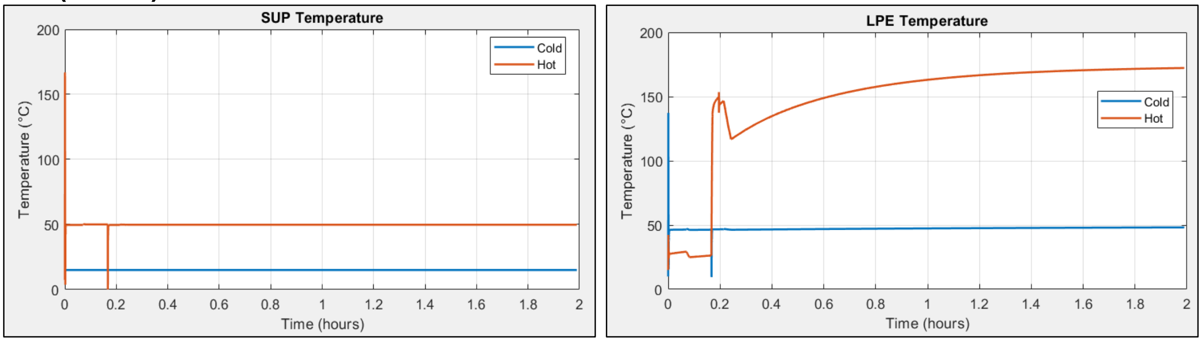
The Demonstrator test plan sequences have been implemented using a detailed Simscape-based transient system model of the Demonstrator plant. The model captures the dominant thermodynamics, providing physically consistent estimates of process air and thermal mass temperatures across the system. The time-resolved formulation enables tracking of key system parameters, including pressures, temperatures, mass flow rates, and net power, allowing system performance to be assessed as a function of operating sequence and test duration. Execution of the Demonstrator hardware tests and systematic comparison of model outputs with HMI data will be carried out after the formal project close, focusing on pressures, temperatures, mass flow rates, and power. Any identified discrepancies will be used to calibrate model parameters and refine modelling assumptions.

DEM-C-01

During the charge sequence, both the supercharger and the LPE operate in charge mode, with the LPE initially running in blower mode for the first ten minutes before transitioning to active compression. This operating strategy allows the supercharger to reach its normal operating pressure and pre-pressurises the LPE pipework, resulting in a smoother and more stable transition to full compression. The pipes and thermal stores are initialised at ambient conditions. The model simulates a continuous compression period of two hours. The supercharger increases the air pressure from ambient to approximately 1.3 bara, after which the LPE further compresses the air to around 6.3 bara. The LPE operates at a fixed speed of 500 RPM, while the supercharger runs at approximately 1900 RPM.

As shown in Figure 19, the supercharger outlet temperature rises to approximately 50 °C, while the LPE outlet temperature reaches around 172 °C during compression. The temperature at the LPE outlet increases as initially the engine thermal mass is cold, and the heat from compressed air goes into heating the engine assembly. However, gradually as the engine thermal mass temperature increases the rate of heat transfer from air to the engine reduces, thus air retaining the heat from compression. The downstream LP thermal store absorbs the heat from the LPE outlet air, reducing the air temperature back to near ambient conditions. The simulated air mass flow rate through the system is approximately 0.06 kg/s. The average electrical power consumption of the combined supercharger and LPE during this operating period is approximately 9 kW.

Figure 19. Process air temperature of supercharger (left) and LPE (right) at cold (inlet) and hot (outlet) side.



DEM-S-01

The supercharger is in charge mode, with a pressure ratio of 2.2, while the LPE runs in blower mode (rather than active compression) at 500 RPM. The supercharger runs at about 2400 RPM. The speed of supercharger is an output from a PID loop on pressure ratio which control its speed. The pipes and thermal stores are initialised at ambient conditions. Ambient air enters the supercharger at 15 °C and is compressed to an outlet temperature of approximately 127 °C. As the LPE is not performing compression, the air experiences cooling as it passes through the machine due to heat losses to the engine structure and surrounding environment, resulting in an outlet temperature of approximately 80 °C by the end of the simulation. The model simulates a continuous compression period of two hours. Downstream of the LPE, the air passes through the low-pressure thermal store, where heat is transferred to the thermal media. As a result, the air temperature reduces further, reaching approximately 15 °C at the outlet of the LP thermal store.

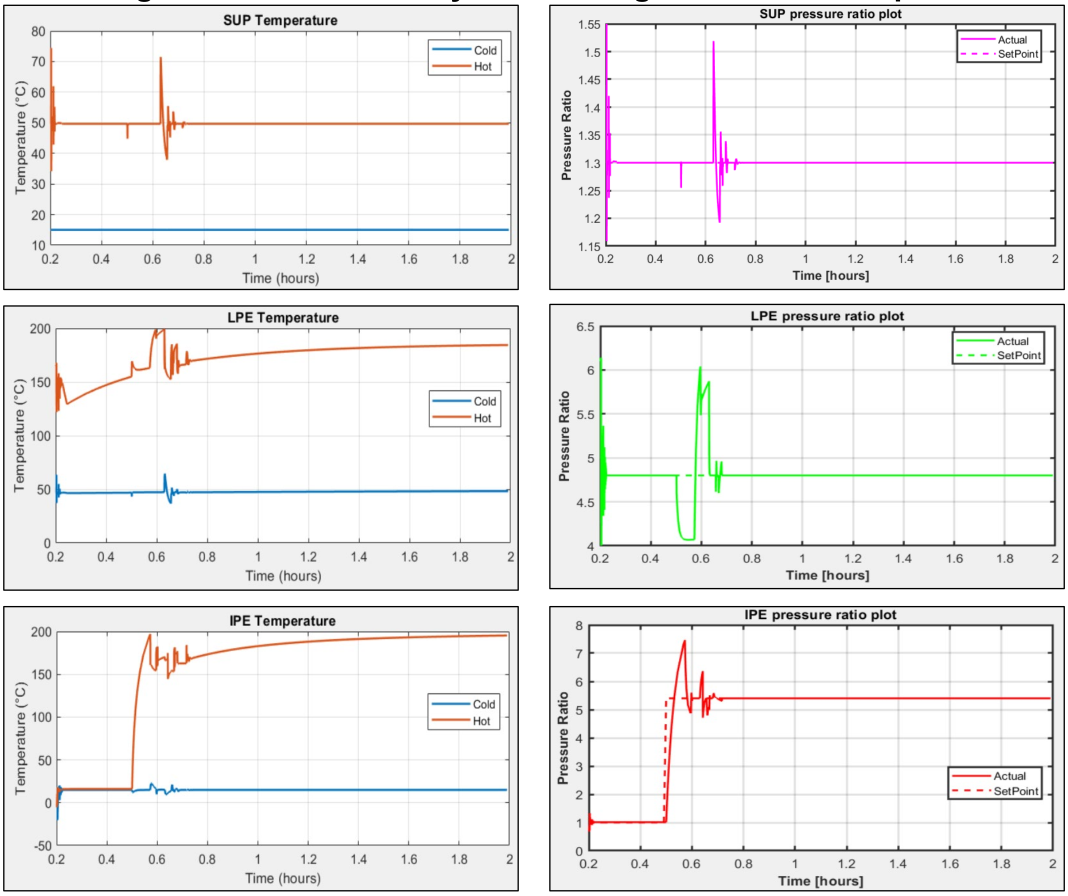
The mass flow rate of air is 0.074 kg/s and the average electrical power consumed by the supercharger is 9.3 kW.

DEM-C-02

This test compresses air using the supercharger, LP and IP stages operating sequentially. The LP stage is enabled in charge mode after an initial 10-minute period, followed by the IP stage after a further 20 minutes. Both LP and IP operate at a fixed speed of 500 RPM. All pipes and thermal stores are initialised at ambient pressure and temperature conditions. The model represents a continuous compression process with a total simulated duration of two hours. The supercharger raises the air pressure from ambient to 1.3 bara, the LP stage further compresses the flow to 6.3 bara, and the IP stage increases the pressure to a final level of 33.4 bara. Over the duration of the test, the average electrical power consumption of the system is approximately 21 kW, with a corresponding mean air mass flow rate of 0.064 kg/s.

Figure 20 shows the air temperature profiles at the inlet and outlet of the active engine stages. The outlet temperature from the LP stage increases steadily, reaching approximately 190 °C, while the IP outlet temperature rises to around 200 °C. A transient disturbance is observed when the IP stage is brought into charge mode, which is reflected as a deviation in the temperature traces. This behaviour is caused by a rapid change in downstream pressure as the IP stage is activated. The controller responds by adjusting the effective volume ratio to rebalance mass flow across the stages. During this transient, the IP pressure initially overshoots, which is compensated by the LP stage, resulting in a temporary reduction in the LP pressure ratio to ensure mass flow continuity through the compression train.

Figure 20. Temperature (left) and pressure ratio (right) profiles for supercharger, LPE and IPE during the simulation. The y-axis scaling differs between plots.



DEM-C-03

In this charge test, the engines are engaged sequentially in the compression train, beginning with the supercharger, followed by the LP, IP, and HP stages after 10, 20 and 30 minutes respectively, to progressively pressurise the system. All three stages are running at a fixed speed of 500 RPM. As shown in Figure 21, the supercharger increases the air pressure to 1.3 bara, after which the LPE raises it to 6.3 bara, the IPE to 33.4 bara, and finally the HPE to approximately 200 bara.

As per Figure 22, air temperatures exceed 150 °C at the LPE and IPE outlets after the thermal losses from engines; this is as designed as these air flows provide heat for storage in the thermal store. Until the downstream engine stages are activated for charge, the air is vented out before entering those engines and hence the temperature profiles do not account for thermal losses during this duration for those stages. A controlled numerical disturbance is observed when the IP stage is activated, arising from the controller adjusting pressure ratios to rebalance mass flow rates across the compression stages. The average air mass flow rate during the test is 0.061 kg/s, and the average net electrical power consumption is 25.7 kW.

Figure 21. Process air pressure at the cold (inlet) and hot (outlet) of the engines during compression. The pressure axis scaling differs between plots.

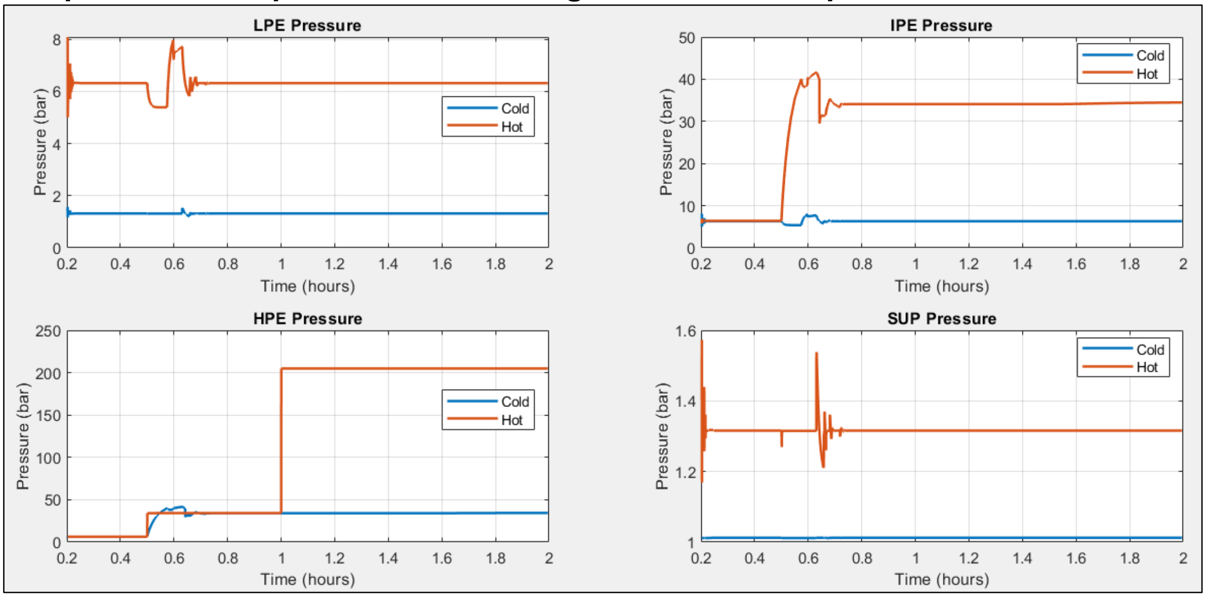
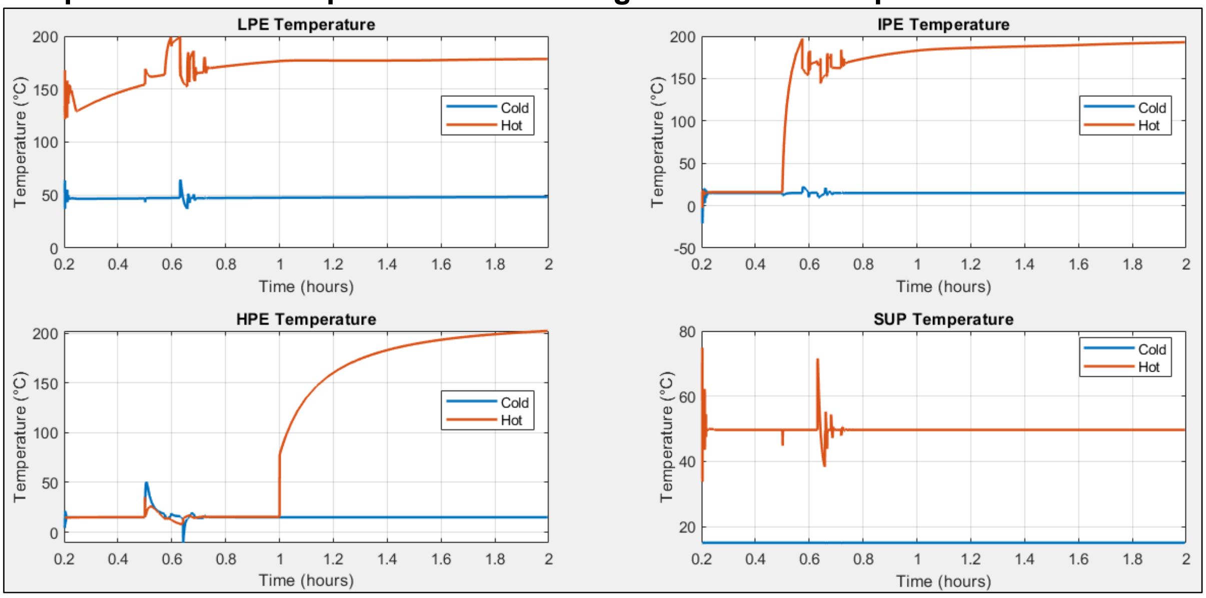


Figure 22. Process air temperature at the cold (inlet) and hot (outlet) of the engines during compression. The temperature axis scaling differs between plots.



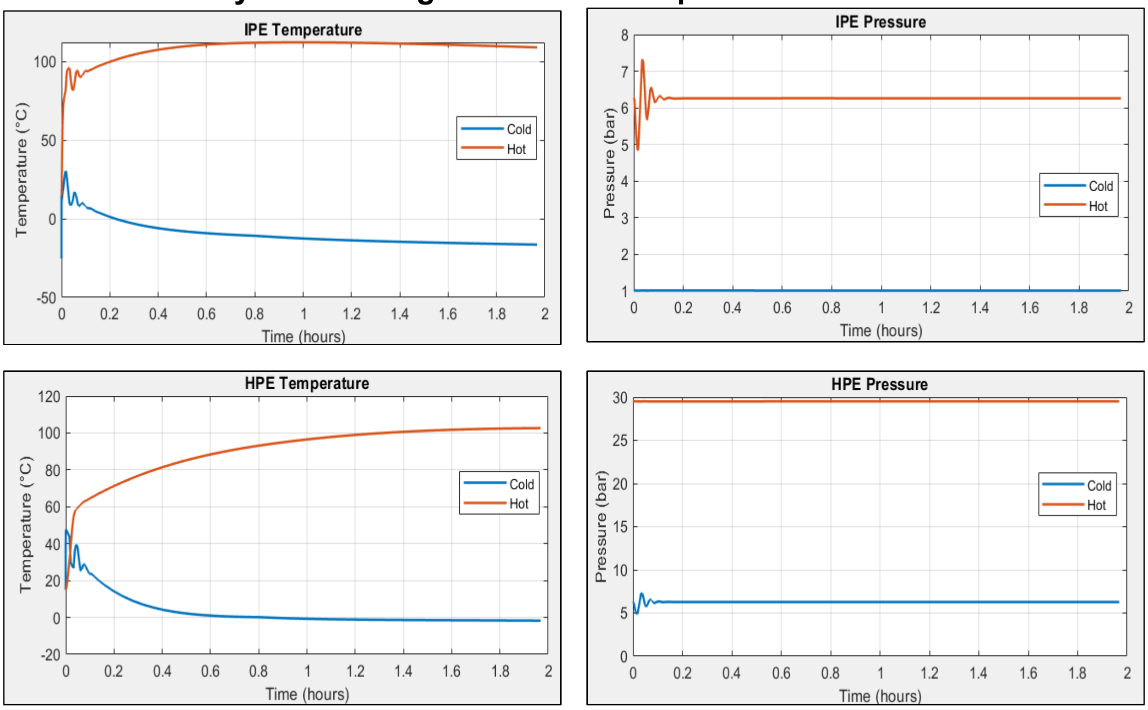
DEM-SD-01

In this discharge test, the IPE and HPE are used to expand air from 29.5 bara to 6.25 bara through the HPE, and subsequently to ambient pressure through the IPE. The system is pre-charged (put into charge mode briefly ahead of commencing a discharge) for 10 minutes, during which the pipes and thermal stores are brought to the required initial expansion pressures using the IPE and HPE, and the pipework is pre-heated to provide residual thermal energy to the process air during expansion. This approach avoids rapid expansion of cold air within the pipes and thermal store, and prevents expansion under low-pressure, thermally depleted conditions. The IHE is running at 500 RPM for a two-hour expansion process. The IP and HP thermal stores are assumed to be at 150 °C, reflecting the practical operating sequence in which discharge is preceded by a charge cycle that deposits usable heat into the system.

The average air mass flow rate during the test is 0.02 kg/s, with an average net electrical power generation of 1.9 kW. During expansion, the outlet air temperatures decrease to approximately 0 °C at the HPE outlet and around -15 °C at the IPE outlet. These temperatures remain above the lower operating limit of -20 °C. The ambient temperature and the downstream pipework end up heating the air back to 15 °C before it is discharged to the ambient.

An increase in the hot-side temperatures of the HPE and IPE is also observed in Figure 23. This arises as the expanding air progressively absorbs heat from the interconnecting pipework and thermal store, leading to a gradual rise in the inlet and hot-side temperatures over the course of the test. As the pipework, thermal store and engine thermal mass progressively lose stored heat over time, the available thermal energy on the hot side reduces. This behaviour is evident in the IPE temperature profile, where the hot-side temperature gradually decreases during continued operation. If the simulation were extended, a similar trend would be expected for the HPE. However, due to the significantly larger thermal mass of the HPE, the stored heat is sufficient to sustain elevated temperatures for a longer duration before a comparable decline is observed.

Figure 23. Temperature (left) and pressure (right) profiles for IPE and HPE during the simulation. The y-axis scaling differs between plots.



DEM-SD-02

This discharge test engages the LPE and IHE in expansion mode. The overall test sequence mirrors that of DEM-SD-01, comprising an initial pre-charge phase followed by a continuous discharge period. At the start of discharge, the thermal mass within the LP, IP and HP thermal stores is initialised to 150 °C, representing a system state in which usable heat is already available from a preceding charge operation.

During the test, the LPE operates at 300 RPM while the IHE runs at 1000 RPM. These rotational speeds are selected to balance the mass flow rates across the active expansion stages. The supercharger is not used and is bypassed via its internal bypass valve, ensuring no contribution to pressure rise or flow restriction during discharge.

The expansion process reduces the air pressure from 29.5 bara to 6.4 bara through the HPE, followed by further expansion to 3 bara via IPE and finally to ambient pressure through the LPE, as shown in Figure 24. Low pressure ratios are deliberately selected for this test, as it represents the first expansion scenario involving the LPE and IHE. This choice provides improved controllability and operational robustness at lower mass flow rates, thereby reducing the risk of failure modes. In addition, the reduced pressure ratios ensure that the cold-side outlet temperatures from the engines remain comfortably within acceptable operating limits (Figure 25).

Over the two-hour discharge period, the average mass flow rate of the process air is approximately 0.046 kg/s. The system generates an average net electrical power output of 8.3 kW.

Figure 24. Pressure profiles for hot (inlet) and cold (outlet) during expansion test DEM-SD-02. The pressure axis scaling differs between plots.

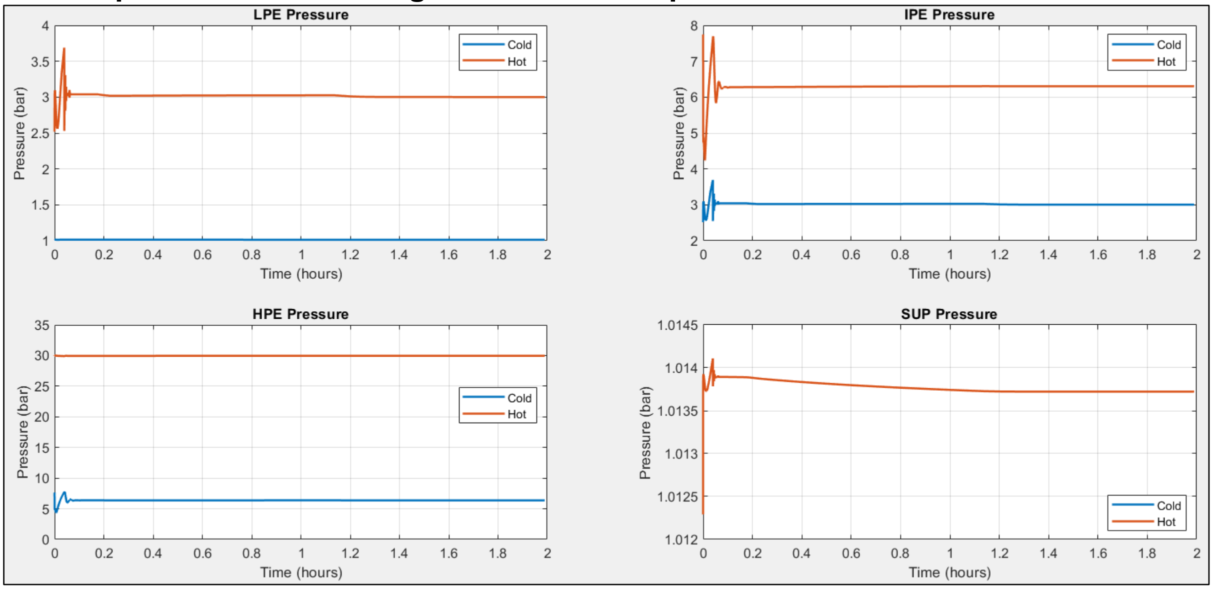
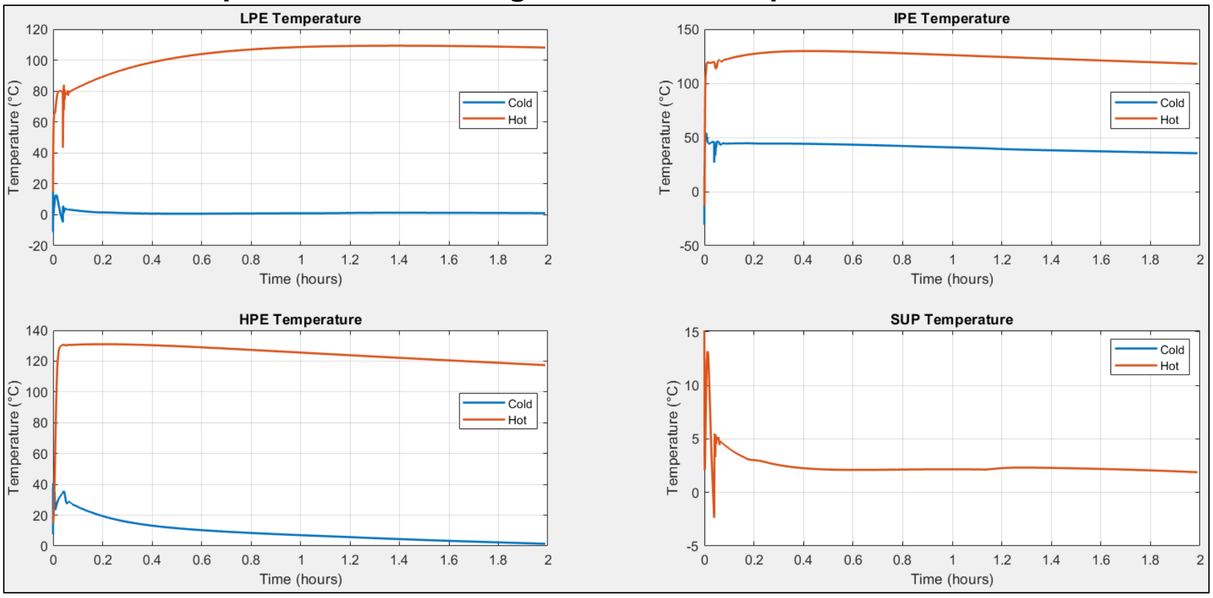


Figure 25. Temperature profiles for hot (inlet) and cold (outlet) during expansion test DEM-SD-02. The temperature axis scaling differs between plots.



DEM-SC-01

This charge test engages the full compression train, comprising the supercharger followed by the LP, IP, and HP engine stages, to compress air and charge the air store. All active engines operate at a fixed rotational speed of 500 RPM over a continuous two-hour compression period. The test configuration is largely identical to DEM-C-03, with the sole deviation being the operating point of the HPE. In this case, the HPE is commanded to a reduced pressure ratio of 3.8, resulting in a final pressure of approximately 129 bara rather than 200 bara.

The resulting thermal behaviour closely mirrors that observed in DEM-C-03. Temperature profiles across the supercharger, LPE and IPE show comparable trends, while the HPE outlet temperature is noticeably lower, 150 °C for current test versus 200 °C in DEM-C-03 due to the reduced compression ratio and correspondingly lower specific work input at this stage. This reduction in HPE temperature also leads to a marginally lower thermal load on the downstream thermal store associated with the HP stage.

Across the duration of the test, the average mass flow rate of the process air is 0.062 kg/s. The average net electrical power consumed by the system is 24.2 kW, reflecting the reduced overall compression work relative to the higher-pressure DEM-C-03 case.

DEM-SD-03

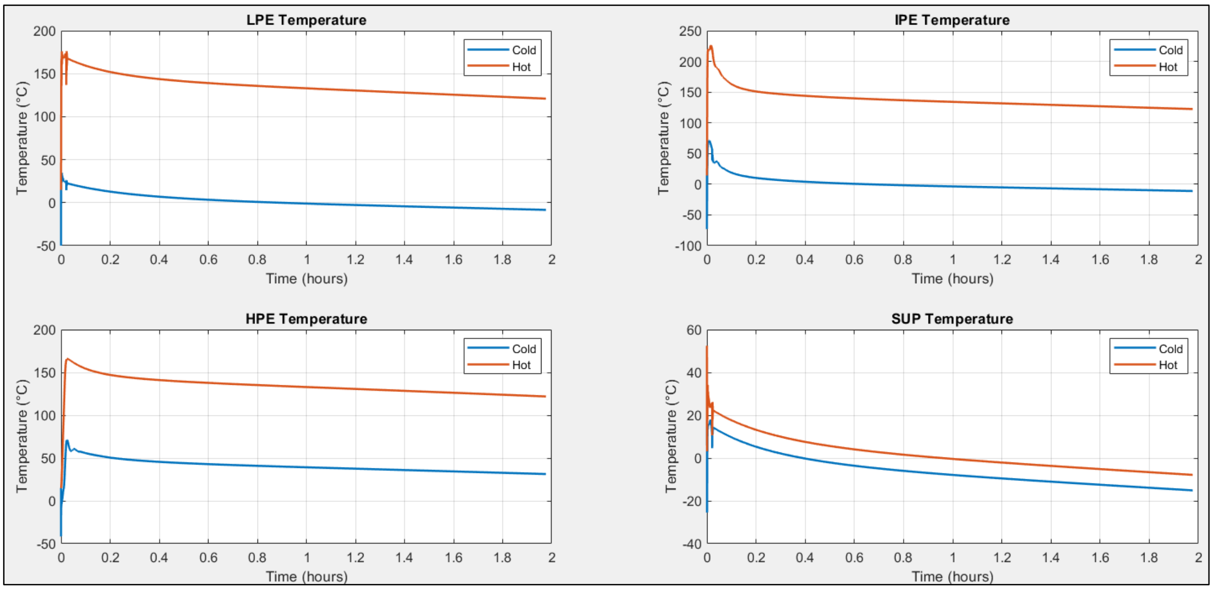
This discharge test engages all three engine stages together with the supercharger to expand the stored air. The test sequence mirrors DEM-SD-01, consisting of an initial pre-charge phase followed by a continuous discharge. Air is expanded from 133.5 bara to 43.5 bara through the HPE, then to 6.6 bara through the IPE, further to 1.2 bara through the LPE, and finally to ambient pressure via the supercharger.

The supercharger operates with a low expansion pressure ratio to facilitate flow balancing across the expansion train. In practice, the supercharger could be operated in blower mode. However, in the present model the control loops were unable to maintain stable flow balance under blower operation. Consequently, the supercharger was operated at a low-pressure ratio set point of 1.05. The LPE runs at 750 RPM, the IHE at 1000 RPM, and the supercharger at approximately 5250 RPM.

The average net electrical power generated during the test is 49.4 kW, with an average process air mass flow rate of 0.2 kg/s.

Figure 26 shows the temperature profiles at the outlets of all engine stages during the discharge operation. A progressive reduction in outlet temperature is observed as expansion proceeds, with the supercharger outlet temperature decreasing significantly over time and reaching approximately −18 °C at the end of the two-hour simulation. This behaviour is consistent with sustained expansion and the gradual depletion of available thermal energy in the system.

Figure 26. Temperature profiles for hot (inlet) and cold (outlet) during expansion test DEM-SD-03. The temperature axis scaling differs between plots.



DEM-SC-02

This charge test is identical to DEM-C-03 in terms of the pressure ratios and operating sequence, with the system progressing through the same staged compression arrangement. The key difference is that all engines operate at a higher rotational speed of 1000 RPM, resulting in a higher throughput of compressed air being charged into the air store.

Due to the increased engine speed, the system processes a higher mass flow rate, with an average value of 0.125 kg/s over the duration of the test as per Figure 27. The higher flow rate leads to a corresponding increase in electrical power demand, with the average net power consumption measured at 59.4 kW.

The elevated engine speed and mass flow rate also result in higher temperature levels (Figure 28) throughout the compression train compared to DEM-C-03. This behaviour is consistent with the increased compression work and reduced residence time for heat rejection within the engines and associated thermal masses. Figure 29 shows the rising air temperature entering the thermal store, with all three stages active after one hour. The staged start-up is designed to mirror a gradual test progression in which each stage is tested individually before the next one is activated – a production system would activate all stages within seconds, not minutes.

Figure 27. Mass flow rate (left) and net charge power (right) profiles for DEM-SC-02

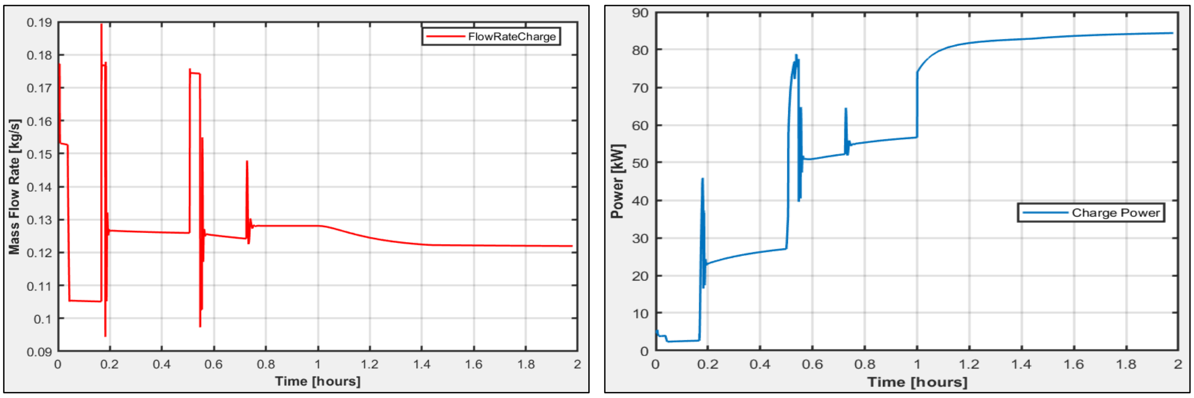


Figure 28. Temperature profiles for cold (inlet) and hot (outlet) for engines for compression test DEM-SC-02. The temperature axis scaling differs between plots.

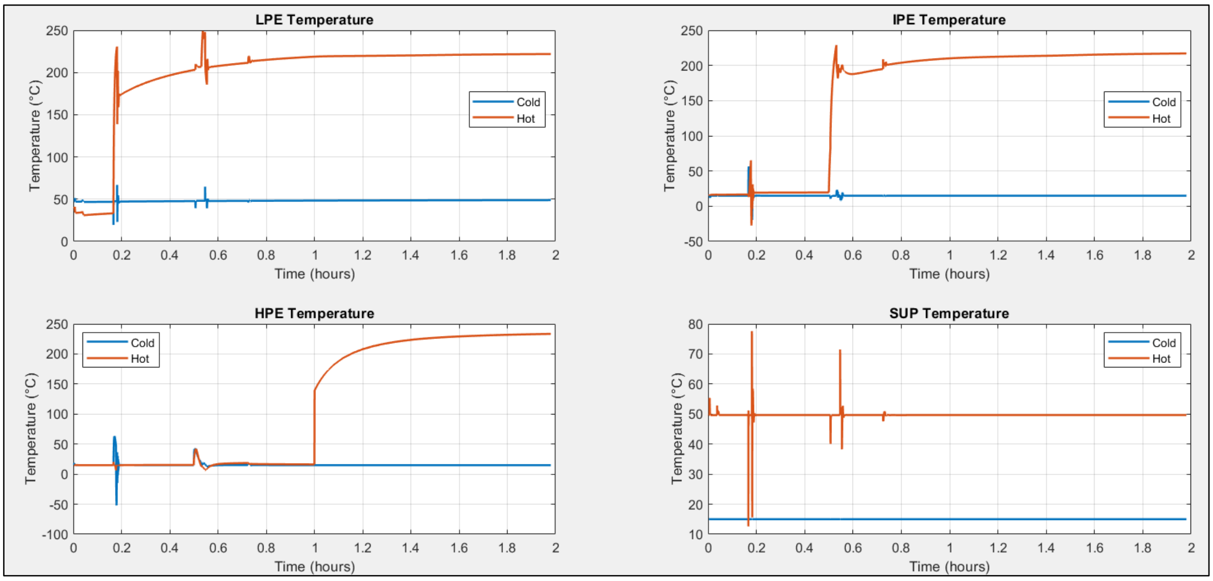
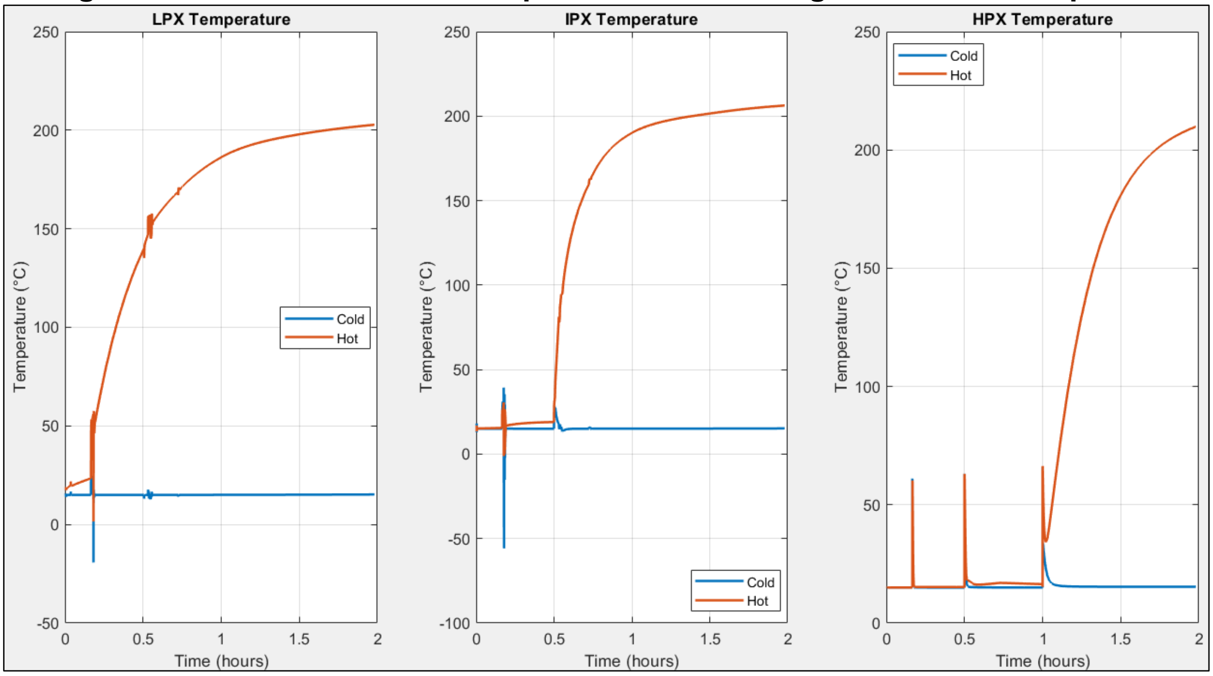


Figure 29. Process air temperature at inlet (hot) and outlet (cold) side of the thermal store during the test DEM-SC-02. The temperature axis scaling differs between plots.



DEM-SD-04

This discharge test uses all the engine stages at a higher speed and a higher expansion pressure ratio. The operating sequence is similar to previous discharge tests – a pre-charge followed by the discharge and the LP, IP and HP thermal stores are initialised at 150 °C at the start of discharge. The LPE runs at 750 RPM and the IHE at 1000 RPM. The air first expands across the HPE with a pressure ratio of 3.9, followed by further expansion through the IPE stage with a ratio of 4.8. The LPE then expands the air with a pressure ratio of 5.5 before the final expansion across the supercharger, which operates at an expansion ratio of 2 to facilitate flow continuity and pressure matching to ambient. This staged pressure reduction results in a gradual decrease in pressure across the train, avoiding large single-stage expansions and limiting excessive temperature drops during discharge.

The average mass flow rate of air during the discharge process is about 0.32 kg/s and the net average power over two-hour period is about 85.2 kW (Figure 30).

It is observed in Figure 31 that the air temperature decreases significantly during expansion, reaching close to 0 °C at the outlets of the LPE and IHE. The temperature reduces further across the supercharger, reaching approximately −45 °C by the end of the two-hour expansion period. This behaviour arises because there is no thermal store between the LPE and the supercharger, and therefore the supercharger expands the already cold air exiting the LPE.

In the present model, as mentioned earlier, the pipework between the LPE and the supercharger is assumed to be perfectly insulated. This assumption is made on the basis that the pipe run is short and located within the engine enclosure. However, this is a simplifying assumption and is not fully representative of the physical system. In practice, inclusion of pipe thermal mass and thermal resistances would allow heat transfer from the surrounding enclosure air, leading to partial reheating of the process air both upstream and downstream of the supercharger. As a result, the actual supercharger outlet temperatures are expected to be slightly higher than those predicted by the model.

In addition, the supercharger is modelled with an isentropic efficiency of 60%, based on off-engine testing carried out. At off-design conditions, the effective isentropic efficiency may be lower, which would further increase the outlet temperature during expansion. Consequently, the predicted supercharger outlet temperature represents a conservative estimate.

Figure 30. Mass flow rate (left) and the transient net discharge power profile for DEM-SD-04.

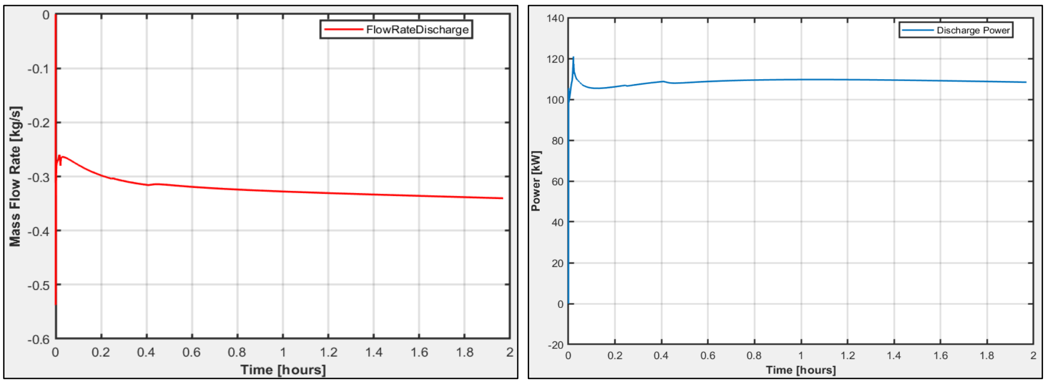
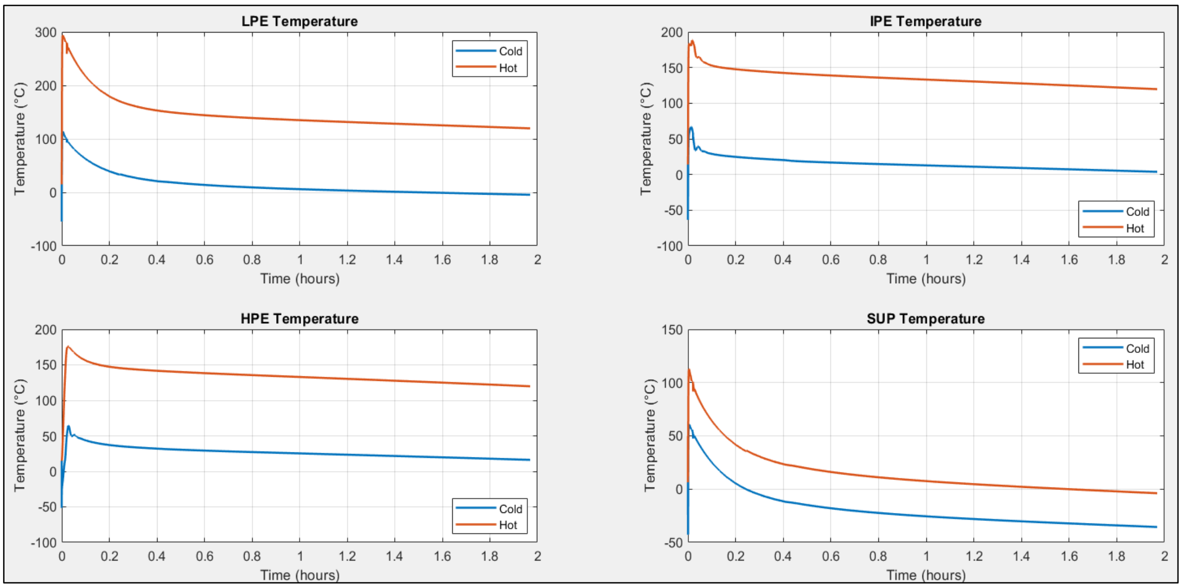


Figure 31. Temperature profiles for engine stages at hot (inlet) and cold(outlet) during expansion for DEM-SD-04. The temperature axis scaling differs between plots.



DEM-CC-01 and DEM-CD-01

Having tested incrementally each of the subsystems, the next step is to carry out repeated charge and discharge cycles to achieve steady-state cyclic operation. This primarily affects the thermal store, which attains a dynamic equilibrium over the course of multiple charges and discharges, with a thermal gradient translating back and forth within each store. The initial system running is predicted to deliver around 150 kW of net output power, leading to a longer discharge duration of over 6 hours. The round trip efficiency is forecasted at 40%.

The most influential driver of performance is the engine valving – small tweaks in the timings of the valves opening and closing can deliver multiple percentage points of stage isentropic efficiency, which translate into similarly large gains in round trip efficiency. Drawing on the live feedback provided by the Demonstrator control system, we will refine the valve timings to deliver optimised performance, and this is expected to drive the round trip efficiency up to 48%, while increasing the discharge power to 195 kW and delivering this over five hours of full-power discharge.

The final improvement proposed is the introduction of hydraulic energy recovery. This is a design modification that has been specified and designed as part of the Demonstrator project but not yet procured. The isobaric pressure store uses water pumped into and released out of the air store pressure vessels to maintain the air pressure at a constant 230 barg. Pumping the water into the vessels during discharge consumes energy, though much less than expanding the equivalent volume of air releases. In its current form, the pressurised water that is released from the vessels during charging, as air is added to the vessels, is simply allowed to depressurise through a pressure control valve. This way of operating is simple and robust but represents an opportunity to capture additional energy during the charge process that would increase the round trip efficiency further. A water-driven turbine has been identified and this would allow the pressurised water to be expanded to do useful work, driving the turbine and its attached generator to produce electrical power. Retrofitting the turbine in place of the existing valve would deliver an additional 4% round trip efficiency, purely by reducing the net input energy required to fully charge the system. The discharge side of the process is entirely unaffected.

Table 3: Summary of overall performance for cyclic steady-state operation

Run	Round trip efficiency (%)	Charge power (kW)	Discharge power (kW)	Charge duration (hours)	Discharge duration (hours)
DEM-CC-01a and DEM CD-01a: Initial full system running	40%	228	150	10.6	6.4
DEM-CC-01b and DEM CD-01b: Optimised valves	48%	219	195	9.7	5.1
DEM-CC-01c and DEM CD-01c: Hydro recovery	52%	198	195	9.7	5.1

The overall result of this sequence is a pathway from initial cyclic testing with 150 kW and 40% round trip efficiency to a system delivering over 50% round trip efficiency and 195 kW of output power and 1 MWh of output energy, in line with the project targets and specification.

Demonstrator test plan and simulation summary

The test plan and simulations map out a sequence of incremental testing, building up from low power and low speed early tests to final cyclic tests that deliver the target of over 50% round trip efficiency, with 195 kW of output power delivered for 5.1 hours for a total of 1 MWh of output electrical energy. This very closely aligns with the design criteria of 200 kW of output power over five hours.

Delivery against objectives

The following tables outline the project outcomes against the competition and project objectives. While final test results for the Demonstrator system are still being established, the vast majority of the aims have been meaningfully met and evidenced.

Table 4: Assessment of outcomes against competition aims

Competition aims	Outcomes
1. Explore the potential for cost reductions of longer duration storage technologies;	A cost reduction pathway has been identified, drawing on engagement with Tata, Ricardo and the wider supply chain. This is explored further in the section on Cost reduction potential.
2. De-risk effective non-conventional storage technologies and therefore	Rapid development has taken place, with two iterations of the technology built out, incorporating major design upgrades and with significant technical and commercial learnings delivered.
3. Secure buy-in from commercial investors;	£6.5m in equity investment has been raised since the start of LoDES and a lead investor has been identified for the upcoming £6m Series A round.
4. Demonstrate capability, securing data to inform policy formulation;	Prototype performance data has been shared, and modelling results provided for Demonstrator though final performance is still to be evidenced.
5. Build a pipeline of storage technologies in the UK, supporting expertise and export opportunities.	KES continuing to emphasise UK applications, manufacturing and supply chain, including expertise in motorsport and grids.

Table 5: Assessment of outcomes against project objectives

Project objectives	**Outcomes**
Deliver a strong multi-unit demonstrator for KES's technology	Multi-unit demonstration has not been possible but a more advanced single-unit demonstrator has been developed and a multi-system design and operating study has been carried out. Objective met through alternative approach.
Engage at meaningful volumes with a scalable supply chain	Work towards the Colchester pilots meant that we engaged with supply chains and extracted learning and costdown information. Objective met
Validate the technology and cost roadmaps to production units	This is ongoing, though the fidelity of the cost roadmap has been markedly increased by work with supply chain and tendering activities. Objective partially met and remains ongoing with work to test the Demonstrator system.
Build customer feedback into technology development	Sustained engagement with Colchester, Shell, Amazon and others has helped put customer requirements into the heart of the design process. Objective met.

Key successes and lessons learned

Technical successes

- Two full CAES systems have been designed, manufactured and assembled.
- Zero lost-time injuries throughout the project and 95th percentile on HSE safety climate.
- Major performances upgrades have been designed and implemented.
- New control system developed for higher cyber security.
- A scalable supply chain, drawing on existing engine assembly shops and contract manufacturing, has been proved out for engine and actuator assembly.
- A viable cost and performance pathway to production systems has been identified.
- Two patents granted and two new patents filed during project.

Commercial traction and engagement

- Memoranda of Understanding signed with Siemens and Volvo Penta, and KES has presented to Volvo Penta's global board.
- A paid feasibility study has been delivered for a major mining player in Western Australia.
- Selected for Amazon accelerator, pilot programme and procurement.
- Working with Northern Powergrid to map out grid strengthening capabilities.
- Selected for Shell Startup Engine.
- Visit from Lillian Greenwood MP, LDES Roundtable with Minister Shanks (Nov 24), Energy roundtable (Jan 26).
- Presentations at CERAweek, Energy Technologies Live, Solar and Storage Live, PowerEx, Innovation Zero, Shell demonstration day, multiple events in Europe and the USA with the Department of Business and Trade.

Lessons learned

Lessons learned are summarised briefly here.

- Rapid partial testing has driven faster progress than full system testing by reducing downtime, for example through reduced engine cylinder running.
- A capable, experienced supplier can come unstuck with a new facility – contractual commitments to specific facilities preferred where possible and additional diligence needed where this is not possible.

- Major blue-chip design houses have had difficulties working at our pace – experienced contractors embedded in the business have been much more effective.
- Actuator procurement and assembly through a contract manufacturer has been successful, injecting pace into a complex process and highlighting simplification opportunities.
- Plan for the end goal but stage technical effort alongside concrete results – e.g. an automated Prototype system control system running was developed but rarely used.

Commercialisation pathway

Commercial opportunities

Energy storage outlook 2026

The global energy storage market reached a record 106 GW of installations in 2025[5] and is expected to continue expanding in 2026, driven by decarbonisation, rising variable renewable energy (VRE) penetration and new applications. Growth has been geographically broad-based, with Europe seeing a 160% increase in installations in 2025[6] and rapid uptake across the Middle East and APAC, while China remains dominant in manufacturing despite margin pressure.

Increasing VRE penetration, reaching around 36% of global installed capacity in 2025[6], is accelerating the need for grid-forming storage, with formal regulation expected in Europe in 2026. Energy storage deployment is increasingly driven by large, inflexible loads such as data centres, with over 230 GW announced in the US alone[6], and by co-located solar and wind projects responding to curtailment, falling capture prices and rising instances of negative power prices.

Specification for KES production systems

The specification for production KES systems closely aligns with that for the Demonstrator. There is a potential further uplift in power from 200 kW to 250 kW as the technology advances, particularly as higher valve lifts and larger supercharger pressure ratios unlock larger mass flow rates. This would improve the economics of the system by extracting more value from effectively the same base hardware. The storage capacity will remain modular, with 800 kWh-1 MWh increments. The number of power and energy modules required for a given site will of course depend on the application in question. The systems will be packaged in a double-stacked 40-foot ISO shipping container for ease of transport and installation, minimising the onsite connections and maximising the offsite commissioning that can be completed in factory conditions. The production systems will run at fixed speed using synchronous electrical machines, rather than the variable speed drives used for testing purposes in the Prototype and Demonstrator systems.

Cost reduction potential

Producing first-of-a-kind systems is invariably extremely expensive, as a result of drawing upon low-volume agile supply chains that specialise in one-off machining and fabrications, plus the

[5] Wood Mackenzie, Global energy storage market surpasses 100 GW annual installation milestone in 2025 (2026). https://www.woodmac.com/news/opinion/global-energy-storage-market-surpasses-100-gw-annual-installation-milestone-in-2025/
[6] Energy Storage News, Grid-forming, hybrids and alternative chemistries in Wood Mackenzie's 2026 energy storage trend predictions (2026). https://www.energy-storage.news/grid-forming-hybrids-and-alternative-chemistries-in-wood-mackenzies-2026-energy-storage-trend-predictions/

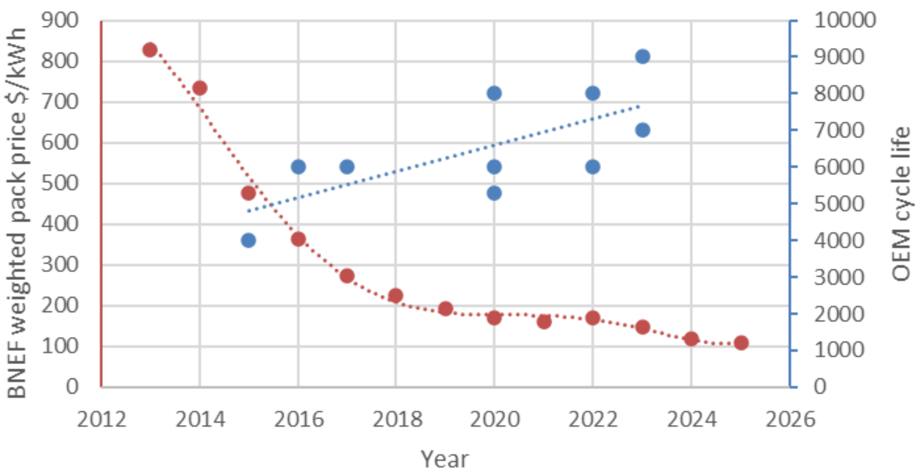
use of development parts which are expected to change further and therefore have not been value-engineered for lowest cost. The cost reduction strategy is as follows:

1. Simplify, reduce pipework lengths and optimise temperatures;
2. Switch from local to global supply chain;
3. Design for manufacture and secure learning by doing effects.

Major opportunities have been identified around reducing temperatures further, unlocking a much more compact thermal store that makes use of pressurised water storage. Containerising the system also brings down pipe lengths, while system simplification allows superfluous valves and flexible testing capability to be stripped out. Removal of the inverters also drives cost out. KES has identified global suppliers for the air store at around half the cost of European suppliers, and machined compressor-expander parts at 50-85% lower cost than UK providers.

The rapid fall in lithium-ion costs over the last few years has put intense pressure on unit economics for novel technologies, as shown below in Figure 32. Eventual production systems would need to cost less than £300/kWh to compete with commercial and industrial scale lithium-ion systems, which have already benefited from decades of investment and technology development. This remains a major challenge and while progress has already been made, it is far from certain that this can be achieved and will require very patient capital to secure.

Figure 32: Evolution of lithium-ion cost (volume-weighted pack price across all applications) and cycle life over time. Data publicly available from BNEF, CATL and BYD datasheets. Pack price is a component of overall lithium-ion system cost.



Focusing on the unique offering of KES technology

The market for flexibility has seen an evolution from decarbonisation being the principal driver towards resilience and speed to power becoming new priorities, in response to growing load demand, increasingly stretched networks and long waits for new connections. Combined with this, the fall in lithium-ion prices (as per Figure 32) means that it is increasingly competitive in longer duration applications, putting severe pressure on the economic attractiveness of innovative longer duration technologies.

In response to these market conditions, the KES product offering has been adapted to emphasise its unique capabilities in delivering the services required to operate the electricity system safely and affordably. Rather than focusing solely on energy storage, the proposition to customers and grid operators centres on what the grid needs to reliably connect additional generation and load, including inertia, fault level, voltage support, and resilience. This positions the technology as a system-enabling asset that addresses structural network constraints, not just a tool for local optimisation, while retaining all of the longer duration energy storage capabilities needed for system-wide energy management and decarbonisation.

Figure 33 maps out the set of services required to operate a grid. Historically all of these services have been provided by fossil-fired power stations, at which the energy storage is simply the pile of coal, tank of oil or stored natural gas. These large centralised plants provide a strong and robust grid, albeit at the cost of harmful carbon emissions and high running costs. As grids move to increasing renewables penetrations and the proportion of synchronous generation falls, however, without additional grid stability measures customers are facing:

- Longer waits for new connections;
- More frequent voltage dips and outages;
- Weaker protection and slower fault clearance.

Figure 33 also identifies the proportion of the essential grid services that can be provided by inverter-based resources such as batteries. Inertia provision, which is required to stabilise grid frequency (50Hz in the UK), can be partially replicated through batteries equipped with grid-forming inverters if configured correctly.

Figure 33: Essential grid services provided by inverter-based battery technologies

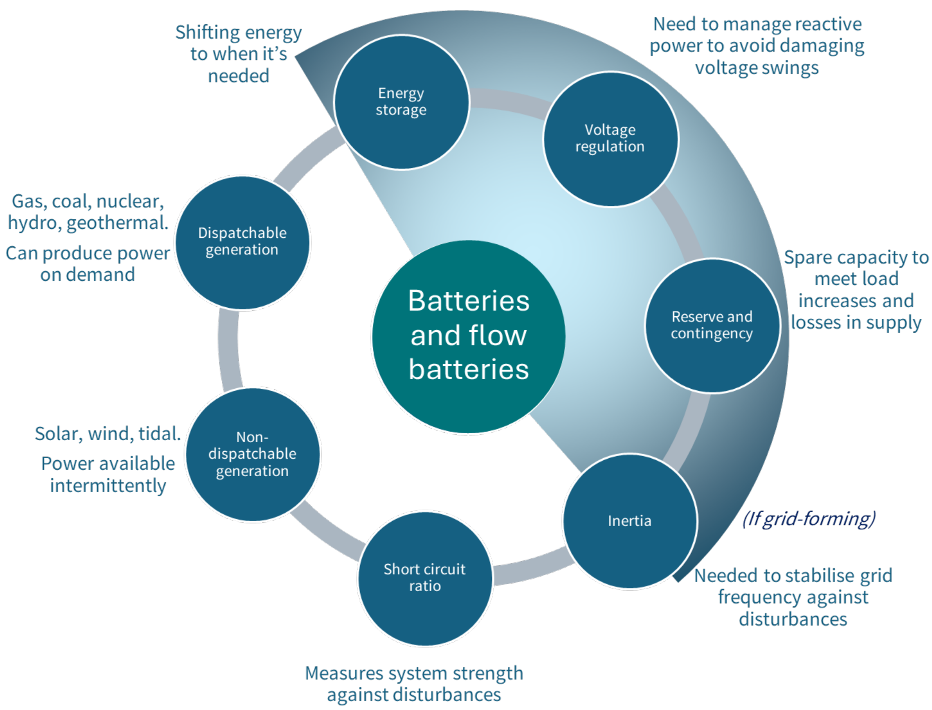
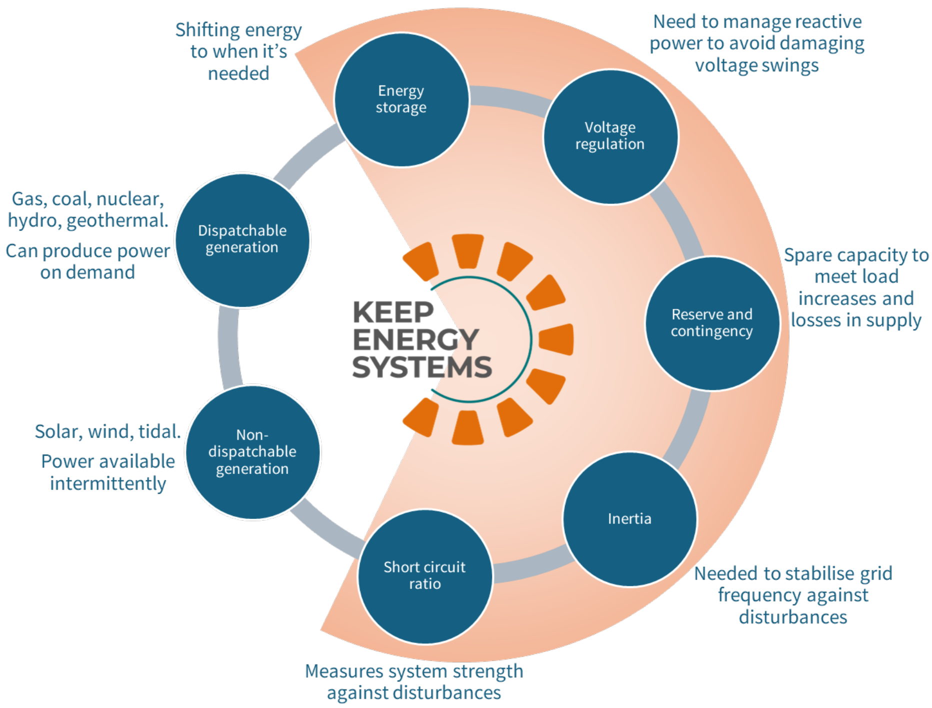


Figure 34 shows the wider set of services which production KES systems can provide. As the systems use the same synchronous electrical machines as diesel generators and fossil fired power stations, they are able to deliver the voltage support, inertia and short circuit level that grids need and batteries cannot fully replicate. Most significantly, the electrical machines are able to deliver several times more short circuit level than even a grid-forming inverter, helping to increase system strength against disturbances and supporting the correct action of grid protection measures.

Figure 34: Essential grid services provided by Keep Energy Systems' modular CAES



Customer needs

Grid constraints and reliability risks translate directly into material financial losses for large electricity users. For a 100 MW AI data centre, each year of delay in securing a grid connection can result in an estimated USD 0.4–1.2 billion of lost revenue[7], reflecting the opportunity cost of idle capacity and deferred service delivery. Once operational, exposure to outages remains a major risk: large continuous-process manufacturing plants face an average cost of approximately USD 56,000 for a single one-second power interruption[8], driven by equipment trips, product losses, and restart delays. For data centres, the impact can be even more severe, with one in five operators reporting that their most recent outage cost in excess of USD 1 million[9], underlining the high value placed on resilience and power quality.

[7] Camus Energy, Encoord and Princeton University, 'Flexible Data Centers: A Faster, More Affordable Path to Power' (2026), https://www.camus.energy/blog/flexible-data-centers-a-faster-more-affordable-path-to-power

[8] EPRI, 'The Cost of Power Disturbances to Industrial & Digital Economy Companies' (2001), https://restservice.epri.com/publicdownload/000000003002000476/0/Product (adjusted for inflation)
[9] Uptime Intelligence, 'Annual outage analysis 2026' (2026), https://intelligence.uptimeinstitute.com/resource/annual-outage-analysis-2026

By drawing on the grid strength, resilience and storage benefits of the KES technology, commercial and industrial customers benefit from:

- Faster connections
- Improved power quality and reduced outages
- Cost and emissions savings from up to 20hrs of onsite storage
- Grid service revenues

In parallel, distribution network operators get access to grid-strengthening services faster and at lower cost than deploying new infrastructure

The commercial and industrial market is approached through three priority segments where the technical characteristics of KES's synchronous modular CAES create value.

Mining and heavy industry

Mining and energy-intensive industrial operators face sustained pressure from high electricity costs alongside shareholder and lender expectations to decarbonise operations. These sites often operate in hot climates where conventional batteries suffer accelerated degradation. The KES technology offers a long-life, high-temperature-tolerant solution that reduces peak power costs, supports integration of on-site renewables, and improves power quality. The synchronous design provides inertia and fault contribution, which is particularly valuable for sites operating weak internal networks or islanded systems. Commercial engagement focuses on resilience, asset longevity, and measurable emissions reduction rather than short-term arbitrage.

Industrial, logistics, and data centres

These customers are increasingly constrained by multi-year delays and escalating costs for grid connections and capacity upgrades. Outages carry high operational and reputational costs. KES energy storage is positioned as a non-wires alternative that enables load growth, reduces exposure to network interruptions, and improves voltage stability. The ability to earn third-party network revenues improves project economics and supports potential energy-as-a-service offerings.

Remote, islanded and weak-grid sites

Remote industrial sites and weak-grid locations struggle to connect new loads or generation. Capacity headroom, resilience, and inertia are highly valued. KES systems provide firm capacity and synchronous grid support, enabling electrification and renewable deployment without full network reinforcement.