LoDES PTES Demonstrator and Fenix - SynchroStor

M20.19.07
Project Final Report

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Contents

Abbreviations

Abbreviation	Meaning
Ar	Argon
BEIS	UK Department of Business, Enterprise and Industrial Strategy
BESS	Battery Energy Storage System
BFD	Block Flow Diagram
C/E	Compressor/expander
CAN	Controller Area Network
CAPEX	Capital Expenditure
CO2	Carbon Dioxide
COP	Coefficient of Performance
COP21	UN Climate Change Conference 2016
D430	D-series compressor/expander machine developed by SynchroStor
DESNZ	UK Department of Energy Security and Net Zero
DHP	Drying Heat Pump
EPC	Engineer, Procure, Construct
FEED	Front End Engineering and Design
FOAK	First of a Kind
FPGA	Field Programmable Gate Array
GUI	Graphical User Interface
GW	Gigawatt
GWP	Greenhouse Warming Potential
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HPV	High Pressure Valve
HTF	Heat Transfer Fluid
HX	Heat Exchanger
IP	Intellectual Property
IRR	Internal Rate of Return
KPI	Key Performance Indicator

kW	Kilowatt
LDES	Long Duration Energy Storage
LH	Lockhopper
Li-Ion	Lithium Ion
LoDES	Longer Duration Energy Storage Programme
LPV	Low Pressure Valve
MRL	Manufacturing Readiness Level
MV	Medium Voltage
MVP	Minimum Viable Product
MW	Megawatt
NOAK	Next of a Kind
OPEX	Operational Expenditure
P&ID	Piping and Instrumentation Diagram
PCB	Printed Circuit Board
PFD	Process Flow Diagram
PHS	Pumped Hydro Storage
PTES	Pumped Thermal Energy Storage
PV	Photovoltaic
PWM	Pulse Width Modulation
RFQ	Request For Quotation
ROI	Return on Investment
WHR	Waste Heat Recovery
WP	Work Package
BEIS	UK Department of Business, Enterprise and Industrial Strategy
BESS	Battery Energy Storage System
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Executive Summary

In December 2022 SynchroStor was awarded a contract to design, build and test a novel Pumped Thermal Energy Storage (PTES) system, with funding from The Department of Energy Security and Net Zero (DESNZ) Longer Duration Energy Storage (LoDES) Demonstration Programme Stream 2 Phase 2. This followed a short feasibility project (LoDES Stream 2 Phase 1) which facilitated entry to the Phase 2 competition. The contract value of Phase 1 was £79,560. The contract value of Phase 2 was £9,439,302.

The target application for SynchroStor's PTES is long-duration energy storage (defined as greater than 10 hours), bridging the gap between Lithium-Ion battery systems and Pumped Hydro Storage.

The project started on March 1st 2023 and concluded on 14th November 2025. The project was structured as an R&D programme, with the objective of developing the technology from TRL 4 before combining all sub-systems in a whole-system demonstrator at TRL 6.

During the project, a broad range of activities were undertaken across nine work packages. Progress and outcomes were reported monthly to DESNZ with over 120 individual milestone deliverables shared.

Major engineering advances were made across all aspects of the design, with notable improvements beyond the concepts which had been developed prior to the project.

There was a significant project change in January 2025 when supply chain challenges made it impossible to deliver the full scope of work to the original project budget and schedule. In discussion with DESNZ it was agreed to terminate the work packages which were running over time & budget. The remaining budget was allocated to areas where the innovation value and commercialization opportunity was greatest, i.e. the use of the core technology in industrial heat pumps.

The project has concluded with some key outcomes.

- Pumped thermal storage was modelled and found to be a viable alternative to other energy storage systems, particularly when deployed at durations > 10 hours.
- The technology readiness of the core sub-system in SynchroStor's PTES – a unique high temperature compressor/expander – was developed and demonstrated at industrially-relevant scale (TRL 6), with market-beating performance, cost profile and versatility.
- The technology readiness of the storage element of SynchroStor's PTES was not advanced beyond TRL4.
- Further R&D is required to fully develop the full scope of SynchroStor's PTES.
- As informed by market research, a Minimum Viable Product using this compressor was identified: a high temperature heat pump for decarbonising industrial processes.

- A route to market and productionisation roadmap for this product was developed.
- Global market pull for this product was demonstrated and follow-on funding is being explored to commercialise it.

This document is a high-level summary of the 32-month project and more detailed information is available in the project deliverables, subject to non-disclosure agreements.

Context for Long Duration Energy Storage

Global Perspective

Today, almost one-third[1] of global electricity comes from renewables, of which almost half is now from wind and solar energy. These sectors have seen particularly dramatic growth in recent years, which has been driven by three factors.

- The need to reduce emissions from the burning of fossil fuels to mitigate climate change;
- The increasing competitiveness of wind and solar;
- The benefits to energy security of avoiding reliance on imported energy sources.

Figure 1: Electricity generation from wind and solar power (UK demand = 300TWh/year)

Source: Ember (2024); Energy Institute – Statistical Review of World Energy 2024.

In December 2015 at the UN Climate Change Conference (COP21), 196 parties committed to the Paris Agreement, a legally binding international treaty on climate change[2]. It entered into force on 4 November 2016. Its overarching goal is to hold "*the increase in the global average temperature to well below 2°C above pre-industrial levels*" and pursue efforts "*to limit the temperature increase to 1.5°C above pre-industrial levels*."

In order to meet this goal, power, heat and transport will increasingly need to be decarbonised. The most efficient route to doing this is by electrification and using zero-carbon electricity

[1] https://ourworldindata.org/renewable-energy ~9000TWh was produced by hydropower, wind, solar and other renewables in 2023.
[2] https://unfccc.int/process-and-meetings/the-paris-agreement

generation such as renewables, nuclear and possibly fossil fuel generation (when combined with carbon capture and storage). At present the lowest-cost forms of generating electricity are from wind and solar, which is reflected in the increasing growth of these technologies globally. However, the scale required for net zero by electrification is significant. It is possible that up to a seven-fold increase in renewables may be required globally to displace existing use of fossil fuels.

Figure 2: Levelized Cost of Energy for wind and solar over time

Source: International Renewable Energy Agency (2023)

To support this transition, it is widely understood that energy storage is a required technology, as evidenced by the major growth in BESS systems globally. Until recently, Li-ion systems (which are the dominant technology in BESS) have targeted short duration storage.

Long Duration Energy Storage

Long Duration Energy Storage (LDES) is generally considered to be of at least 6 hours duration and potentially up to several days duration, differentiating it from stand-alone lithium-ion battery systems which to date have mainly been deployed with 1-2 hours of capacity duration and are not considered to be economic at long durations, even with continued cost reductions.

The market for LDES is evolving. McKinsey estimate that this will grow to $1 trillion capital investment by 2035[3]. This is driven by:

[3] https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zero-power-long-duration-energy-storage-for-a-renewable-grid

1. The growth in wind and solar PV deployment due to increasing cost competitiveness but decreasing price capture with coinciding generation. Renewable generators will increasingly require long-duration storage to shift production to when it is needed and to maximise revenues.

2. Maximising asset utilisation and efficiency. Electricity network operators need storage for balancing grids, optimising network investment and to obtain grid services that keep the lights on.

In 2022, DESNZ launched the LoDES programme[4] to advance the development of LDES technologies.

[4] https://www.gov.uk/government/publications/longer-duration-energy-storage-demonstration-programme-successful-projects

SynchroStor PTES

System Description

The proposed PTES is a grid-scale energy storage concept which uses electricity to move heat, via a closed Brayton-cycle heat pump, storing the thermal energy (both heat and cold) within a low-cost, mineral-based material (glass balls) and re-converting heat back to electricity by running the cycle in reverse as an engine. The Brayton cycle is ideally reversible, though there are inevitable component losses in the process, giving an expected round-trip efficiency of between 65 and 70 percent. Losses include friction in rotating parts, heat loss and minor electrical inefficiencies in the motor and controls.

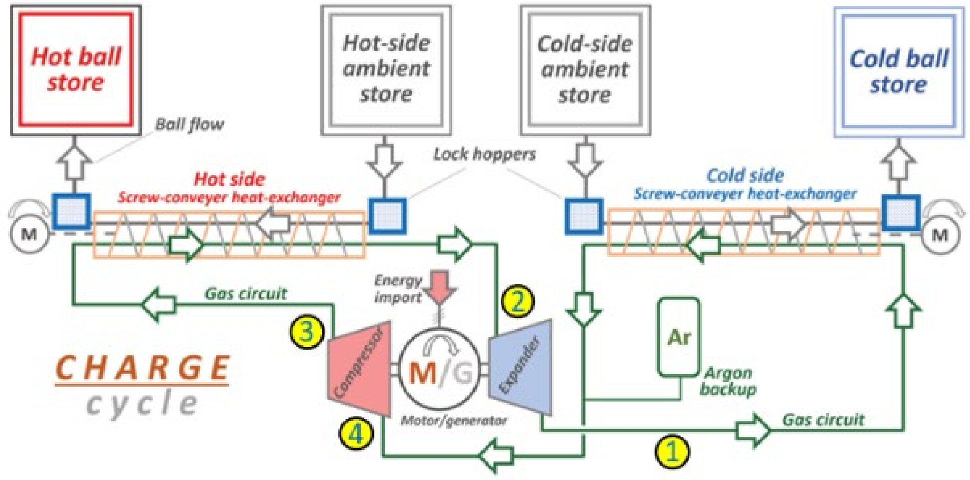
In a Brayton cycle, a gas is initially compressed to raise its temperature. This heat energy can be used to do meaningful work – or in this context be removed from the gas and used to heat a storage media. Once this heat energy is removed, the remaining high-pressure gas is allowed to expand – returning power to the system. At this stage the gas becomes very cold and can be used to cool a storage media. After this, the gas returns to the compressor in a closed loop.

The key element in the system is a bespoke compressor/expander (C/E). The SynchroStor D430 is a reciprocating machine with compression cylinders mounted radially around a driveshaft. A unique hydraulic transmission enables high pressure ratios and versatility of operation. This machine is SynchroStor's core IP.

Figure 3: CAD view of the D430 compressor-expander

Because of the unique design of the compressor-expander machine, the PTES process should be fully reversible between charge- and discharge-modes in as little as 30 milliseconds, allowing rapid frequency support to electricity networks. The power rating and duration of storage are both modular and independent of one another, allowing systems to be sized according to need – with the possibility of easily upgrading capacity at later dates. The minimum power rating and storage duration are 1MW and 5 hours, respectively. The glass storage material is inert and inexpensive, and the plant equipment is largely made of steel, allowing for full recycling of the facility at end of life.

Figure 4: Operation of PTES system during charge (storing energy) [as proposed during Phase 1]



Innovative features of the technology are as follows.

1. The reciprocating, multi-cylinder, compressor-expander, allows the charge/discharge function to be reversed within 30 milliseconds. This machine is designed from first principles to maximise thermal efficiency – an unusual requirement in reciprocating machines, where intercooling and heat rejection are usually desirable.
2. Glass balls are used as the thermal storage medium. When not moving through the heat-exchangers, the balls 'rest' in hot, cold, and ambient-temperature storage silos.
3. Hot and cold argon gas and glass balls pass in opposite directions through direct-contact heat-exchangers. Compared with most systems, this effectively halves the number of heat-exchange processes and reduces the associated losses. Argon is chosen because it has favourable thermodynamic properties, is readily available at modest cost and poses no flammability or toxicity challenges.
4. Lock-hoppers introduce and remove the balls to and from the pressurised heat-exchangers. This allows all ball stores to operate at atmospheric pressure.

System Benefits

Flexible implementation

The PTES architecture allows power rating and storage depth to be completely decoupled. This allows plant configurations to be optimised for different end users who may be targeting very different market use cases. A wind farm operator may wish to install a relatively large storage depth (measured in MWh) to offset prolonged wind curtailment. A utility-scale PV operator may want up to 12 hours of storage to flatten out their diurnal generation profile, or a peaking plant may only need around four hours of storage capacity. Similarly, the power rating (measured in MW) can be specified to suit the application.

Given the low marginal cost of PTES thermal storage capacity, it is expected that the system will be most economically deployed in applications requiring storage depths greater than ten hours.

Site agnostic

The PTES is site agnostic in that no special climatic, geographical, or physical features are required for its location. It could be installed in virtually any site that has been zoned for industrial or light-industrial use, with the ideal locations being adjacent either to electrical distribution or power generation assets. Advantageously for both planning and operations, there are no hazardous materials on site, and during normal operation there would be no fume-generating processes. The land area requirement is modest (estimated at 0.5x the requirement for equivalently-rated Li-ion BESS), thanks to its high power and energy densities and the predominantly vertical arrangement of the system. There is no risk of land contamination to complicate decommissioning or site re-purposing.

Synchronous operation

The PTES is designed to use a directly connected synchronous motor-generator, the same type as the electrical workhorses used in traditional fossil and nuclear power stations. Unlike the electronic-power-converters that connect most wind and solar plants to the network, synchronous generators support the network by providing increasingly valued rotating-inertia, voltage support and excellent fault ride-through capacity. In market terminology, Dynamic Containment and Firm Frequency Response can be offered. Using synchronous machines also negates the need for costly inverters. However, to allow for experimental work and ease of commissioning, the arrangement under the LoDES project specified an asynchronous machine with an inverter.

Fully reversible within milliseconds

As the PTES can change its mode of operations within tens of milliseconds, it can be treated as fully dispatchable generation. It can also respond to the ancillary services market. Examples include peaking and frequency response. This allows the PTES to offer ancillary services to the grid, including Dynamic Firm Frequency Response.

Very low energy loss when charged

Parasitic energy loss from the ball storage silos will be very low. Using appropriate thicknesses of high-performance insulation, energy loss can be limited to less than 0.5 % per day.

Long system life

The PTES system components and storage material are projected to have a long life. Apart from some wear and tear typical of industrial equipment (which can be managed through planned maintenance) there is no substantial degradation of the storage material itself. Based on comparisons with similarly constructed process and generating plant, a plant life of 20 years is a reasonable minimum expectation. This can be compared with the materials that are used in Li-ion batteries, which can typically require complete replacement after seven years (Jimenez, 2018). However, in the case of the PTES, as a precaution during cost and saved-emissions estimations, we factor in the planned replacement of the PTES glass balls after every 5,000 cycles, at low marginal cost.

Technology Status Prior to Project

Prior to the LoDES Phase 2 project, SynchroStor had focused on demonstrating the key sub-systems and areas of greatest novelty, at lab-scale:

5. The digital compressor/expander machine;
6. Heat transfer process between the argon gas and glass balls;
7. Use of auger for transfer of balls;
8. The lockhopper.

Reporting on these research and development activities is outside the scope of this document but all aspects had been successfully demonstrated to TRL 4, ‘laboratory demonstration’ level prior to 2023.

Project Structure

The objective of the project was to increase the PTES technology maturity to TRL 6 and validate the value proposition. The Phase 2 plan was a methodical, costed, and de-risked programme to develop and demonstrate a system with a one-megawatt power rating and a storage capacity of ten megawatt-hours (1 MW/10 MWh).

SynchroStor aimed to significantly increase its UK-based operation while collaborating with other expert organisations. By de-risking the technology, SynchroStor expected to attract further private funding to accelerate commercialisation steps and identify a robust route to market.

From the start, SynchroStor planned to work with sub-contractors. At the outset, PM Projen, Sequentec and PNDC were identified.

PM Projen is an award-winning project engineering consultant with a focus on the energy and process industries and extensive experience in taking innovative concepts at early technology readiness levels to operational plants. PM Projen later restructured as PM Group.

Sequentec is a specialist provider of control systems to the energy systems market.

PNDC (Power Networks Demonstration Centre), a research and testing hub founded by government, industry and academia, with specific facilities for testing and operating grid-connected equipment, for demonstration and validation.

Over the course of the project, PNDC's role was reduced as their site was no longer suitable. Other sub-contractors were introduced including Orion Research, Quoceant, Caelulum and a wide range of component suppliers and manufacturers.

The project was structured around seven engineering work packages supplemented by market engagement and project management.

Table 1: Work package breakdown as proposed

Work Package ID	Work package Name	Description (inc. key tasks)
1	Compressor Expander components	Design and delivery of all compressor/expander cylinder mechanical components. This includes testing on the 200kW test rig, iterating components and developing the 1MW components.
2	Compressor Expander machine	Design and delivery of compressor/expander main machine & performance data. This includes the design and delivery of a containerised test-rig suitable for the full-scale compressor/expander demonstration.

3	Low level controller hardware and software	Design and delivery of compressor/expander low-level controller. This controller will be implemented on the early test rigs in WP1 and WP2, for parallel development until integration into the PTES demo.
4	Lock-hopper / heat-exchanger	Design, validation and delivery of hot heat-exchanger and lock-hopper. This includes the sequential testing of individual sub-assemblies before integration into the complete HX&LH required for the PTES demo.
5	Storage: Silo / conveyer / Glass balls	Delivery of the storage system hardware required for the demonstration plant and other test-rigs. This includes all aspects relating to the thermal storage infrastructure. The scope includes the sourcing and testing of glass balls and the design and sourcing of insulated storage-silos, material-conveyors, and argon-gas management equipment.
6	System control Hardware and Software (HW and SW) and simulation	This work packages will develop a higher-level system controller to control the complete PTES system including the heat-exchangers, lockhoppers and ball transfer equipment. Development of the controller will be supported by Matlab modelling of the sub-systems.
7	Demonstration plant	Design & delivery of 1MW x 10MWh demonstration PTES. This work-package comprises the design, sourcing and supervision of all components and services necessary for the installation of the complete demonstration plant. A system control team will run the demo plant through agreed test schedules and data collection campaigns.
8	Market / stakeholder engagement	This WP includes the updating of the Phase 1 market study to refresh our understanding of the best short and long-term market opportunities for PTES technology. We will use the outputs of the backward-facing simulations from WP6 to examine the sensitivity of our business case to market variables. As we achieve key project milestones, we will seek to interact with specialist and general presses and will look for opportunities to publish the outcomes of our work in peer-reviewed journals.
9	Project Management	Project management, recruitment, reporting and financial control.
10	NZIP KPIs	KPI reporting to BEIS as required at startup, mid-way and close.

In the following sections, each work package is described including work completed and outcomes. In total, over 120 individual deliverables were submitted to DESNZ to document project process. This document is a high-level summary of the work undertaken in this project.

Work Package 1: Compressor/Expander Components

Objective

The core components of the D430 compressor/expander are the valves and pistons in each of its cylinders. The digital control of each cylinder means that it can be controlled independently, making the technology easily scalable. This arrangement also allows rapid development as quick iteration can be done with a single cylinder prototype before committing to batch manufacture. This work package covered design and delivery of all compressor/expander cylinder mechanical components.

A 200 kW test-rig suitable for performance and short-endurance testing was proposed. Based on experience with it, and a final machine specification, a second major iteration of the components was planned for the 1 MW demonstration plant.

Outcome

Valve Development

Over the course of the project, the valve designs progressed through three major design iterations with a fourth design prepared for implementation just beyond the project period.

The valve technology represents some of SynchroStor’s core IP. Hence the design detail is not reported on in this document.

Learning from machine testing informed design iterations which included:

- Improved packaging for ease of assembly;
- Reduced part count for cost reduction;
- Development of design features to improve quality;
- Increased flow areas for reduced pressure drop.

The net result of the work package was greatly improved machine performance, achieving the target temperature for LoDES and isentropic efficiency >85%.

Test Rigs

Rig 1

In parallel with valve development, significant upgrades were made from what was previously SynchroStor’s only C/E test rig. Initially, the rig was only capable of basic seal leakage tests and lacked the infrastructure for continuous flow and temperature control. The first upgrade under LoDES introduced three major subsystems: a high-pressure heat exchanger, an advanced pressure regulation system, and a low-pressure heat exchanger. These additions allowed the rig to handle high-temperature gas flows, testing compression up to 475°C and pressures up to 200 bar, while maintaining safe and stable operating conditions. In expansion, testing showed successful cooling of gas from 260°C to 20°C.

Rig 3

A second, higher-power test rig (“Rig 3”) was also designed and built to allow full machine testing. This became SynchroStor’s key tool for validating machine performance and carrying out endurance testing.

Figure 5: C/E Rig 3 under construction

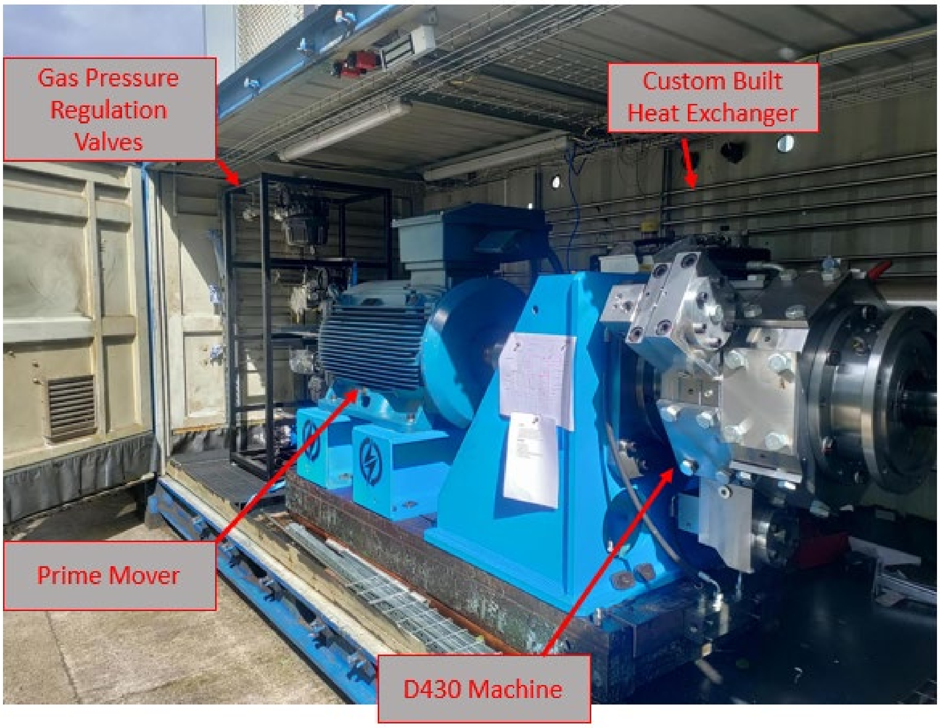
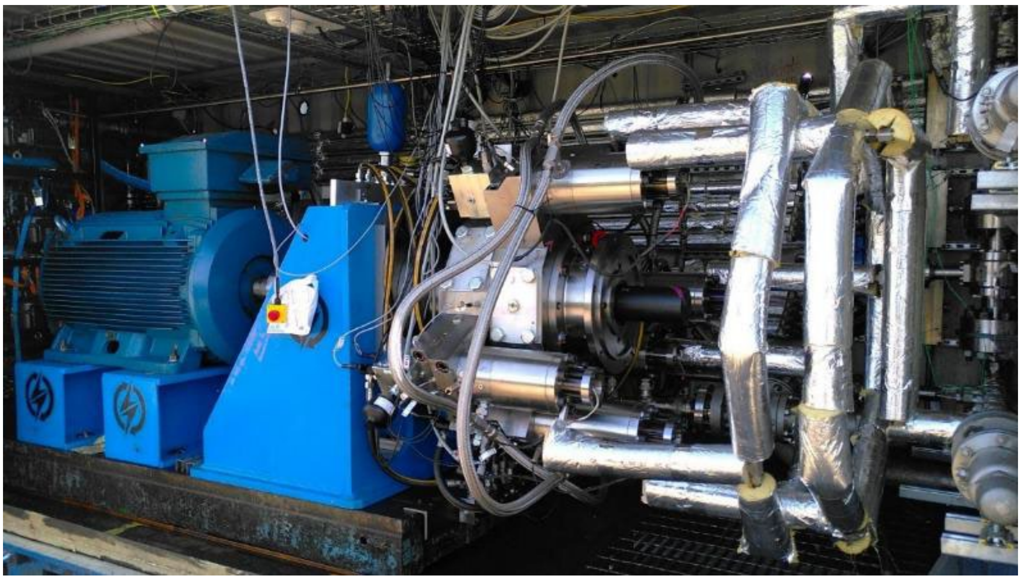


Figure 6: C/E Rig 3 completed



Work Package 1 Conclusion

This work package concluded with:

- The SynchroStor compressor/expander valves were successfully developed over four major design iterations.
- SynchroStor test infrastructure was greatly improved in capacity and capability.
- Compressor/expander performance was found to be in line with expectations.
- Machine isentropic efficiency was measured above 85%.
- Reaching 400°C temperature when operating in compression-only with Argon gas, hence meeting the LDES performance target.
- Capable of >200°C single-stage temperature lift when using CO_2 gas. This is a major differentiator in the heat pump market.
- Demonstrating other unique features such as idling, high part-load efficiencies and rev-by-rev controllability.

Work Package 2: Compressor/expander machine

Objective

This work package included the design and delivery of a containerised test-rig suitable for the full-scale compressor/expander demonstration.

Outcome

During this work package, the general arrangement of the machine went through many iterations. The design concluded with a more modular design using a number of smaller machines rather than two larger units as initially envisaged. This has multiple benefits including following.

- Increased pool of suppliers, which drives competition and reduces part costs.
- Reduces lead times, allowing more iterations of components and reducing overall risk to the project timeline.
- Improved redundancy – if there is a failure in the machine it is possible to remove/replace a single machine and continue testing.
- Design efficiency – part commonality with the D430 reduces design burden, and the spares requirement.
- Assembly – Assembling several machines of the same design allows for an element of “productionisation” thus increasing manufacturing maturity.
- Commissioning – machines may be commissioned as smaller D430 modules, utilising the same test setup and equipment as the first D430 build.

Later in the project, this work package included assembly of machines as parts were delivered. All parts were inspected by SynchroStor staff and assembled according to procedures developed in-house. The machines were then assembled onto the test bed (called “C/E Rig 2”) where the machines were connected to a common shaft from the 1MW motor. Ancillary equipment – hydraulics, cooling, controls – were also installed and commissioned. These are illustrated below.

Figure 7: C/E Rig 2 Arrangement developed during Phase 2

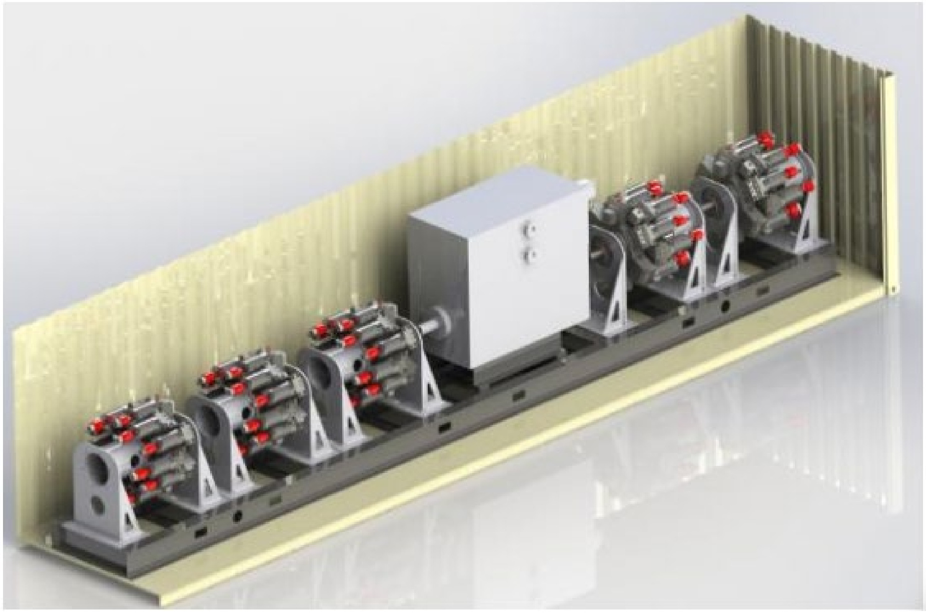


Figure 8: D430 machines being assembled for C/E Rig 2

Endurance Testing

In the latter stages of the project, SynchroStor has been developing at Minimum Viable Product (MVP) for industrial heat pump applications. The specification of any MVP should include a sufficient product lifetime such that customers can visualise long-term operating costs and emissions savings. With a working prototype on a robust test rig, SynchroStor's focus has been to demonstrate the long-term reliability of the machine.

Initially, the accumulation of test hours was slow as testing focused on short-term performance tests across a variety of operating conditions to better understand machine behaviour. Periodic downtime was required to make upgrades to the test rig for general operability and to make it suitable for operations with CO2 as a working fluid. Once confidence in the machine and test rig was established, the rig could be run for much longer hours.

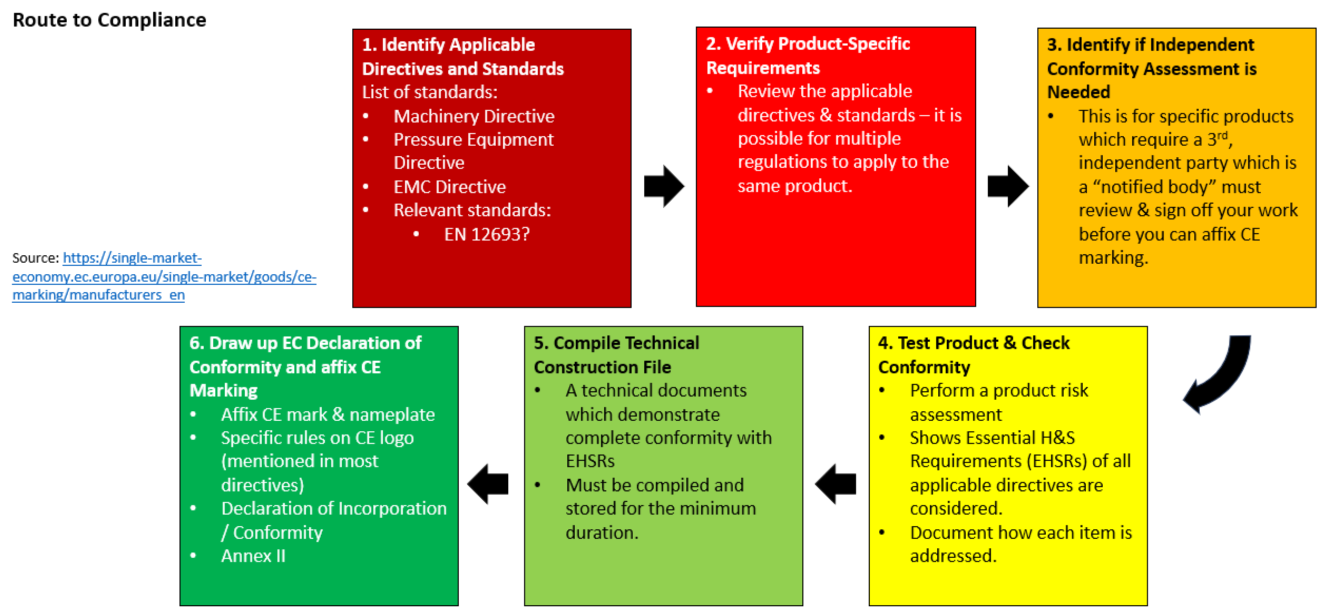
Productionisation

A significant task within this work package was to explore the productionisation roadmap for the SynchroStor compressor/expander, i.e. how the machine would be made market-ready. The study was structured around three topics: cost reduction, supply chain and regulatory compliance. All three relate to increasing the Manufacturing Readiness Level (MRL) of the product.

Regulatory Compliance

SynchroStor is looking at both the EU and UK markets as the first markets to deploy the D430. To achieve this, the machine must have a CE mark affixed to the product (the UK accepts CE Marking in addition to UK CA marking for the indefinite future) (https://www.gov.uk/guidance/ce-marking). A roadmap was developed for pursuing compliance with relevant regulations, illustrated below.

Figure 9: Route to regulatory compliance



Five core directives were identified and explored in detail to identify next steps.

The final step in the process would be to create a Declaration of Conformity / Declaration of Incorporation that can be issued to the purchaser to indicate that the complete system is compliant with EU Regulation and that all applicable directives and standards have been correctly adhered to.

A CE mark and nameplate, detailing model number, serial number, and other key information, must be affixed to the product being sold. An appropriate nameplate and declaration of conformity would be created upon completion of technical construction file.

Work Package 2 Conclusion

This work package concluded with:

- The SynchroStor compressor/expander machine was developed into a higher-TRL, modular, stackable unit in line with PTES design ambitions.
- All supporting sub-systems including control, hydraulics and driveline were similarly developed to a scalable design.
- Endurance testing showed good overall reliability apart from one component for which a design change was already underway.
- A comprehensive productionisation study identified the cost trajectory, supply chain and regulatory requirements for market entry.

Work Package 3: Low-level Hardware & Software

Objective

The low-level hardware and software components of the compressor/expander machine complement its mechanical components. ‘Low-level’ is used in this context in contrast to the ‘high-level’ system-controller that will look after the entirety of the PTES system. The low-level control system operates on a timescale of microseconds because it must provide precisely orchestrated timing signals for the coordination of valve switching across the many cylinders of the compressor/expander machine.

This controller and its embedded software have many parallels with the those developed for the 7MW wind transmission referred to above. Hence the functional requirements and operating framework are familiar to SynchroStor engineers, and its development has been underway since 2020.

The methodology follows that of the mechanical compressor/expander components - increasing in scope as the machine grows from single-cylinder testing to multi-bank 1 MW scale.

Outcome

At the outset of the project, the test rig compressor-expander was controlled by an Arduino (a microcontroller designed for rapid-prototyping) and used an evaluation board as a coil driver. This setup had a lot of limitations, in particular it was not scalable to larger machines due to the delicate assembly & wiring. It was decided to develop a custom PCB which evolved over three iterations to a stable control platform now used on all SynchroStor’s test rigs. The firmware and front-end GUI continue to be developed, rolling out new features as required.

As per WP1, this technology represents some of SynchroStor’s core IP. Hence the design detail is not reported on in this document.

Work Package 3 Conclusion

This work package concluded with following.

- The embedded hardware and software required to control SynchroStor’s compressor/expander developed to a highly refined stage with all functionality in place.
- Front-end user interfaces also developed.
- A comprehensive productionisation roadmap in place.

Work Package 4: Lock-hopper and Heat Exchanger

Objective

The direct heat-exchanger developed by SynchroStor allows a high heat-transfer efficiency. Its design was based on a rotating screw-auger, moving balls in one direction while pressurised argon is pumped in the opposite direction, in a contraflow arrangement.

A unique feature of the SynchroStor concept is the introduction and removal of glass balls to and from the pressurised heat-exchangers, whilst avoiding otherwise inescapable pressure losses. This is achieved by a specially developed isenthalpic lock-hopper system.

Both sub-systems, the heat-exchanger and the lockhopper, had been demonstrated independently by SynchroStor. The design and manufacturing processes involved are those of pressure-vessel and heavy hydraulic engineering,

This work package included design and delivery of the 1MW scale heat exchanger and lockhoppers.

Commissioning was to be carried out step by step, starting with static pressure testing and gradually increasing in scope by adding dynamic interactions. This is the same, risk-controlled approach in the compressor-expander work package.

Outcome

The SynchroStor lockhopper concept is highly innovative, using pairs of large poppet valves to control the flow of glass balls into and out of a high pressure heat exchanger. This had been demonstrated at lab scale prior to the project so the first task was to demonstrate at larger scale. A test rig was designed and assembled.

While these heavy-walled pressure vessels were being manufactured, other test rigs were built to test the flow of balls through the system. Bespoke knife and iris valves were conceived and tested successfully, required to control the flow of material.

This work package also managed the design of the heat exchanger vessels. These were substantial, 600mm internal, 915mm external diameter x 2500mm long, heavy-walled steel tubes to be mounted between the upper and lower lockhopper assemblies. The large diameter was required to give sufficient cross-sectional area to reduce the gas pressure drop through the stack of balls inside the heat exchanger. A wall thickness of just under 160mm was needed to satisfy the high temperatures and pressures.

The wall thickness and steel grade requirements were outside standard ‘off the shelf’ tube supply, so a custom forging was required. Several options for the supply of the two heat exchanger tubes were explored in UK and Europe. Ultimately the tubes were sourced through C+R Hydraulics who managed the forging, heat treatment, machining, coating and delivery process using specialist subcontractors in Italy.

Figure 10: Forged tube prior to heat treatment and machining

Figure 11: Finished tube after delivery to Edinburgh

Work Package 4 Conclusion

This work package concluded with:

- Lockhoppers were successfully trialed and procured for the PTES demonstrator;
- Innovative valves were developed for controlling the flow of glass balls;
- The components for SynchroStor’s unique direct-contact heat exchanger proved to be readily available, although not from the UK supply chain.

Work Package 5: Silos/Conveyors/Glass Media

Objective

In this work-package, all aspects relating to the thermal storage infrastructure were to be finalised. Its scope includes the sourcing and testing of glass balls as well as the design and sourcing of insulated storage-silos, material conveyors and argon-gas management equipment.

Most of the sub-systems developed in this workstream can be specified using off the shelf components and processes repurposed from other industries.

Outcome

Silos

Silos are required in the PTES demonstrator to store the glass balls used as the energy storage medium. In July 2023 early engagement with suppliers showed the cost to manufacture vertical silos, as planned during the concept phase, was beyond the available budget. Traditional cylindrical, vertical silos would need to be substantially re-worked to resist the high temperatures. Additionally, the height required for the balls to flow through the silos added cost to the conveyors and surrounding support structure. A substantial amount of research was done to explore how to reduce the height of the silos and associated ball transport ductwork. It became clear that more research into material behaviour was required.

The angle of repose (the steepest angle at which a granular material can be piled without slumping) of regular sized balls is approximately 30°. However, the angle that the balls roll reliability on a flat surface is about 10°. The design concept of the silos and ball ducting was revised so balls rolled to fill and empty the silo and rolled through the connecting ductwork in and out of the heat exchanger. This change in design substantially reduced the height of the conveyors and ductwork but required the ducting and silos to have flat, smooth rolling surfaces.

Orion Research were contracted to design and build the “hot” and “ambient” storage silos. These were based on modified 20ft shipping containers using the flat floor as the rolling surface to ensure that the containers emptied reliably. Two similar units were specified. Modifications to the “hot” shipping container/silo included:

- Sand blasting and removal of all paints and coatings;
- Gas leak testing and seam welding to completely seal the volume;
- Adding fill and empty features and an access hatch;

- Lining with a thin, insulating later of vermiculite insulation to prevent the walls of the container from warping when hot balls are loaded;
- Adding a layer of stainless steel sheet on the inside of the insulation to give a smooth rolling surface.
- Suspending a flat loading chute to the ceiling so the balls load evenly
- Reinforcing the outside of the container with a steel exoskeleton to ensure structural integrity
- Decoupling the container from the support structure with bearing pads which allow for thermal expansion as the container changes in temperature
- Adding sensors for measuring fill level, pressure and temperature

The ambient silo was modified in a similar way but suitable for lower temperatures.

Figure 12: Silo delivery & installation

Conveyors

Conveyors are needed to lift the balls from the outlet of the heat exchanger to the inlet of the silos and from the outlet of the silos to the inlet of the heat exchanger. 11m lift height was required. Two types of conveyor were investigated:

- Tube chain/drag conveyors that pull material through a tube with a chain and discs
- Bucket conveyor which uses a series of buckets attached to a chain or belt to transport materials horizontally, vertically, or at an incline

While a tube conveyor would have been easier to insulate and make gas-tight, and could have provided a longer-term, more cost-effective solution, no off-the-shelf high-temperature products were available and a bespoke system would have been required. Several test assemblies of a tube conveyor were built in-house but it was concluded that a full solution would have taken too long to develop and put the project at risk.

An Italian manufacturer, MDG Handling Solutions, was identified who could supply gas-sealed bucket conveyors that could operate at the required temperature. Although these were expensive and over-sized for the PTES Demonstrator, they could be manufactured and delivered within schedule.

Glass Balls

11mm diameter SiLi (Soda Lime) glass balls were chosen for the heat storage medium, for the following reasons.

- The material has good heat capacity.
- Balls have a regular spherical shape which means the heat transfer process is easily modeled and their rolling/flowing is predictable.
- Glass balls are extremely robust.
- Glass balls have an existing, accessible, high-volume supply chain.
- Glass balls are relatively cheap. Longer-term, they can be manufactured from recycled glass cullet to reduce the cost substantially.

Specialist consultants, GTS (Glass Technology Services), were contracted to confirm the mechanical properties of glass balls, also to explore methods for improving their toughness (if required) and advise on large scale manufacturing.

Testing at SynchroStor indicated the delivered glass beads performed well, and while a potential increase in strength might be attractive, it was likely to add cost. GTS considered thermal toughening to induce compressive stress onto the exterior surfaces of the glass spheres as well as water quenching.

Thermal toughening was not effective as the glass is above the softening point and will tend to bond to other glass items, can stick to the container used and will distort away from a spherical geometry. Quenching using air jets was effective gave rise to a 39% increase in strength compared to the delivered beads.

GTS research into high volume marble manufacture showed that ball production is by ‘rolling’ and it would be possible to add additional air cooling as a quenching mechanism. This could offer an in-factory process improvement to increase the final residual stress in the spheres.

Procurement

50 tonnes of 11mm Diameter SiLi glass balls/marbles bought from Sigmund Lindner GmbH. These glass balls are more expensive and higher purity (clear rather than coloured) than would be used in a follow-on PTES projects but were available in the quantities needed for this project, on schedule.

Work Package 5 Conclusion

This work package concluded with following outcomes.

- Silos proved to be more complex than expected but a modular solution was identified for the PTES demonstrator.
- Conveyors had also been expected to be off-the-shelf but time pressures meant a sub-optimal procurement route was selected. Future PTES would require deeper supply chain engagement to deliver a bespoke design.
- Glass beads were confirmed to be readily available at reasonable cost, with significant cost reduction potential.
- Glass beads are mechanically durable and suitable to the PTES application.
- Glass beads are highly suited to storing heat at high temperatures. At low temperatures, greater volumes are required which reduces the system cost effectiveness unless operating at scale. Future projects should down-select the optimum combination of hot/cold media on a project-specific basis.

Work Package 6: System Control

Objective

The system controller takes overall control of the complete PTES system including the heat-exchangers, lockhoppers and ball transfer equipment. The high-level system ensures smooth inter-operation of all sub-systems and integration of the whole with the power grid. The objective of this works package was two-fold: developing detailed models of the system to optimise design details; develop the control system for operating the PTES.

Outcome

Model-based Software Development

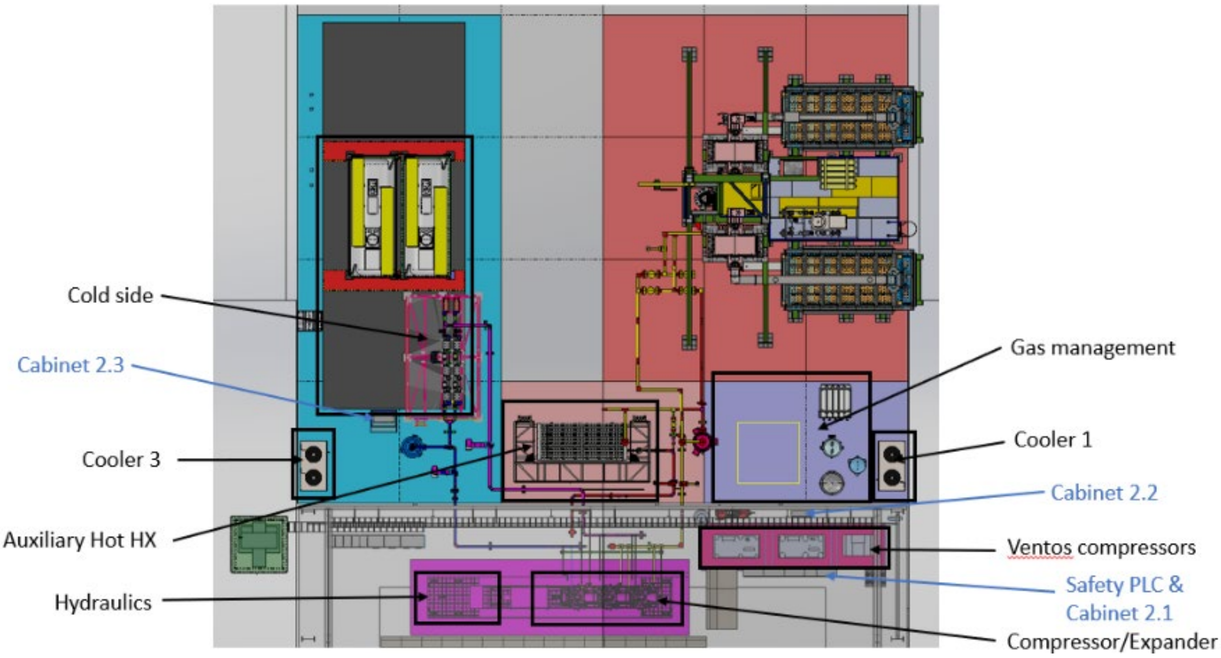
As planned, models of all sub-systems were created in a virtual environment: Matlab Simscape. This work was non-trivial and required specialist skills from both SynchroStor's team and a sub-consultant Quoceant. Over the course of the project, a complete model including the following elements was developed:

- The Compressor/Expander (C/E) machines;
- The Hot Heat Exchanger (HHX) and its twin lockhoppers (LH);
- The conveyers that feed the glass balls into/out of the LHs from/into the stores;
- The 2 silos where the glass balls will be stored. One ambient and one hot;
- The Cold Heat Exchanger (CHX);
- The cold material, storage volume and transfer method. Whether it is glass balls, engineered cold fluid or indirect fixed packed bed;
- The gas management system;
- The auxiliary heat exchangers;
- The electric motor;
- The hydraulic circuit;
- The pipes.

Control Logic

Following on from this model development, subsequent work in this work package developed the control logic for the PTES plant, illustrated below.

Figure 13: Plan view of PTES plant showing control elements



Work Package 6 Conclusion

This work package concluded with:

- Comprehensive modelling of all sub-systems to support design, sizing and procurement decisions;
- Development of system control of the full PTES. This included the ‘full stack’ including transducer/actuator I/O, control hardware, PLC code, control logic and user interfaces.

Work Package 7: Demonstration Plant

Objective

This work-package comprised the design, sourcing and supervision of all components and services necessary for the installation of the complete demonstration plant. This included:

- Definition of safety procedures and implementation of safe-systems-of-work to assure operator safety and plant integrity for different life stages of the demonstration plant;
- Definition of the interfaces between sub-systems;
- Coordination of contractors for such as civil works, grid connection and building modifications;
- Support of engineering teams in the different work-packages during the installation, commissioning, and operation of the plant.

It was planned that PM Projen would be one of the main contributors to this work package, but SynchroStor would also rely on engineering resources from other work packages as required and engineers with responsibilities for different sub-systems will provide support as required. Design and implementation of the electrical balance-of-plant to connect to PNDC's grid network would also be executed in this package.

Outcome

Location

Early in the project, SynchroStor moved site to a location which offered (a) a high-capacity 11kV grid connection and (b) ample outdoor space. This presented an option for the PTES Demonstrator to be located here rather than at PNDC's site. This had obvious logistical benefits and was agreed with DESNZ.

Table 2: Justification for change of site

Variable	PNDC	Edgefield Road
Electrical Supply	11 kV, >1 MW	11 kV, >1 MW
Working Area	Potentially up to 8m x 50m outdoors if we negotiated use of most of the site. Indoor space limited to a meeting room.	Outdoors 30m x 32m, with good access on 3 sides. Indoors 15m x 15m
Machine shop and assembly area	Not available. Would need to fit our containers and bring with us for smaller jobs on site. Shuttle runs to SycnhroStor's workshop for larger jobs.	On site
Demonstrator location	45-minute drive from SynchroStor's offices.	Co-located with SynchroStor's offices.
Civils	Concrete pour required.	Concrete pour required.
Post LoDES	Pressure to free up site for new PNDC clients.	Lead tenant status – reduced pressure to remove the demonstrator immediately after LoDES Phase 2.

Demonstrator Infrastructure

Civil works and supporting infrastructure were large aspects of the work package. A 300m2 concrete pad was laid and a large supporting frame designed & assembled. In addition, temporary bunds were specified to capture any spilled fluids. The existing 11kV electrical connection to the site was used, with an 11kV-690V transformer installed.

Figure 14: PTES frame (left), bunding and ISO tanks (stainless steel pressure vessels built to 20-foot shipping container dimensions, conforming to standards by International

Organization for Standardization, (right)

Figure 15: 11kV to 690V transformer and cabling

Gas Management & Sub-system Integration

The purpose of the gas management system was to tie together the compressor/ expander with the hot and cold thermal stores and maintain operating pressures within the full plant. Many of the safety controls of the PTES plant were designed into the gas management system. As such the design was an iterative process requiring input from all design teams in SynchroStor as well as support from external experts.

Most equipment procurement started towards the end of the P&ID phase however, some long-lead time equipment such as the high pressure trim cooler (Figure 16) and gas management compressors (Figure 17) were purchased early on in the project (before the completion of P&IDs) to mitigate against risks of delays. Following the completion of the P&ID phase by PM Group, the design was handed back to SynchroStor.

Figure 16: Cold Heat Exchangers (left); ISO Tank for Cold Storage (middle) and High Pressure Trim Cooler (right)

Figure 17: Gas Management Compressors (LP, MP and HP left to right)

Following a bidding stage for pipework design, manufacturing and installation, R&M Engineering (now Aurora Energy Services) were engaged to carry out the work. As part of the design they made a 3D scan of the PTES demonstration site and major equipment (Figure 18). The high pressure (hot) heat buffer imposed significant delays on the project due to the manufacturer's inability to source hardware on time. This increased pipework design costs due to uncertainty about tie-in locations.

Pipework design was split into Phase 1 (Figure 19) which would be sufficient to commission the compressor/ expander with a thermal load, whereas Phase 2 would be the tie-in to the hot heat exchanger and hot store system. The intention of the phasing of construction was to prevent construction and equipment delays impacting the full project, allowing testing to start before the completion of the complex hot store system.

Figure 18: Point Cloud Map of PTES Demonstrator for Pipework Design

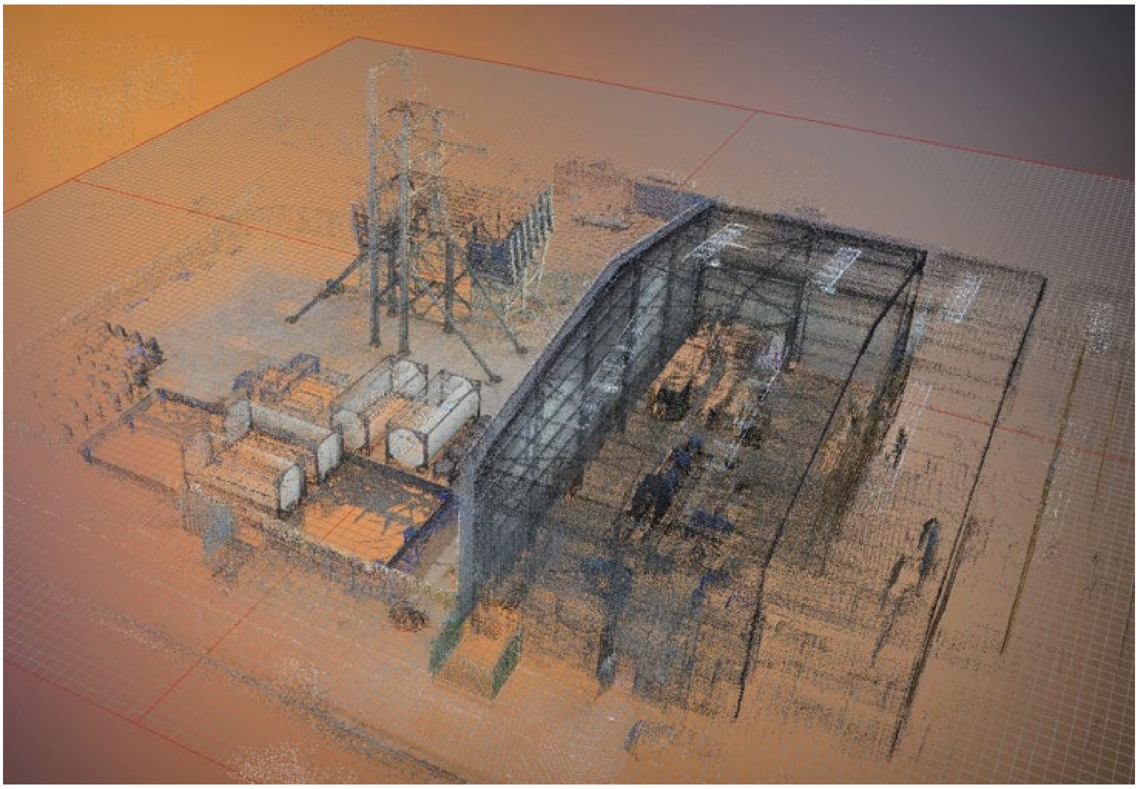
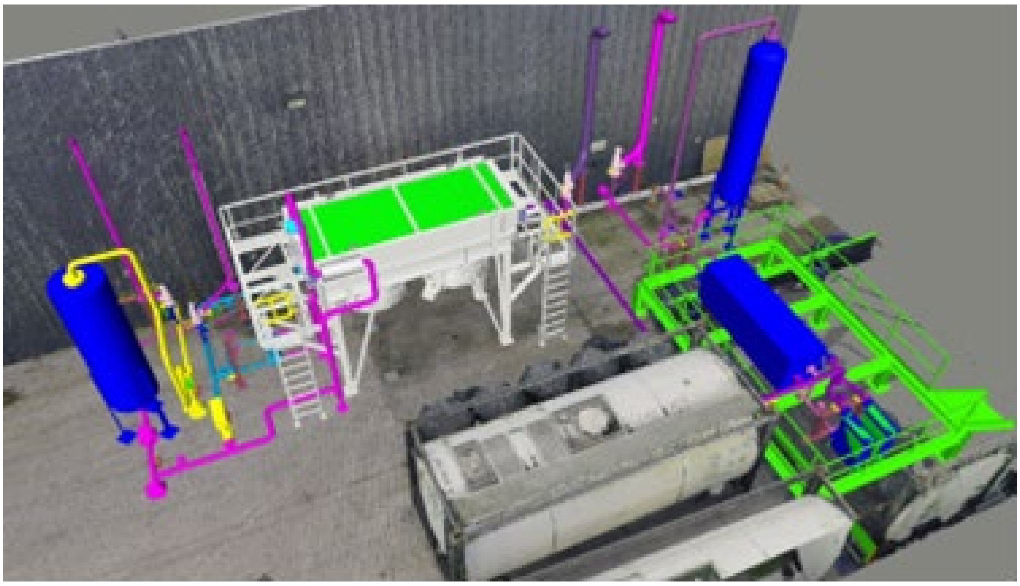


Figure 19: Phase 1 Pipework Design Overlayed on 3D Scan



Upon pausing the project in April 2025, the gas management compressors were ready for commissioning; phase 1 pipework and gas management design had been approved and was ready for construction with all major equipment, including valves, on-site. The hot thermal buffer was still delayed. RFQs for piping phase 2 had also been submitted, with the design having been done by SynchroStor.

Work Package 7 Conclusion

This work package concluded with:

- The PTES plant was designed appropriately with extensive input from sub-contractors.
- Civil and electrical works were completed to specification.
- All pressurised systems were subject to HAZOP studies, as per industry standards.
- As the design developed, this work package presented the greatest challenges, with cost increases which could not be accommodated.
- This work package would have benefited from more extensive work during the feasibility stage, e.g. a FEED study, prior to LoDES phase 2.

Work Package 8: Market/Stakeholder Engagement

Objective

This work package aimed to refresh SynchroStor's understanding of the best near-term and long-term market opportunities for PTES technology. A deep analysis of the market and potential revenue streams for the technology was completed alongside a long-term cost prediction for commercial plants. Both fed into a techno-economic analysis of the technology.

An important objective was to consolidate SynchroStor's visibility and credibility by communicating PTES capabilities to potential licensees, purchasers and the wider public. For the PTES technology to reach maturity and for SynchroStor to become financially viable, further investment was to be sought.

It was also planned to present potential productionisation partners with intermediate project outcomes and market intelligence. Some of the key stakeholders targeted during the programme would be potential end customers. The intention was to be able to demonstrate to them that the PTES technology was credible from a technical, financial and business perspective, and that investor and partner risks had been identified and contained.

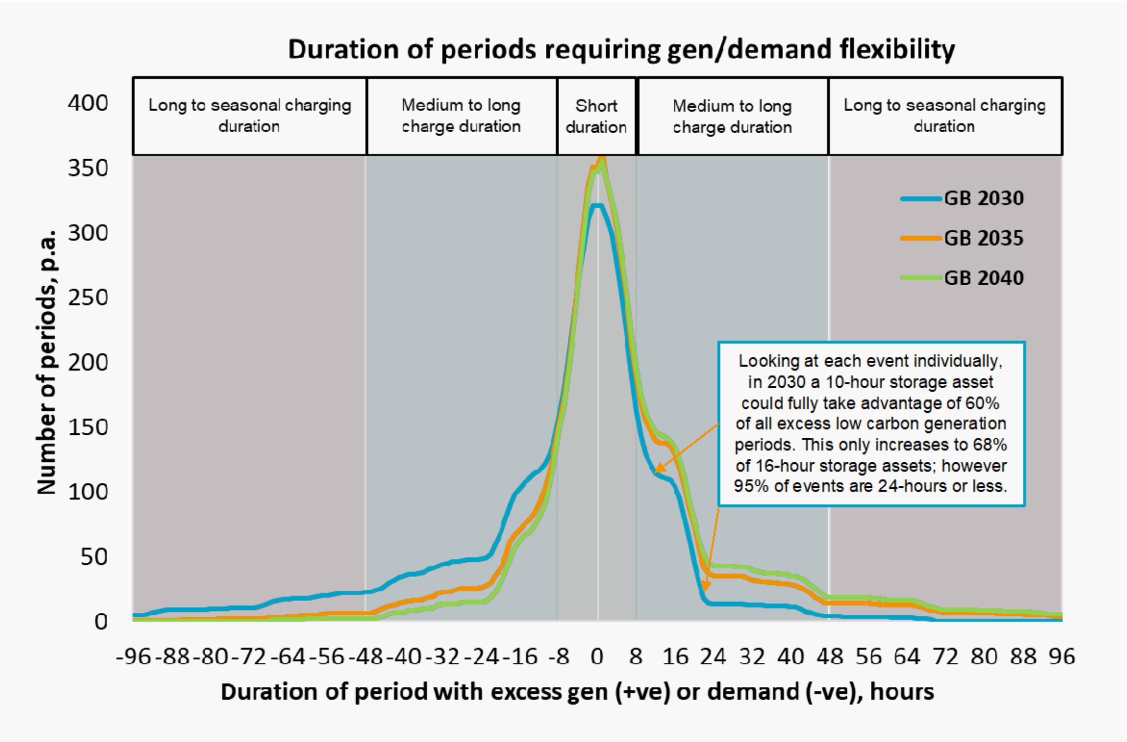
Market study

Over the course of the project, over 160 stakeholders were engaged with, both in the UK and overseas, across:

- End users;
- EPCs / Project Developers;
- Investors; and
- Politicians / industry groups.

An initial area of analysis was the duration of storage required. LCP Delta were engaged to explore this. Their analysis showed that annually, in a decarbonised grid in the UK by 2030-2035, there will be more than 100 periods requiring discharge time of 15 to 24hours. This justifies the business case for LDES. The analysis also concluded that assets able to discharge for 24 hours or more will be able to participate in 95% of events requiring generation and will attract the largest revenues.

Figure 20. LCP Delta analysis of 2040 - 2050 UK electricity supply/demand

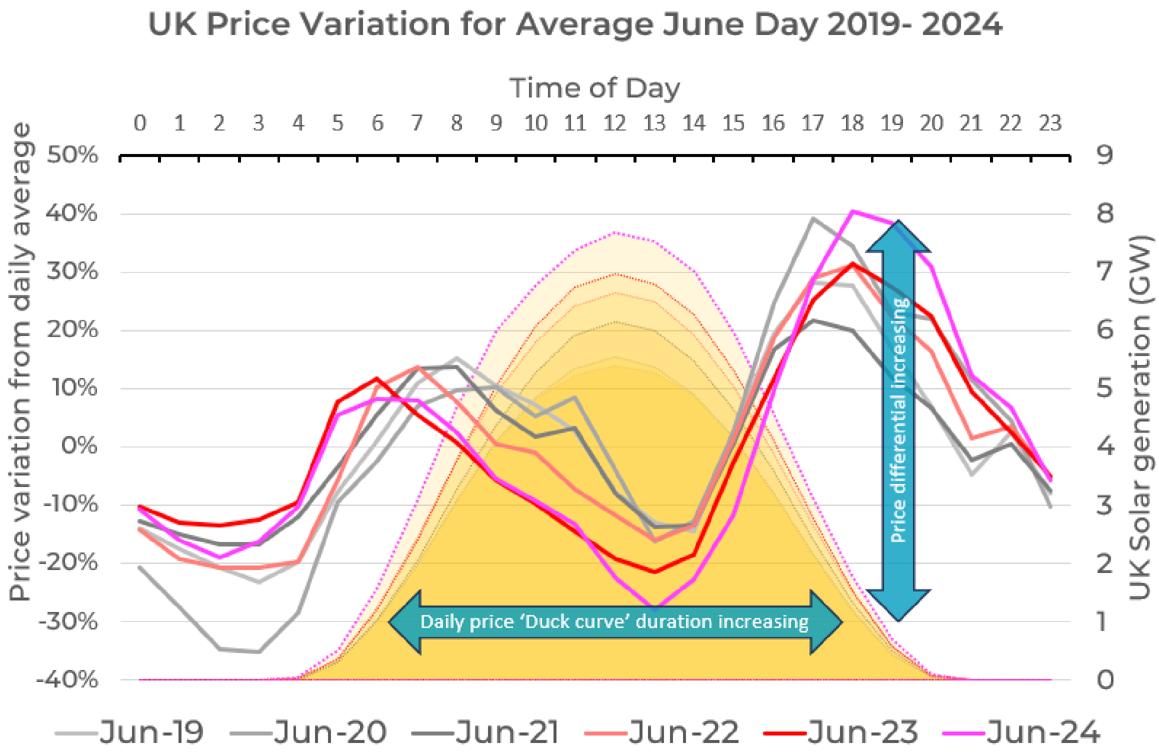


Solar is a key area of growth. UK Government's Clean Energy System target is 45-47GW of installed solar[5]. SynchroStor believes that with >2/3 of this likely to be non-domestic, the market opportunity for co-located storage is ~£10bn for 10GW capacity storing up to 240GWh.

Renewable generators will increasingly require long-duration storage to shift production to when it is needed and to maximise revenues. Analysis showed that the 'duck curve' is changing shape as more renewables are added to the UK grid. The curve is getting broader and deeper.

[5] Solar roadmap: United Kingdom powered by solar (accessible webpage) - GOV.UK

Figure 21. SynchroStor analysis of Duck curve evolution



Discussions with stakeholders (e.g. developers of solar projects) highlighted three key challenges which SynchroStor's PTES can address.

Economics

- Solar projects face uncertain prices and returns over their project lifetime.
- Average daily price captured by solar is falling as more solar is deployed.
- SynchroStor can mitigate price risk and increase revenues by arbitraging cheap solar and cheap off-peak electricity over periods of 8-24hours+.

Planning consent

- Solar developers looking to co-locate short duration lithium batteries have faced rejection due to public concerns about safety.
- SynchroStor's technology is considered benign and unlikely to raise local environmental objections.

Grid connection

- UK grid capacity is scarce with some connection offers now being for 2035+.
- With a relatively low capacity factor, existing solar projects have poor grid utilisation.
- SynchroStor can enable a 3x larger project on an existing grid connection, a faster route to market and significantly better grid capacity utilisation.

In summary, co-locating PTES with solar presents an opportunity: significant increased revenues on constrained grid connections, reducing risks for project developers. Further modelling to quantify the benefit confirmed an attractive use case co-locating PTES with solar. The benefits to project developers are:

- 3x increase in size of project on same grid connection for existing projects:
- 66% less grid capacity requirement for new projects;
- 2x increase in revenue (vs project without SynchroStor Storage);
- Increased ROI.

Long Term Cost Analysis

During the project a concept study of a commercial plant was developed and used to estimate the long term cost trajectory. The demonstration plant was developed as a test rig to validate the performance and viability of the different subsystems and not as a fully integrated commercial plant.

For a commercial plant, SynchroStor is planning to develop factory-built power modules (compressor expander skid and heat exchanger conveyor skid), which can be dropped in place, very much like Li-ion battery containers. This strategy would allow the development of more efficient dedicated production lines, reducing work on site, reducing cost and improving quality.

The energy storage component is made of lightweight structures to store materials in atmospheric enclosures. The duration of the energy storage is completely independent of the power rating and can be extended to reach the required storage depth. The storage enclosures can be made of modular components which can assembled on site very rapidly.

The complete system has a relatively small footprint and elevation, which together with the absence of dangerous materials or risk of fire is expected to significantly reduce planning cost.

The experience gained during the design phase of the demonstration plant and particularly the sourcing work with suppliers and development partners, has allowed SynchroStor to gain solid experience in designing complex process plants at commercial scale and provide a robust baseline to estimate cost of a complete system.

The capital (hardware) cost required to duplicate the First of A Kind (FOAK) plant was estimated at $5.3m / MW + $150k / Hr of discharge.

Considering a 10% learning rate and 1GW cumulative installed capacity, the FOAK plant cost is expected to drop at $1.3m/MW + $30k/Hr of discharge.

The cost of capital was compared with other LDES options such as Li-ion Battery Energy Storage and Pump Hydro Storage. Although the SynchroStor PTES is more expensive than BESS and PHS for first commercial projects, SynchroStor expect that the system would have lower CAPEX than PHS and would be cost competitive against BESS from ~7hours of discharge duration.

SynchroStor conducted extensive modelling of performance to optimise purchase and selling of electricity that could be applied to any geographic market. An example study was carried out for a Greek client that analysed prices in the Greek day-ahead market. Results showed that a SynchroStor system could enable 3x the size of PV project on the same grid connection and 4x the revenue of the PV project without storage. Combining the Capex of the PV project with the SynchroStor Storage project increases the IRR to 13.1% from 6.8% for a stand-alone project.

Figure 22. Comparison of Li-ion and PTES value proposition

Moreover investment returns would be substantially increased compared to projects without storage as more renewables are deployed; the best return obtained was with 24 hours of storage. 1-hour batteries can make similar returns but are far less useful for meeting Greek renewables targets since they will be unable to make any meaningful impact in displacing fossil fuel generation.

System Benefits

Broader system benefits were also identified:

- The consumer could save significant sums in unnecessary network build through the use of distributed Long Duration Energy Storage and better grid utilisation.
- The UK could achieve clean power targets much quicker than might otherwise occur through expansion of existing renewable energy generation sites and use of existing network connections.

BESS and PHS storage offer higher Round Trip Efficiency than the SynchroStor system, but SynchroStor's PTES provides additional benefits, in addition to those described earlier.

The technology has virtually no locational constraints and can be co-located with a large number of distribution grid connected assets such as wind or solar farms, large industrial users, or close to major grid equipment such as substations. In most cases the co-location of Long Duration Energy Storage enables the deployment of larger systems for a given grid connection, enabling expansion opportunities for existing sites bypassing grid connection queues.

The technology can be directly connected to medium voltage distribution grid, avoiding the long lead time and losses associated with transformers. As well as offering energy storage, the technology can provide physical inertia providing grid stability and ancillary services in a distributed way around the network. This has the opportunity to avoid large grid strengthening cost and providing revenues for the operator. Mott MacDonald carried out an analysis for SynchroStor which modelled a £9.3bn cost saving in avoided network costs through the use of SynchroStor's technology.

While lithium-ion batteries continue to follow a cost reduction trajectory, in SynchroStor's modelling they are unlikely to be viable for long durations of more than 8 hours. Deeper penetration of renewables, particularly wind energy, will require longer durations of storage. Based on SynchroStor revenue analysis an optimum discharge time of 16 to 24hr will make best use of otherwise curtailed wind energy.

The supply chain of BESS is dominated by China. SynchroStor's technology offers diversification opportunities improving resilience of supply chains. It will also generate job opportunities locally. The technology is well aligned with the oil & gas supply chain and could provide transition opportunities for the sector.

Work Package 8 Conclusion

The work package concluded with some key outcomes:

- Analysis confirmed the LDES value proposition.
- Co-locating PTES with solar showed tangible positive outcomes.
- PTES was modelled and found to be a viable alternative to other energy storage systems, particularly when deployed at durations > 10 hours.
- Broader system benefits of co-locating on the MV network could offer up to £9.3bn system cost savings.

Work Package 9: Project Management

Objective

As is appropriate for all major projects, a dedicated project manager was assigned who had experience of delivering complex projects. The project was managed robustly using appropriate tools – waterfall and agile systems to both forecast work and track activities. It was anticipated that DESNZ would also provide project management templates for communications and project tracking.

Lessons learned are reported separately.

Outcome

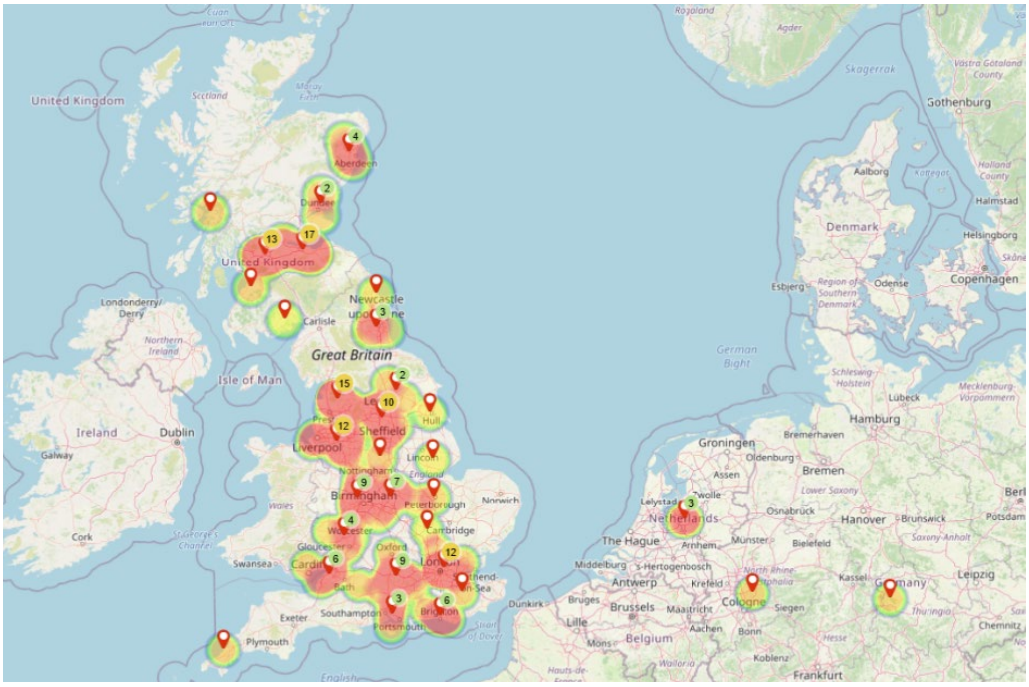
SynchroStor used both MS Project and Atlassian Jira for task management and tracking. Financial tracking was done using Xero, Excel and a cloud-based timesheet tool.

Reporting to DESNZ was monthly, with milestone deliverables either quarterly or bi-monthly. Change management was strict. Ten formal change requests were submitted and approved. The DESNZ team was consistent throughout. This was enormously helpful, avoiding any time wasted bringing new staff up to speed. Financial management was good. All milestone payments were made in a timely manner and cashflow challenges were avoided.

The greatest challenge to the project was engagement with the supply chain. On numerous occasions, SynchroStor was let down by suppliers, incurring major delays. In the context of a 2-year project, this was very difficult to deal with. In conjunction with cost challenges, this led to the change of focus in 2025. Over 160 suppliers were engaged, of which 95% were in the UK (based on invoice address). However as described elsewhere, the origin of many key components was outside the UK.

From the outset, a comprehensive risk register was developed. It should be noted that some of the risks identified at the start with medium/high consequences still affected the project, despite control measures.

Figure 23: Supplier mapping



January 2025: Major Project Change

In January 2025 budgetary quotes that were received for the gas piping installation (Work package 7) significantly exceeded the available budget. Firm quotes were received later than expected, and the forecast cost overrun presented a critical challenge to project execution. The budget had been set in 2022, when the system TRL was lower and design uncertainty was higher. Since then the overall plant design had matured and SynchroStor's team had grown substantially. However, the piping supply & installation costs were not a capability that could be fully internalized, and SynchroStor were dependent on the supply chain for this specialized activity.

Several options were discussed with DESNZ over a 3-month period and it was concluded that the best use of the remaining time & budget was to capitalise the innovation value of the compressor/expander. Over the course of the LoDES project it became obvious that the compressor/expander had an opportunity to contribute to the decarbonisation of high temperature heat production, by enabling electrification of large segments of many industrial markets. This is distinct from the LDES application. Considering this, it was agreed to terminate work packages 4, 5, 6 and 7. Other work packages would continue until November 2025. To avoid confusion, the project was renamed Fenix.

Project Fenix

For the period April 2025 to November 2025, SynchroStor's focus shifted to the compressor/expander only and its application as a core component in an industrial heat pump. The project was re-named Fenix and new objectives were defined:

Key Deliverables:
1. Compressor/Expander component development
2. Compressor/Expander operation and productionisation study
3. Electronics design, manufacture and test
4. Techno-economics to identify launch customer and concept MVP
High-Level Requirements:
1. 100 hours of cumulative testing under application conditions
2. Productionisation study including route to C/E Marking.
3. More compact electronics
4. Target launch customer and concept design of MVP completed

Table 3. Fenix deliverables and objectives

The project structure was similar to the LoDES project, with distinct work packages reporting regularly to DESNZ, triggering payment milestones. All deliverables were submitted on time. Output of the engineering work packages has been described in earlier sections. Work Package 16 – market push/pull – was introduced to look specifically at the dynamics of the industrial heat market and is summarized below.

Market Push/Pull

Industrial Heat Background

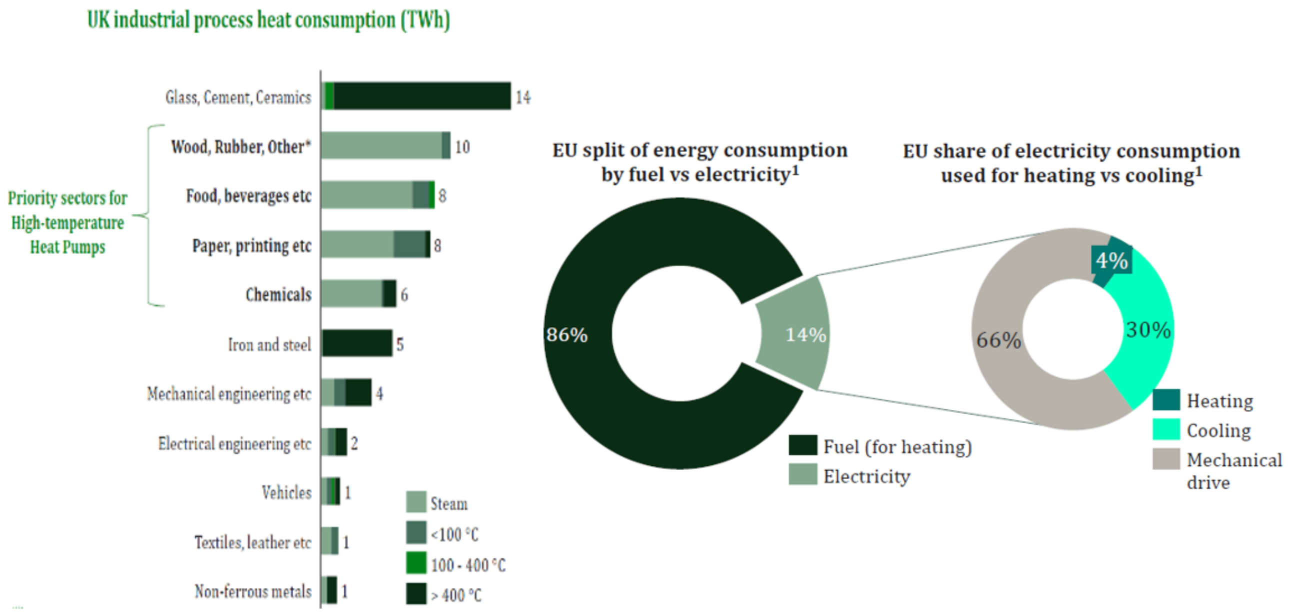
This work packaged kick off with a market study to consolidate SynchroStor's understanding of the market, identifying the best segment to target.

An estimated $4 billion is expected to be invested in industrial heat decarbonisation across the UK and EU between 2024 and 2030[6]. In the UK alone, approximately 60% of industrial heat

[6] McKinsey, 2024, Tackling Heat Electrification to Decarbonize Industry, https://www.mckinsey.com/industries/industrials-and-electronics/our-insights/tackling-heat-electrification-to-decarbonize-industry
Heat Demand Charts: ERM, 2024, 'NZIP Task 1: SynchroStor Best-fit First Use Case' (for SynchroStor Ltd)

demand falls below 400°C, aligning with SynchroStor's target operating range. There is growing interest in heat pumps capable of delivering temperatures above 150°C, which is currently the upper limit for most commercially available systems. At present, higher temperature requirements are typically met using less efficient electric heaters, leading to increased operating costs. This trend, combined with the push to phase out fossil fuel heating, is driven by the need to cut emissions, reduce exposure to volatile gas prices, and avoid rising carbon and emissions taxes.

Figure 24: Industrial heat energy use



Barriers to High Temperature Heat Pump Deployment

There are currently very few mature heat pump technologies for temperature greater than 150-200°C, meaning industries at these temperatures are either staying with fossil fuel heating or deploying direct electric heating. Other key barriers include:

Most heat in the target industries range is currently delivered by steam (UK 81%, EU 76%). Steam has become a very common heat transfer fluid in industry, and many are reluctant to move away from systems they understand well.

Currently, most heat pumps delivering steam either use a technology called mechanical vapour (re-)compression (MVR) or cascade solutions at lower steam pressures. This drives CAPEX, complexity and level of modifications that need to be made to the heating system.

In the priority industries (dairy and food) steam is used to generate hot water which is then used in the process. This increases losses. A heat pump system could eliminate the requirement for the steam circuit, improving the efficiency of the heating system.

Generating steam is not an ideal application for a high temperature heat pump. Deployment of high temperature CO2 heat pumps, such as that proposed by SynchroStor, would require considerable changes to the standard heating system to unlock all the benefits on offer. Available space and the difficulty in retrofitting new equipment into legacy factory processes have been cited by stakeholders. This make new heat pumps difficult to justify for existing installations but could be a lot more feasible in a new build.

A high spark-gap (ratio of price of electricity to the price of gas) in the UK and some EU countries makes the deployment of electrical heating solutions economically unattractive. In the UK this can be as high as 4.7[7].

High Temperature Drying: An Unmet Market

High temperature drying is the process of removing moisture from a product, usually to produce powder or other dried substance. It is achieved by typically blowing hot air over a stationary or moving wet product. Water is evaporated into the air, reducing the moisture content of the product. Wet air is either vented to atmosphere or cooled to remove water and reheated. Heating of air is typically achieved by electric heaters, steam or burning of fossil fuels because many drying temperatures are significantly higher than that delivered by conventional heat pumps.

Drying requires high temperature glides, maximising the amount of heat that can be extracted from the heat pump whilst also supplying waste heat in the form of moist air, making it an ideal application for transcritical CO2 heat pumps which have a large temperature difference between the gas sink and source. This results in a high coefficient of performance (COP) – efficiency. Hence CO2 is a common working fluid for heat pumps thanks to its thermodynamic properties and also offers a low GWP (Global Warming Potential) compared to HFCs or HFOs.

An example drying application, based on data shared by an end-user, was explored and confirmed to be an excellent use case for a heat pump using a SynchroStor compressor/expander. High temperature drying is a great match with SynchroStor's heat pump due to large temperature glides and requirement for high temperature lifts. It is also prevalent in many industries as a unit operation or full process, thus many customers.

As one of the most energy-intensive unit operations in industry, drying can use about 12–15% of the total industry energy use[8]. Assuming this global annual industrial consumption is 160EJ[9], we can estimate up to 630GW of installed drying capacity globally. The equivalent consumption in EU is 8.7EJ[10], with up to 33GW of installed dying capacity.

[7] Price gap between gas and electricity hits highest level since energy crisis of 2022 | Nesta
[8] Kemp, Fundamentals of Energy Analysis of Dryers, Modern Drying Technology Volume 4, 2012, Wiley
[9] https://www.iea.org/energy-system/industry
[10] https://iopscience.iop.org/article/10.1088/1748-9326/abbd02/pdf

MVP Specification

The final deliverable of work package 16 is a description of the Minimum Viable Product (MVP), i.e. the simplest version of a system which needs to be developed and sold into a market.

As informed by the market segmentation work, the MVP was defined as the SynchroStor Transcritical Drying Heat Pump (DHP) designed to offer complete heating and waste heat recovery to high temperature drying processes. The system is designed with intermediate heat transfer loops allowing for easy integration regardless of process and site design. However, the DHP can also be installed without additional heat transfer equipment, exchanging heat between the air and CO2 which is used as the working fluid inside the heat pump.

Figure 25: Drying Heat Pump Integration Concept.

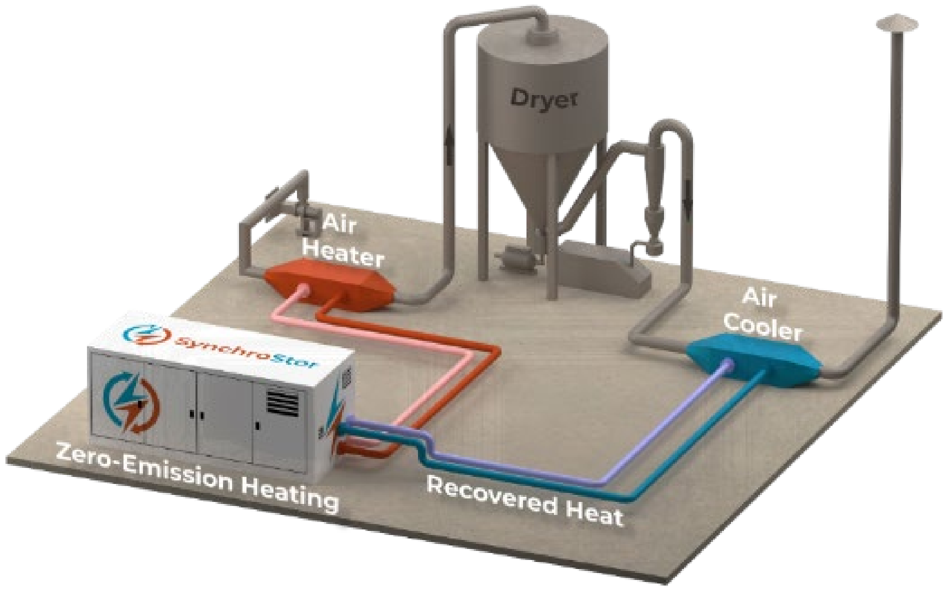
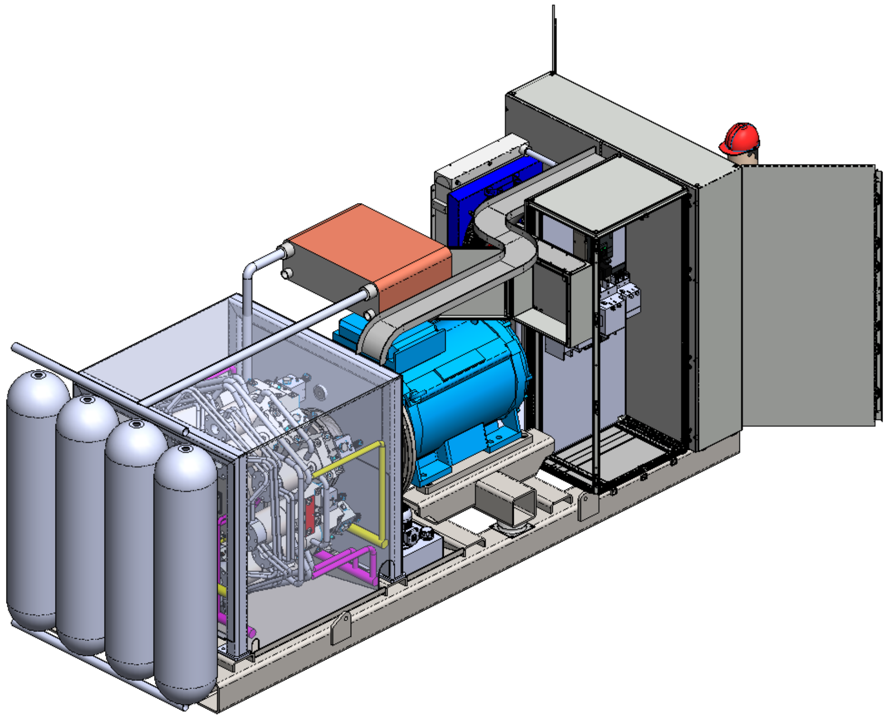


Figure 25 shows one integration concept for the DHP. The internal heat pump skid is built around SynchroStor's D430 compressor/expander, which generates high pressure, high temperature CO2 while offering unparalleled controllability and efficiency. Heat is supplied to the process by passing hot CO2 exhaust gas through a heat exchanger. Depending on process specifics, the heat exchanger can be a shell-and-tube, printed circuit or a finned tube heat exchanger for direct heating of air. Integration is site-specific and sometimes heat from the CO2 is transferred to a heat transfer fluid (HTF) (e.g., thermal oil, pressurised water) which is pumped through the circuit and provides heat to the fresh air via a HTF-to-air heat exchanger). The end user may opt to heat the air directly without an intermediate circuit in which case, the HTF-to-air heat exchanger is not required.

Figure 26: Concept design of the containerised skid component of the heat pump



SynchroStor's unique system architecture takes cooled high-pressure CO2 leaving the heat exchanger and expands it to low pressure and low temperature. By expanding instead of throttling, energy that would otherwise be wasted is recovered, boosting the overall system efficiency and thereby reducing the cost of heat for the end-user. Low-pressure, low temperature CO2 is passed through an evaporator which uses heat recovered from the dryer exhaust via a waste heat recovery (WHR) heat exchanger. There is an option to move the heat from the WHR exchanger to the evaporator via an intermediate heat transfer fluid circuit (e.g., water) or to recover heat directly to the CO2 without the need for an additional heat transfer circuit. The system architecture will depend on project specifics.

Fenix Conclusion & Next Steps

SynchroStor are carrying out feasibility studies with a number of potential end users to identify a first project. The most promising applications include:

- Commercial laundries looking at low-carbon solutions for providing high temperatures to their plants.
- Distilleries looking at decarbonisation opportunities.
- Food & beverage feedstock suppliers who want to remove gas burners from drying systems.
- System integrators of chemical plants looking to electrify heating processes.

For each of the above, the technical fit has been confirmed and techno-economics have been assessed. The next step for each is to explore funding opportunities to support CAPEX of installing pilot equipment on site.

Conclusion and Next Steps

This Research, Development and Demonstration project had the objective of developing SynchroStor's PTES from TRL 4 to TRL 6. Major engineering advances were made across all aspects of the design, with notable improvements beyond the concepts which had been developed prior to the project.

There was a significant project change in January 2025 when supply chain challenges made it impossible to deliver the full scope of work to the original project budget and schedule. In discussion with DESNZ it was agreed to terminate the work packages which were running over time & budget. The remaining budget was allocated to areas where the innovation value and commercialization opportunity was greatest.

At the peak of the project, 20 new jobs were directly created, 15 key sub-contractors engaged and over 160 component suppliers delivering.

The project has concluded with some key outcomes.

- LDES is a requirement for the UK energy system.
- Pumped thermal is a viable alternative to other energy storage systems, particularly when deployed at scale >10 hours of storage.
- Further R&D is required to fully develop SynchroStor's PTES.
- The core sub-system in SynchroStor's PTES – a unique high temperature compressor/expander – was demonstrated at industrially-relevant scale, with market-beating performance, cost profile and versatility.
- As informed by market research, a Minimum Viable Product using this compressor was identified: a high temperature heat pump for decarbonising industrial processes.
- A route to market and productionisation roadmap for this product was developed.
- Global market pull for this product was demonstrated and follow-on funding to commercialize the technology identified.

Next steps

- A continuing watch on the LDES market and new opportunities to restart PTES R&D.
- Delivering a pilot heat pump project with an industrial partner to demonstrate SynchroStor's value proposition.
- Securing follow-on funding to advance the TRL and MRL of the compressor/expander.
- Identifying partners for longer-term market access and product development.

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