LoDES Phase 2
Final Project Report

RheEnergise High Density Hydro

February 2026

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Introduction

In September 2022, RheEnergise was awarded just over £8 million (subsequently increased to £9.8m) under the government LoDES Stream 2 Phase 2 funding programme to build a first of a kind High-Density Hydro longer duration energy storage demonstrator. The demonstrator plant has been designed to provide peak power of 500kW and four hours of storage duration in an operational (TRL7) environment.

This report summarises the design and development of the project, provides performance results and documents successes and lessons learnt.

Executive Summary

The LoDES Demonstrator Project has successfully advanced RheEnergise's High-Density Hydro (HD-H) technology from laboratory scale and small field trial, toward near-commercial (TRL7) readiness. Despite an extension of timelines and adjustment to scope, the project has delivered clear evidence of technical viability, established critical operational capability, and generated learning essential to the next phase of commercial development. Once delivered at a commercial scale, HD-H is expected to achieve a lower Levelised Cost of Storage (LCOS) at durations beyond four hours than all competing technologies, with the exception of conventional pumped hydro.

The Funding Programme

Funding was awarded to the project by the Department of Energy and Net Zero as part of the Net Zero Innovation Portfolio (NZIP) Energy Storage and Flexibility innovation challenge. The NZIP aims to "accelerate the commercialisation of innovative low-carbon technologies, systems and processes in power, buildings and industry" .

Project Aims

The project aims were to:

- Progress the HD-Hydro technology from laboratory-scale to a near-to-commercial scale demonstrator in an operational environment, advancing it from TRL 4/5 to TRL 6/7.
- Provide validation of the turbine design approach and thus confidence in scaling to larger megawatt-class machines.
- Gain valuable experience of high density fluid (HDF) production and operation at scale.
- To undertake a programme of knowledge-dissemination activities, deepening market understanding and strengthening engagement with potential customers, investors, and stakeholders

- To build traction and support the pathway toward commercialisation of the technology.

Project Successes

The project achieved its primary goal of demonstrating HD-H technology in an operational environment. The transition from laboratory-scale prototypes to a near-commercial demonstrator represents a significant achievement given the scale, novelty, and technical complexity involved. Turbine performance testing produced positive results that closely aligned with internal modelling, validating the core design approach and providing confidence in scaling to larger megawatt-class machines.

A major project outcome has been the establishment of a dedicated HD-H testing facility. This installation now enables continued development, optimisation, and validation across the full system. It also provides an essential platform for investor engagement and has already supported the successful award of €2.5m in European Innovation Council funding to advance turbine development.

The project has strengthened RheEnergise's intellectual property position and deepened relationships with manufacturers who recognise the commercial potential of the technology. The internal team has also gained extensive experience across design, engineering, commissioning, and operational domains—skills that will be critical as the technology progresses towards commercial deployment.

RheEnergise has significantly expanded its commercial reach during the LoDES project, securing three Memoranda of Understanding with developers across three continents and building strategic relationships with vertically integrated utilities worldwide. Engagement with industrial customers—particularly in mining—has demonstrated the value of HD Hydro through targeted modelling and case studies, helping accelerate project development and convert interest into strategic partnerships. The company now has a commercial pipeline valued at $1.75 billion (project capital expenditure) across its top 35 opportunities.

Key Lessons and Development Areas

The project highlighted several areas that will inform future design, contracting, and construction strategies. The selected design and owner's engineer lacked the breadth needed for a multidisciplinary, first-of-a-kind system, contributing to gaps in design quality and late identification of defects. Earlier and more sustained in-house engineering oversight—particularly on site—would have mitigated several of these issues.

The sequencing of design and construction activities was impacted by schedule pressures, leading to overlaps that increased complexity and coordination challenges. Future projects would benefit from a more linear design-then-build approach and more integrated contracting structures.

Subsystem integration and testing emerged as a substantial lesson. Some delays and rework were caused by insufficient off-site system integration and limited factory testing of minor components. More rigorous FAT processes will be essential at commercial scale.

Fluid production and management also provided significant insight. The project delivered the largest-ever batch of HD fluid, uncovering critical learnings around moisture sensitivity, material handling, mixing rates, operational procedures, and the level of automation required.

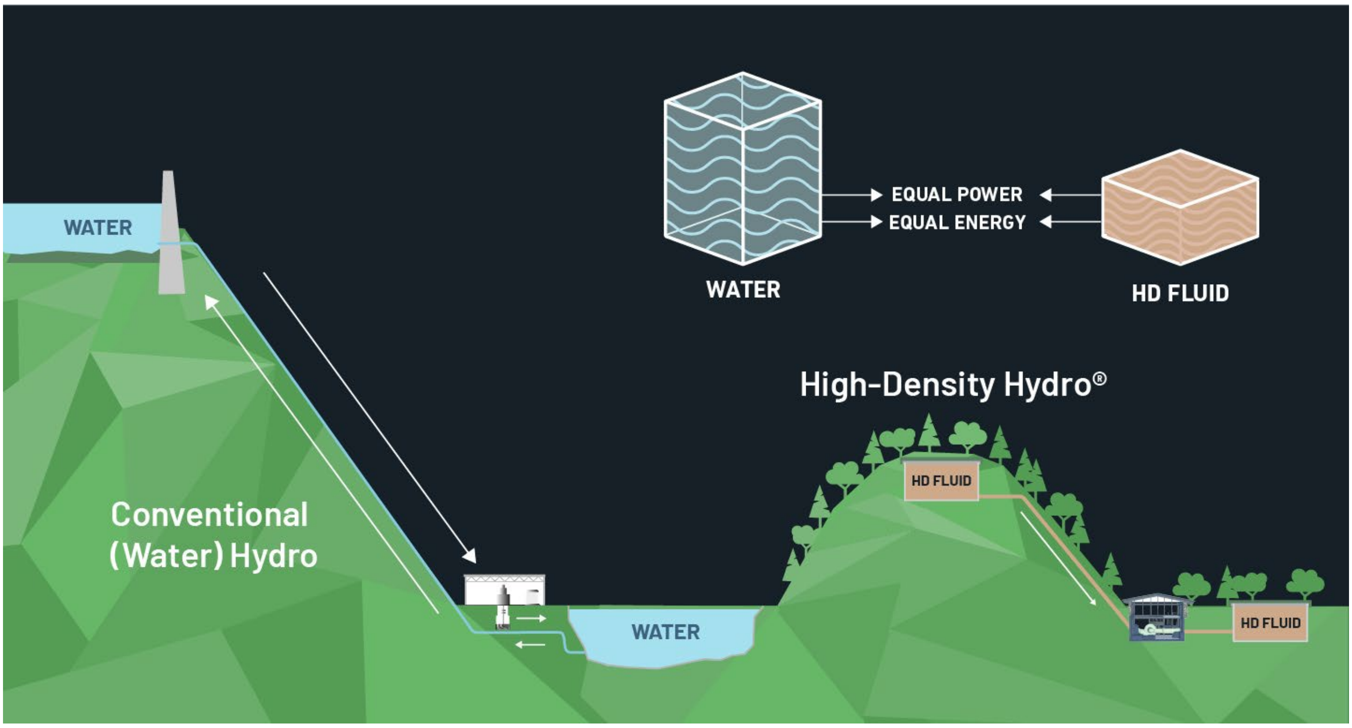
Further details are provided in the Lessons Learnt section of this report.

Figure 1 The RheEnergise team celebrating reaching full turbine power.

The Technology

RheEnergise's High-Density Hydro (HD-H) builds on a mature form of energy storage: conventional pumped hydro. Instead of water, this technology uses a **proprietary, environmentally benign high-density fluid** (HDF) in a closed-loop system. At times of low energy demand, the fluid is pumped to the top storage tanks. When the energy is required, the fluid is released and passes through turbines regenerating electricity.

Figure 2. High-Density Hydro illustration



For future commercial scale projects this technology will offer:

- **Lower construction costs and times** - using the HDF, rather than water, means that projects are 60% smaller volumetrically for the same power and energy, lowering construction costs and times.
- **Globally scalable** – use of HDF lowers the vertical elevation needed from ~500m to between 75 and 300m, to achieve the same power generation and energy storage capacity. RheEnergise has identified around 6,500 potential sites throughout the UK and over a million sites globally. Taken as an indication of the addressable market and with a typical project size expected at 40 MW and 10 hours storage, this would provide enough sites to meet the needs of the energy transition several times over.
- **Excellent environment credentials** – HDF is an environmentally benign fluid. The closed loop sealed system requires 20% of the water volume and has a significantly reduced footprint versus conventional pumped hydro. There are also opportunities for HDF to be created from waste material from other industries in the future.

- **Over 60-year project lifetimes with a low-risk technology** – HD-H builds upon the proven technology of pumped hydro.
- **High levels of efficiency** - the precise level of efficiency will be validated through longer term development, but analysis and experimentation suggest that 80% round trip efficiency (RTE) is achievable. Current experimental results are shared below on page 39.

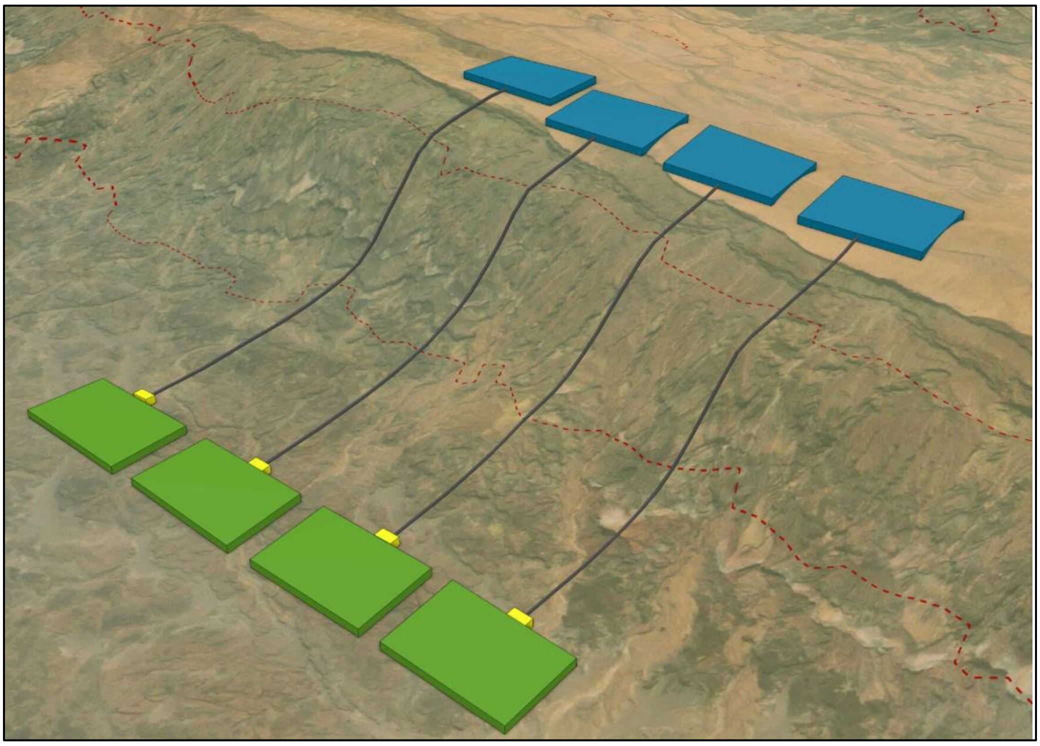
Commercialisation of HD-Hydro

Our engagement with the market, from analysis provided by industry experts and energy-users experiencing pain due to rising costs, has identified that as grids decarbonise, Long Duration Energy Storage (LDES) is required to balance the intraday cycle of solar and the two-weekly cycle of wind. Modelling suggests that as markets mature, 8-10 hours of energy storage will be required to undertake the vast majority of balancing between intermittent supply and variable demand.

RheEnergise aims to be a solution provider for LDES and flexibility, a solution that is flexible over time, which can address multiple wholesale and ancillary service markets and can integrate with other solutions.

RheEnergise are developing a product that will be delivered in 10-20 MW, 4-8 hour modules, maximising off-site powerhouse construction. A typical project is expected to be 40MW (400MWh) but system sizes can be expanded as required to meet site needs. Development and construction is expected to take 3-4 years.

Figure 3 Illustration of a proposed RheEnergise product with four 20MW (8-16hr) modules installed along a ridge line at a site in Chile



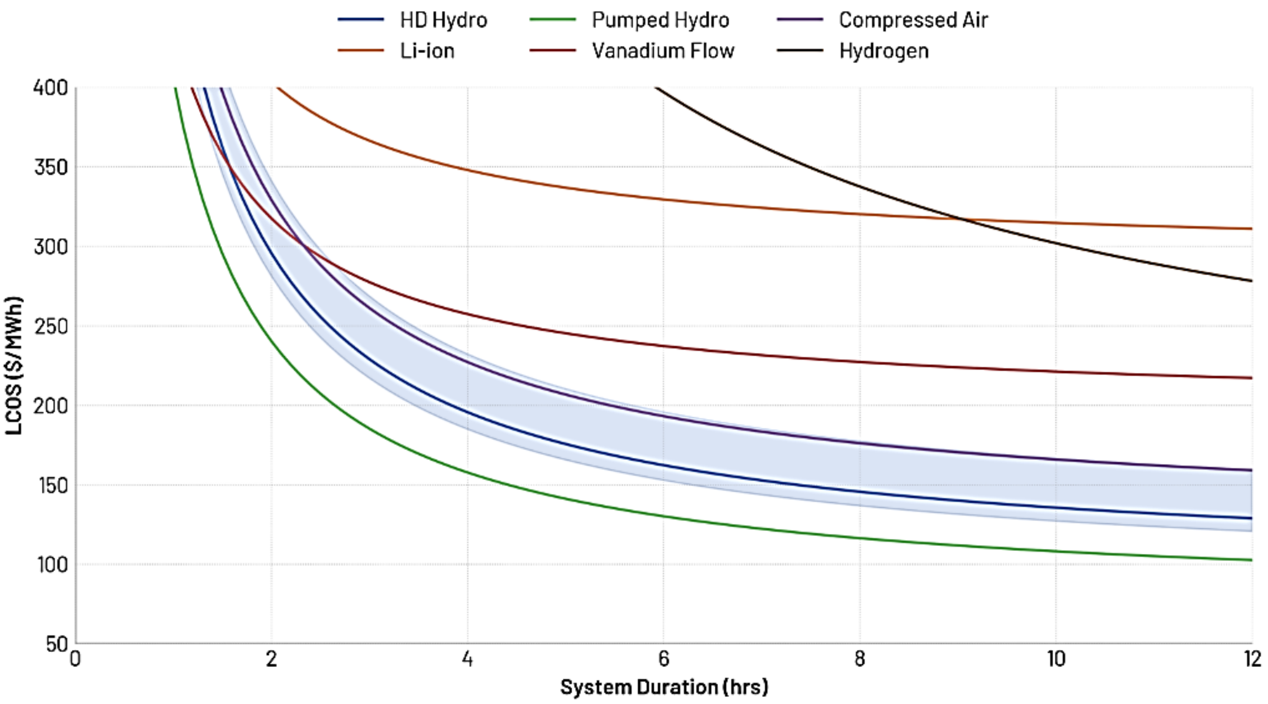
Competition

Any solution that provides flexibility to the grid or a generation asset is a potential competitor to RheEnergise. There is some overlap in the market with both Li-ion batteries and with conventional pumped hydro (PHS), but the extent of that overlap is limited. Developers increasingly recognise that for more than ~4-6 hours of storage, Li-ion batteries may not be the solution for both capital and operational cost reasons. Given the investment requirements and decade-long timescales of conventional PHS projects, these are only likely to be developed where there are good sites, and a government backed contract (or revenues) to proceed. The prevailing form of flexibility for durations above 1-2 hours today is gas OCGTs or CCGTs. High Density Hydro's costs are already competitive with gas.

The advantage is expected to grow as increasing low electricity price periods imply low-cost charging for energy storage, but lower utilisation and therefore higher costs for gas.

RheEnergise carried out a Levelised Cost of Storage (LCOS) analysis based on the methodology of Imperial University consultants Schmidt and Staffel.[1] The analysis uses the Imperial University data for all other technologies alongside HD Hydro parameters based on a bottom-up model created for RheEnergise by Mott MacDonald. These results based on the consultants' and Mott MacDonald's work are summarised in Table 1and Figure 1 below.

Figure 4 LCOS by system duration and technology as a function of system storage in a full daily discharge use case. HD Hydro cost scenarios range indicated by light blue bar



[1] LCOS is the total cost of an energy storage system over the course of its lifetime, including the costs initial investment, charging, O&M, replacement and end of life, divided by its lifetime units of energy discharged and discounted.

For HD Hydro, the LCOS is given as a range (represented by the light blue bar) which is based on a range of Capex per kWh installed (using upper, lower and central scenarios). At higher head heights, savings arise from a reduction in the reservoir and required fluid volume, while increased power capacities give cost savings (in terms of Capex £/kWh) due to economies of scale.

Table 1 Technology-specific parameters used in LCOS analysis and projected figures for RheEnergise HD Hydro technology

	HD Hydro Upper 80 MW 300m	HD Hydro Central 50MW 250m	HD Hydro Lower 20MW 150m	Pumped Hydro	Comp-ressed Air	Li-ion	Vanadi-um Flow	Hydro-gen
Specific power CAPEX $/kW	1310	1377	1539	1100	1300	250	700	5000
Specific energy CAPEX $/kWh	113	144	266	50	40	300	450	30
Round trip efficiency (%)	80	80	80	80	45	86	68	35
Self-discharge (%)	0	0	0	0	0	1	0	5
Lifetime (cycles)	30k	30k	30k	30k	15k	3.5k	20k	10k
Depth of discharge (%)	100	100	100	100	100	80	100	100

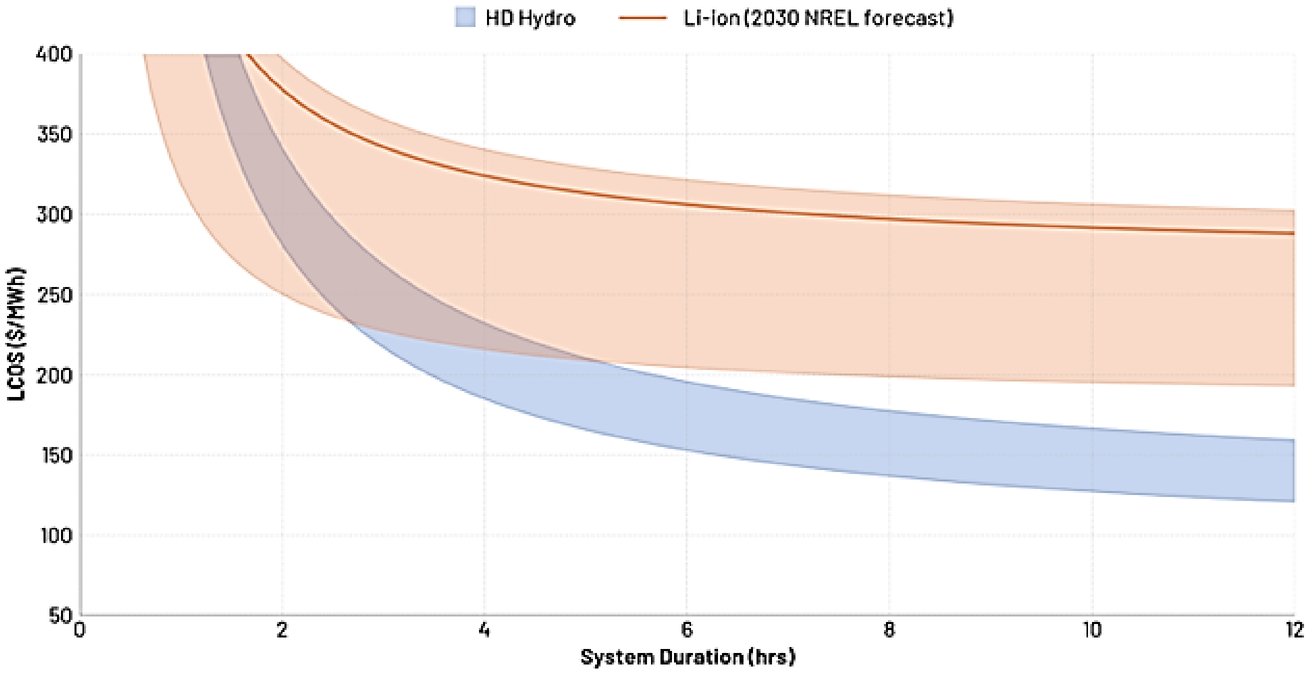
The results show that HD Hydro is the lowest cost storage technology for durations beyond 4 hours, with the exception of conventional pumped hydro that requires highly specific geographies. Most true LDES solutions (e.g. HD Hydro) have decoupled power and energy costs, which means that as the storage duration increases, the cost per MWh decreases. Therefore, at greater storage durations, the cost gap between LDES solutions and Li ion widens. At four hours, HD Hydro and Li ion have a comparable LCOS, but at 10 hours, the LCOS of HD Hydro is almost half that of Li ion. This is due to attractive CAPEX but also low degradation, long project lifetimes and an abundant global supply chain.

Due to its strengths across efficiency, system lifetime and flexible discharging capabilities, HD Hydro is well-positioned to capitalise on the vast incoming market for energy storage, particularly as demand shifts towards longer durations with increasing renewable penetration.

HD Hydro Positioning vs Li-ion Forecast Cost Reductions

RheEnergise has conducted sensitivity analysis beyond the initial analysis to assess its position relative to cost reductions for lithium-ion, today's fastest deploying short-duration technology. The cost projections come from NREL's '2023 Cost Projections for Utility Scale Battery Storage'. As before, the HD Hydro range is for head heights between 150-300m.

Figure 5 Sensitivity analysis of HD Hydro cost scenarios (blue bar) versus NREL L-ion cost reduction forecasts (red bar)



Against the optimistic bound of the NREL forecast, HD Hydro remains competitive beyond 4-6 hours, depending on head height. For systems beyond 10 hours, the US Department of Energy's definition of long duration, HD Hydro maintains a pronounced cost advantage (for example, the 50MW, 250m head system is 31% below NREL's most advanced Li-ion scenario at 10 hours).

The large bounds for lithium-ion are due to the large uncertainty within the cost estimate by NREL due to:

- **A complex supply/demand balance with demand for electric vehicles**. EV uptake has been slower than expected so far, prompting overcapacity in the supply chains of Li-ion in 2023/24. In 2024 there was a glut of Li-Ion production capacity, so we see production supplying the stationary market. If we look over the next 15 years, one of the fundamental problems is that Li-Ion cannot meet the mobility and stationary energy storage needs. In the long-term, Li-ion is unlikely to maintain this excess supply as bottlenecks and constraints in component commodities arise with accelerating demand for both EVs and stationary storage.
- **The extent to which reductions in cell costs will be matched by savings in the other components of power and energy components.** We still expect HD Hydro costs will be significantly lower than Lithium-Ion costs (35-50% below) even with their cost down projections for medium duration applications; even before taking into account that there are also opportunities for significant cost reductions for HD Hydro.

HD Hydro's cost profile demonstrates a strong competitive position, that is resilient to cost reductions in other technologies. For example, the modelling above is based on a UK scenario where construction costs, which represent approximately 50% of the capital expenditure, are high compared to other markets.

Target Markets

RheEnergise's business model thinking and approach has evolved significantly during the period of the LoDES project. This in turn has impacted our route to market and beachhead market customers.

Beachhead customers

These now include:

- **Mine and quarry operators**, where we have had significant engagement including signing Memoranda of Understanding with owners. These operators not only recognise the need for energy storage coupled with renewables to decarbonise (and lower costs of) their operations but also see opportunities to be a major part of our supply chain, i.e. the supply of fluid weighting agents for future projects.
- **Data centres** global demand in this sector has surged since the start of the LoDES project, driven largely by the rapid expansion of Artificial Intelligence. The International Energy Agency projects that data-centre electricity consumption will more than double within five years, reaching levels comparable to Japan's current national demand by 2030. In some US states, new datacentre load could add up to 30% to existing demand and must be met within extremely short timelines of 3–5 years. Traditional supply options—new gas generation, nuclear, and conventional PHS—are constrained by long lead times, infrastructure limitations, and decarbonisation challenges. Renewable

energy combined with HD Hydro provides a solution that could be developed within these constraints.

- **Locations of grid constraint**, where LDES can absorb power when there is power in excess of capacity and then dispatch as demand exceeds supply. LDES becomes a solution to enable the increase of locations of demand, allowing businesses and communities to expand and an increased supply of renewable energy to connect.
- **Vertically integrated utilities**, i.e. energy companies who owns and operates every stage of the electricity supply present a particularly good opportunity. LDES provides multiple benefits in this sector due to savings from avoiding network upgrade, reduced fossil fuel turn-up and maximised value capture from renewables assets.

Developing Commercial Relationships

Throughout the course of the LoDES project, RheEnergise has progressively strengthened its relationships with our key customer groups. We have signed three Memoranda of Understanding with developers on three continents and have established strategic engagement with a number of vertically integrated utilities operating across the globe.

We have worked closely with industrial players, particularly in the mining and data centre sectors; providing modelling and case studies demonstrating how HD Hydro can add value and support decarbonisation of their assets. Through this work RheEnergise has been able to accelerate project progress and successfully persuade customers to achieve target signed strategic partnerships, moving projects towards to the next phases of development.

Our current commercial pipeline is valued at $1.75bn project value. This figure corresponds to the top 35 deals in the pipeline. The successful delivery of the demonstrator project has provided an invaluable technical proof point as these opportunities are progressed and the next stage is to secure a First of A Kind (FOAK) project.

First Of A Kind Project Opportunities

The opportunities presented here are examples of our FOAK opportunities, where partners are comfortable with the risks of FOAK and moving at pace. Each opportunity is analysed on a set list of criteria including development feasibility and economic viability.

- **Polish FtM project**: 10MW, 6-hour prospective FtM (front of meter) FOAK project with a developer on partner-owned site in South East Poland, revenue focus primarily arbitrage. Currently at environmental permit stage.
- **Scottish projects**: Landowner pull for 2x 10MW, 8 hour projects on two neighbouring Scottish estates. Good revenue opportunities with constraint management revenue uplift potential.
- **Italian projects**: Evaluating sites in the portfolio of a UK and Italy-based developer partner and seeking new sites to co-develop HD Hydro. MACSE auction potential route to market.

Demonstrator Delivery

Work commenced following the funding award in October 2022, as the company expanded the team, engaged consultants and contractors, began detailed design and embarked on the permitting process for the Hemerdon Mine site identified during the feasibility stage. This section of the report outlines the project approach and provides a brief overview of each phase of work.

Site Permitting

Landowner Agreement

In November 2023, negotiations for the original site came to a halt due to issues with the mine's operating permits and the site's ability to host the project on a timeline suitable for both the NZIP programme and RheEnergise's overall aims.

Fortunately, having foreseen the potential for this scenario, RheEnergise had begun discussions with a number of alternative landowners. Negotiations progressed well with a new site in close proximity to the original location. In April 2024, the team were able to secure a lease agreement to build the generator at Sibelco's China Clay mine site just outside of Plymouth.

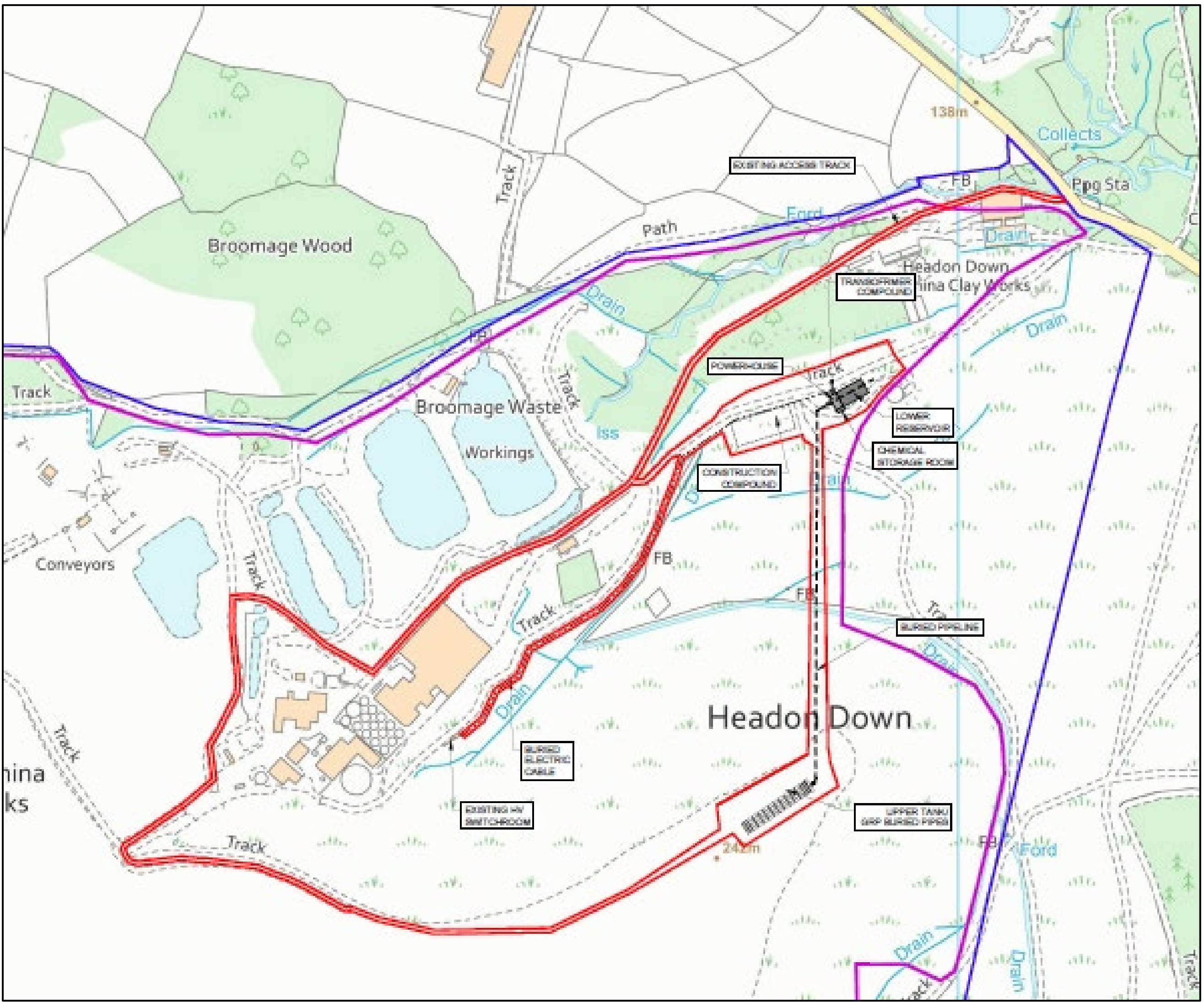
A change in site meant that surveys, initial civils design and the permitting process (grid connection and planning) had to be repeated.

Planning

Achieving timely planning permission for the project was key to its successful delivery. Having gone through the successful but lengthy process of a full planning application for the original site, it was feared that re-applying for the new site would reduce the chances of the being able to deliver the project in the timescales prescribed by the NZIP programme.

However, RheEnergise were advised that the works would be likely to fall within the Permitted Development Rights (PDR) of the site which could significantly accelerate the process. This was confirmed and the local planning authority issued a Certificate of Lawfulness for the development in March 2024.

Figure 6 Sibelco site layout



Grid Connection

The RheEnergise system is connected Behind-The-Meter i.e. it is designed to predominantly serve electrical loads on site ahead of exporting any excess to the grid. Sibelco operate a 1.4MW CHP (Combined Heat and Power) plant at the site to dry their mined product. In addition, a 450kW solar PV plant is planned for future development. These additional generating assets had to be accounted for when applying for grid connection for the HD-Hydro plant.

RheEnergise was supported in its grid connection application by a specialist consultant with significant experience working with the local Distribution Network Operator NGED. After a period of assessment and negotiation, RheEnergise accepted a final ‘no works’ grid connection offer in November 2024.

Project Design and Manufacturing

Whilst landowner agreements and site permitting were established, works progressed with the main design packages.

Design Approach

In order to meet the time constraints of the funding programme, it was necessary to progress design on all sub-systems concurrently. The work was divided into the following packages:

- **Site Specific System Design**
- **HD Hydro Turbomachinery**
- **LV/HV System & Software Controls**
- **HD Hydro Specific Valves**
- **HD Hydro Fluid Management System**
- **Fluid Supply Chain**

Due to the constraints of RheEnergise's in-house design resources, the team worked with expert consultants to develop the detail design of the various sub-systems. This helped us make decisions and produce results more quickly whilst up-skilling the existing team.

The design work carried out within each work package is summarised in the sections that follow.

Site Specific System Design

Civil Works Design

RheEnergise engaged an experienced small-scale hydropower consultant, as designer and owner's engineer. Their scope was to provide detailed design and oversee construction of the lower and upper reservoirs, powerhouse, pipeline and cable route for the High Voltage (HV) electrical connection.

The change of project site meant that certain elements of the civils design had to be completed twice. Once the location had been finalised and tenders had been received for the construction, budget overruns necessitated further civils design development.

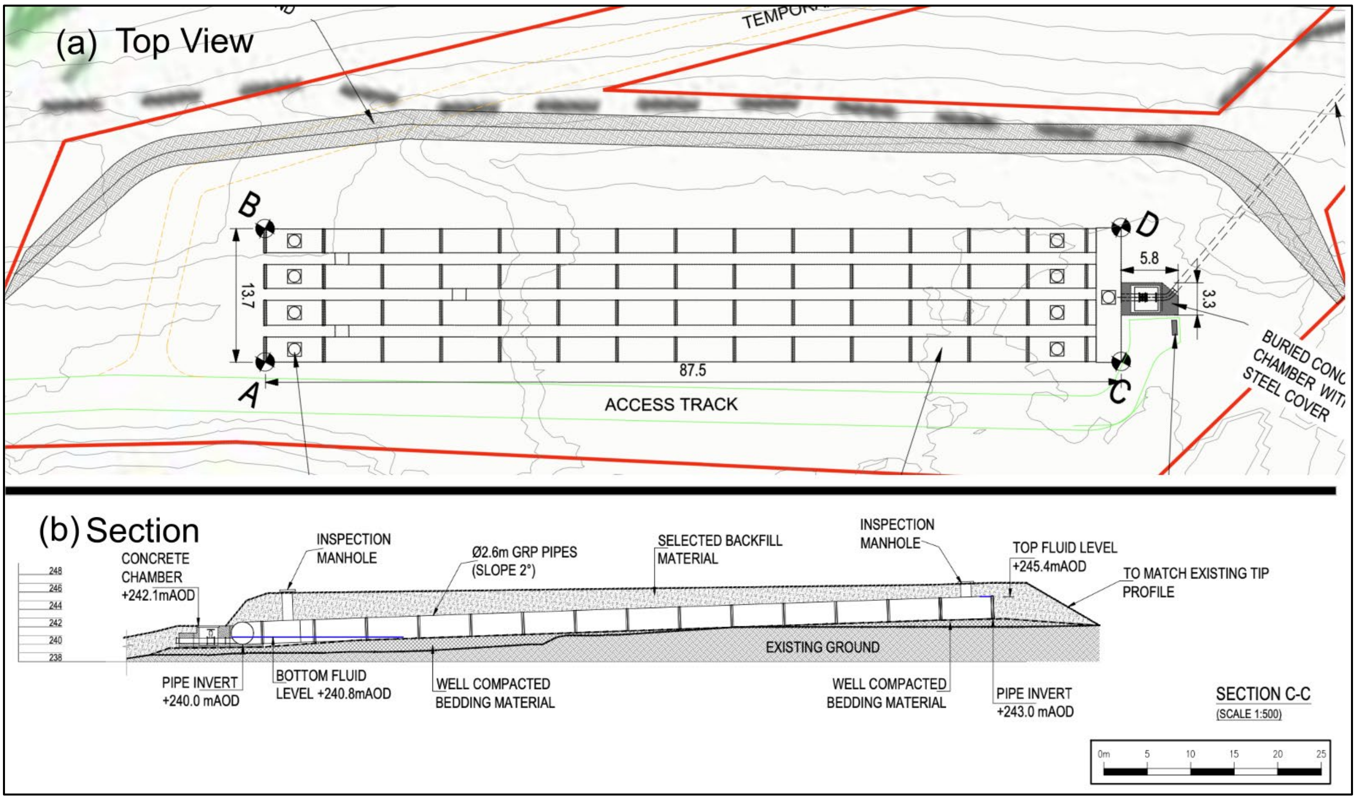
Changes in Reservoir Design

The most notable changes were a reduction in size of the lower and upper reservoirs and adoption of a new construction method for the upper reservoir.

A 50% reduction in tank size was implemented for both reservoirs to achieve significant cost savings. This led to a reduction in fluid capacity for the system, but it was agreed that the original storage duration could still be achieved albeit with the turbine running at lower power.

The design of the upper reservoir construction was revised from a more conventional concrete structure to one based on large-diameter glass-reinforced plastic (GRP) pressure pipes.

Figure 7 Revised upper reservoir design



Alongside cost savings, this allowed RheEnergise to test both reservoir designs concurrently, maximising learning from the project, mitigating the risk of following just one design approach and allowing demonstration of further commercial viability for the technology.

Whole System Modelling

A critical aim of the demonstrator project was to validate the whole system and sub system modelling carried out during design of the system. Once the initial site design and main component choices had been made, a full transient analysis for the system was carried out. This would provide theoretical performance curves and inform the overall system design and control principles. RheEnergise collaborated on this exercise with TUV-NEL who provided hydraulic optimization and computational fluid dynamics (CFD) analysis services.

HD Hydro Turbomachinery Design and Manufacturing

RheEnergise engaged Energy Revolution Services (ERS) as Owner's Engineer to support in the development of the HD turbine. Design work took place in two stages:

- **Hydraulic Design** - developing a preferred turbine concept and refining the geometry for optimal flow characteristics.
- **Mechanical Design** - developing the turbine geometry into fabrication drawings with appropriate details of welds, materials, cutting, machining, testing, and coating requirements.

Two fundamental design decisions were made early in the project.

Separate Pump and Turbine

It was concluded at feasibility stage that it would be most practical to implement a separate pump and turbine design rather than developing a Reversible Pump Turbine (RPT) often found in conventional pumped hydro systems.

Designing a small-scale RPT would have added significant complexity, risk, time and cost to the project and it was felt that the benefits of an integrated RPT unit were not likely to be realised in a project of this scale. An additional benefit of this approach were greater opportunities to add test instrumentation, maximising the opportunity for data gathering and analysis of the turbine performance.

Change in Turbine Configuration

It was identified in the early stages of design that it would be necessary to substitute a single 500kW turbine for the two 250kW turbines originally conceived at feasibility stage. Having identified a turbine geometry best suited to the project's research and development requirements, it became clear that manufacturing a 250kW turbine to withstand the pressures (head) at the proposed site elevation would not be technically or economically viable. Use of a single 500kW unit would lead to a turbine design better matched to project needs with added advantages of reduced complexity in the power control system and other system components such as the generator and valves. The compromise was a loss of the ability to demonstrate the parallel operation and control of two machines which could have been useful in the design of future commercial projects.

Hydraulic Design Considerations

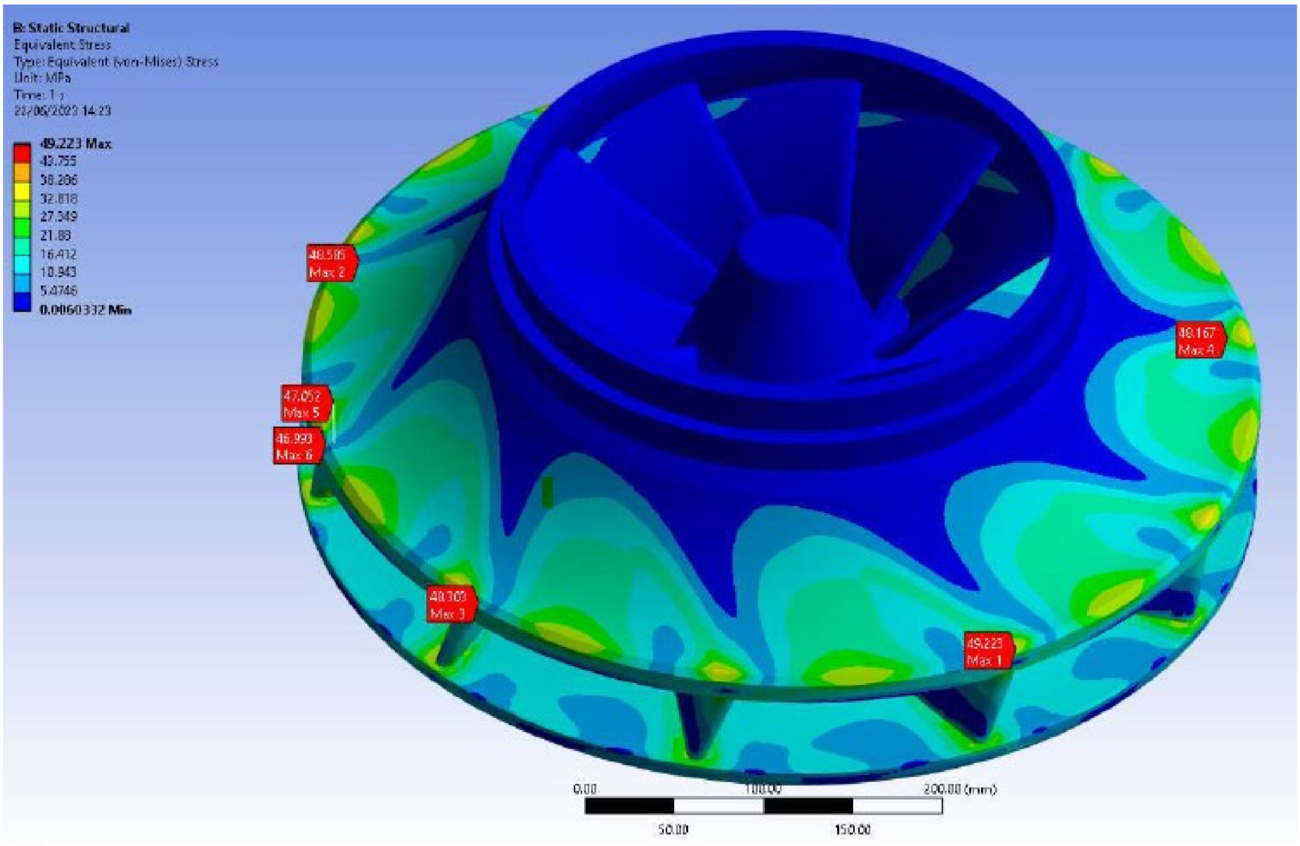
Four key areas were selected for investigation within the project focusing on the aspects that differ most substantially from traditional (water) hydropower turbine technology.

- **Changes to machine performance characteristics** - the fluid density alters the specific speed (and machine performance characteristics) for a given head.
- **Altered fluid viscosity** - this will result in differing shear stresses, friction losses, boundary layers and resulting overall flow behaviour. Understanding this 'non-Newtonian' fluid behaviour will draw from past research into slurry pumping, as well as RheEnergise's fundamental fluids work package. These findings will then be adapted to the HD Turbine design.
- **Increased abrasion** – it was expected that this would increase in a manner likely closer to a slurry than sediment-laden water. An understanding of abrasion behaviour will draw from analogous phenomena in slurry pumping and hydropower applications, with experimental review of behaviour specific to the HDF and its application to turbomachinery design.
- **Changes to the part-load (vortex rope), cavitation and transient behaviour of the turbine**.

The Turbine Performance Specification describes the design process and design parameters in more detail, but key points are:

- The turbine hydraulic design was adapted from an open-source high head Francis reference turbine developed at the Norwegian University of Science and Technology (NTNU). rescaled to match the design conditions.[2]
- Mechanical design was completed using standard hydropower turbine design approaches including CFD analysis, providing sufficient detail to enable manufacture.

Figure 8 Finite Element Analysis of the turbine runner

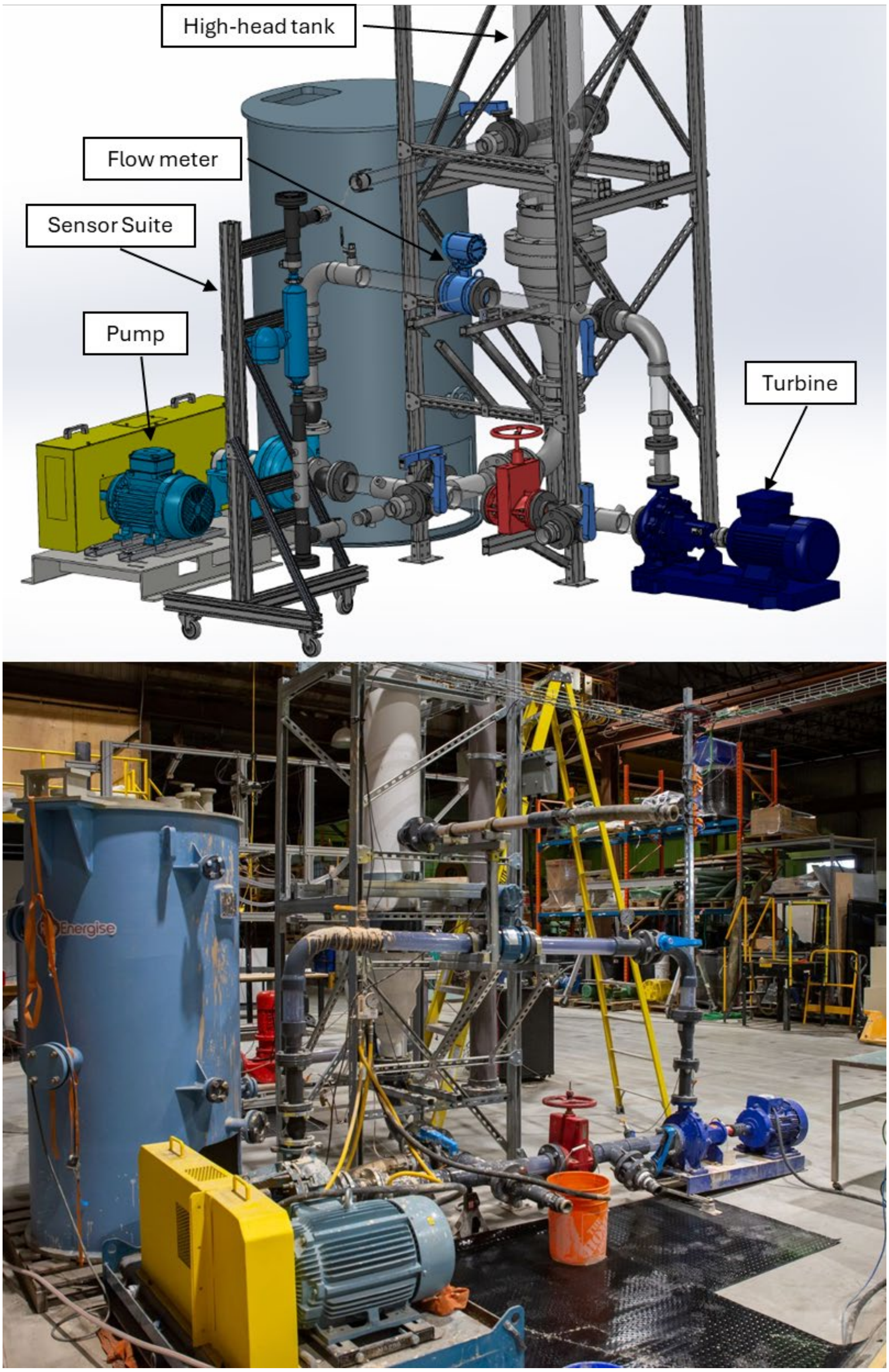


[2] https://www.ntnu.edu/nvks/about

In-House Testing Facilities

A fluid test loop was developed in the Montreal facility allowing the team to test and develop the theoretical modelling by running scaled down equipment with HDF.

Figure 9 Fluid test loop



Turbine Manufacturing

An Inspection and Test Plan was developed for the turbine to ensure quality control during manufacturing. The RheEnergise team carried out Factory Acceptance Testing with our Owner's Engineer.

Figure 10 Turbine Factory Acceptance Testing

Pump

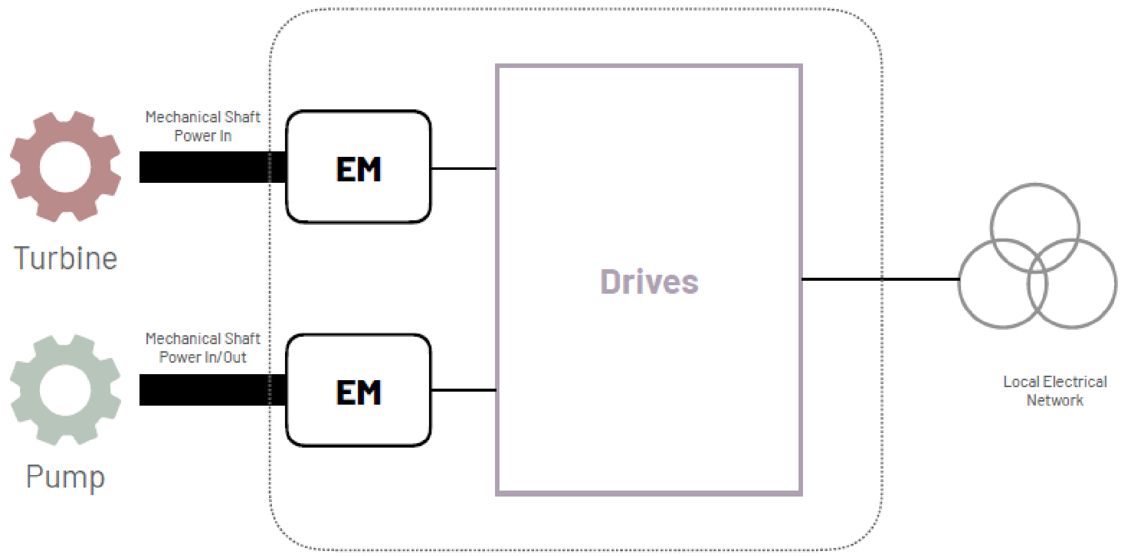
In addition to turbine design, ERS provided support in the selection of the pump for the system. It is notable that the pump was not optimised for efficiency but reliability. Its main purpose was to provide the required fluid in the upper reservoir to allow testing of RheEnergise's demonstrator turbine. This is a significant difference to a commercial project, where the entire system design would be optimised to provide the best economic and technical solution for the site.

Low Voltage and High Voltage (LV/HV) System & Software Controls

Power Conversion System

The power conversion system (PCS) is defined as being the system that converts shaft power from the turbine (or to the pump) into electrical power supplied to the grid. As such, it also includes the electrical machines (generator and motor, or EM) for the pump and turbine.

Figure 11 The power conversion system and system interfaces



The objectives of the design for the PCS were as follows:

- **Use latest technology**: Where it makes sense to do so, use the latest technology to get the maximum performance (see point 2) and futureproofing (see point 3). The conventional hydropower industry has not been taking full advantage of the powerful technology developments of the last few decades.
- **Unlock revenue streams via enhanced capability**: long-duration energy storage can access multiple revenue streams if the technology is capable of doing so. This translates into a need for variable power input/output, dynamic ramping capability (and therefore excellent control), and potentially black-start capabilities.
- **Pathway to commercialisation**: develop a solution that can scale with the technology as it approaches TRL9 and ultimately commercialisation.
- **Reinforce the HD Hydro whole system design**: the power conversion system interacts with most other systems. Where it is possible, leverage new technologies to maximise the sum of the whole and unlock new possibilities.

During the development of the design RheEnergise built a strong relationship with the main equipment supplier (Danfoss) which proved to be invaluable throughout the installation and commissioning of the system.

Main Control System (MCS)

The MCS is the core command centre for the demonstrator system, tasked with automating and overseeing all operational aspects. Important functions of the MCS include gathering data from remote sensors that monitor various process variables, comparing this data with operator-set parameters, and generating appropriate command functions to control the process through final control elements.

The design of the MCS was developed by the in-house RheEnergise team following a modular design approach. This enhanced the system's robustness and reliability and facilitates software maintenance.

The control system has been designed to be a representative version of the eventual commercial product. The modular design provides scalability, allowing for ease of future expansions and adaptations.

Test and Instrumentation (T&I System)

While the T&I system shares several features with the MCS—including sensors, data-acquisition components, and data-storage capability—its purpose is distinct. The T&I system is designed to independently capture the maximum amount of high-quality performance data, whilst operating without the practical constraints of the control system.

HV Design and Grid Connection

RheEnergise worked with an HV design consultant and contractor who had an existing relationship with the site owners and good understanding of the site and its operating constraints.

The high voltage (11kV) connection point was in an existing substation close to the main incoming substation. This was located c. 600m from the RheEnergise powerhouse and transformer compound. The HV cable route involved crossing both a road and a brook.

The system was designed to be connected Behind-The-Meter i.e. to predominantly serve electrical loads on site ahead of exporting any excess to the grid. Sibelco operate an existing 1.4MW CHP (Combined Heat and Power) plant at the site and a 450kW solar PV plant is planned for the future. RheEnergise worked with a grid consultant to design a compliant system that took all these elements into account.

G99 Compliance[3]

NGED, the local Distribution Network Operator (DNO) required that the RheEnergise system was installed in compliance with the Engineering Recommendation G99.

G100 Compliance[4]

[3] Engineering Recommendation G99 outlines the technical requirements for connecting power generating modules to distribution networks in Great Britain

[4] Engineering Recommendation G100 sets out the technical requirements for export and import limitation schemes.

Due to the CHP plant, there is an existing 1MW export agreement with NGED for the site. Adding the additional generation capacity of the RheEnergise system (and futureproofing for the solar generation) necessitated adding G100 Export Limitation equipment to ensure that net export from the site never exceeds 1MW.

Initial designs for export limitation were produced by our HV design consultant. It was suggested that a secondary metering unit would be required for the main incoming high voltage supply. This would have led to significant expense, potential delay to the project and the need for a full site shut down. RheEnergise worked closely with our grid consultants, Sibelco and NGED (the DNO) to simplify the design such that a new metering unit could be avoided and hence accelerate the implementation of the system.

HD Specific Valves

The valves developed for the project were specified with more of an R&D leaning that would be typical in a commercial project. They play a critical safety and operational role in isolating the turbomachinery and all the subcomponents of the powerhouse and lower tank from the very high hydrostatic pressures generated by the HD Fluid in the penstock and upper reservoir.

Figure 12 Main Inlet Valve (MIV) Factory Acceptance Tests

RheEnergise chose to work with a partner manufacturer to develop the HD valve design. A company who specialises in valves for slurries and that has a long-term interest in future RheEnergise projects.

The pump and turbine Main Inlet Valves (MIVs) have an identical specification, developed in collaboration with the partner manufacturer. A testing plan was designed which combined tests by the valve manufacturer with tests involving the HD-Fluid carried out by RheEnergise using a smaller scale version of the valve installed in the Fluid Test Loop described above.

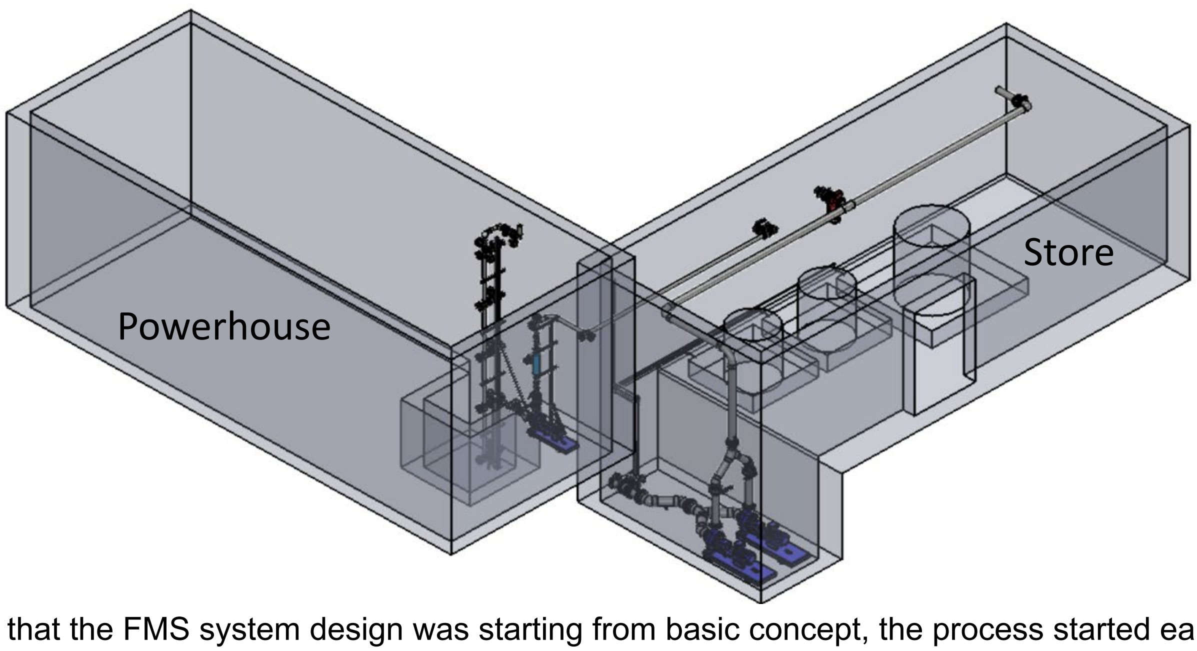
Ahead of finalising orders RheEnergise visited both the valve and actuator manufacturers and attended Factory Acceptance Tests.

Fluid Management System

The unique fluid characteristics of HDF necessitated the inclusion of a Fluid Management System (FMS) within the lower reservoir to monitor the fluid, interact with and signal control system parameters in real time. The design process was a challenge given that the formulation for the HDF was being developed concurrently and thus the fluid final properties were still being finalised. The aim was to find the line between ‘over designing’ for problems that would not necessarily manifest and providing a system with good functionality.

Having originally intended to out-source the design work, RheEnergise moved to developing the design in-house. Some support was given by the team from a design consultancy which helped up-skill the RheEnergise team, specifically in the area of design risk assessment through the process of DFMEA (Design Failure Mode and Effects Analysis).

Figure 13 3D rendering of FMS in the powerhouse and store

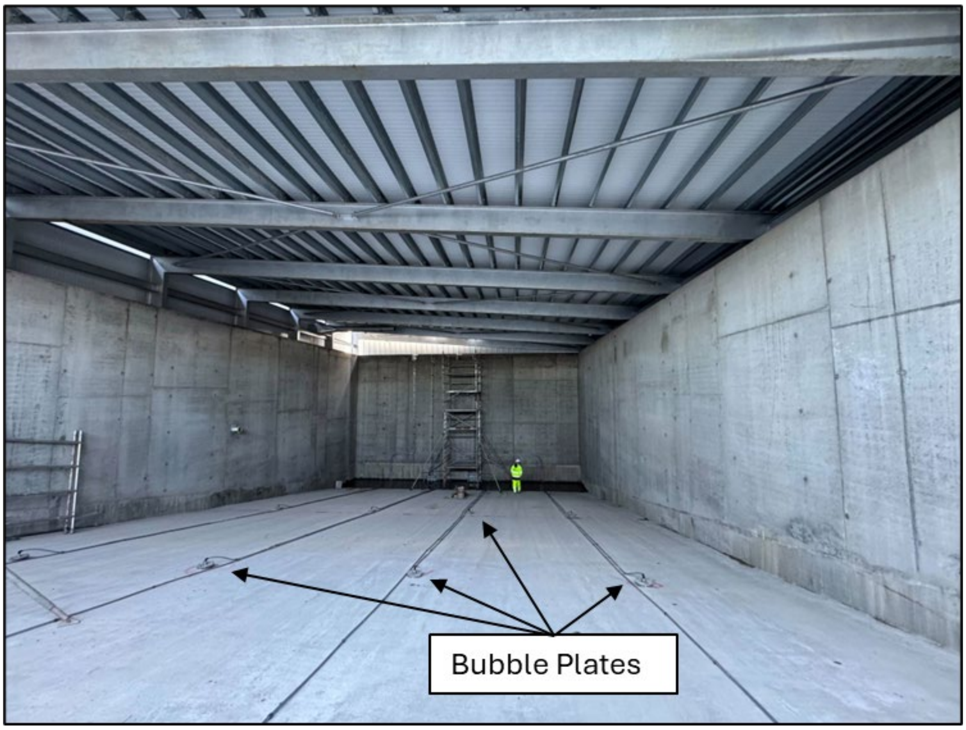


Given that the FMS system design was starting from basic concept, the process started early in the project. Initial stages were spent exploring the techniques to control the HDF properties deemed crucial for a healthy fluid.

Sensor selection, mechanical and control system design followed. As with the other sub-systems a test rig was set up to test components and validate design iterations. The FMS was designed to take samples of HDF as it moves within the system from sampling points within the pump, turbine and lower reservoir. Following analysis of key fluid health metrics the FMS control system is designed to implement measures to maintain the health of the fluid via fluid movement or the control of PH, by countering evaporation or dosing with biocides.

Once installed on site, the FMS design continued to evolve. As understanding of the fluid's behaviour at scale improved, the team introduced new techniques to optimise its maintenance. Originally a simple fluid circulation system formed part of the design, pumping HDF around a loop to the powerhouse and back into the reservoir via a 'spray bar' which spanned the width of the reservoir. This aimed to prevent settling and separation of the fluid. As the design progressed, and following successful laboratory testing, 'bubble plates' were incorporated in the floor of the lower reservoir using a pneumatic system to periodically pump air through the fluid and hence provide additional agitation.

Figure 14 Bubble plates in the lower reservoir



Finally, at the later stages of the project, with learnings from the initial fluid production and storage, a more significant fluid agitation system was implemented making use of some of the original circulation pipework and pump. The existing systems were adapted to implement these changes which meant some design compromises and varying levels of success, but the development of the system provided many valuable learning opportunities.

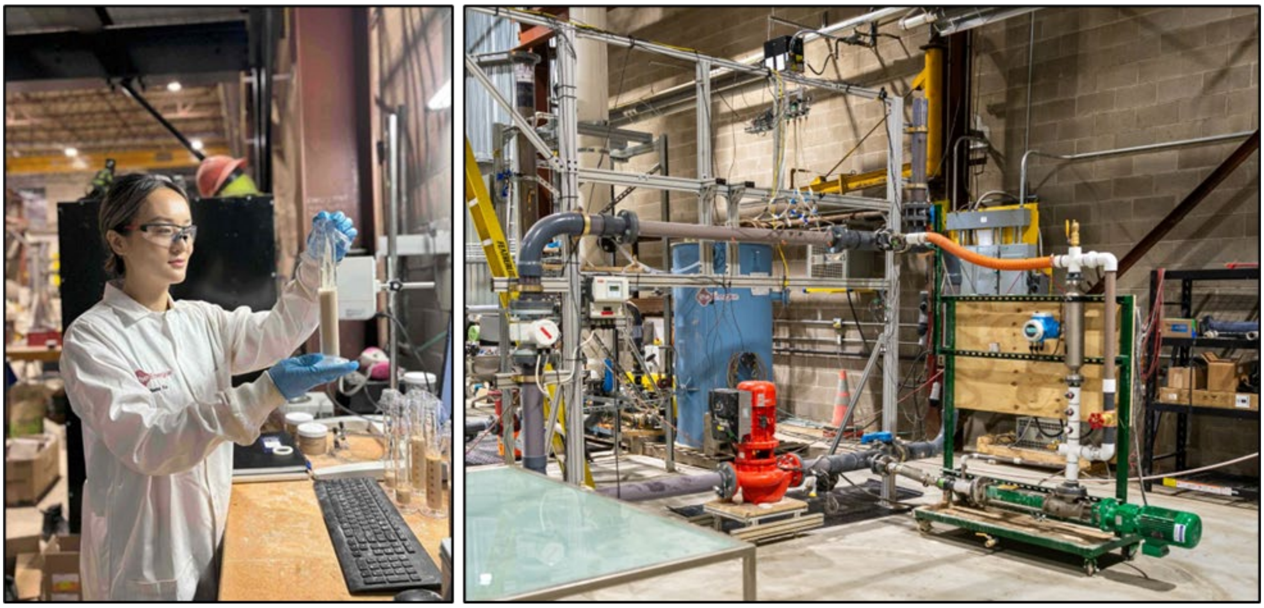
High Density Fluid Supply Chain

This work package was concerned with the production of HDF to provide first fill of the LoDES demonstrator reservoir. The first months were focused on finalising the formulation for the fluid and developing the concept design for the HDF production system.

Fluid Formulation

The team recognised early on that the pre-mixed off-the-shelf powder originally selected would not be suitable due to availability and cost of the volumes required to operate at scale. A second based formulation was investigated and worked through test rigs but was found to be unstable. The fluid formulation was finalised in Summer 2024.

Figure 15 Fluid chemistry & flow test loop



HDF Production Design

The HDF production system was divided into two sections – the HDF Engineering System and the Mud Mixing System (MMS). The first covering the production of the solid constituent at the required specification, the second comprising the material handling, wetting, mixing, conditioning, and transfer of the final on-spec fluid to the LoDES reservoir.

The initial concept design work and testing enabled the team to finalise design of the HDF Engineering System, working with the bulk material handling manufacturers and to place orders for long lead time equipment.

Having developed the concept design and settled on the final fluid formulation, it was recognised that the team would benefit from the input of additional expertise to develop the design of the Mud Mixing System and progress to procurement. A product design consultancy was engaged and helped move the design to a greater level of detail.

Having completed work on the mud mixing design attention turned to the control system. The proposals received for development and manufacturing of this system both from the original product design consultants and other parties significantly exceeded the budget and timescales allowed and hence RheEnergise decided to bring this work back in-house. This also giving the team the opportunity to use learnings from the initial development of the powerhouse Main Control System.

Fluid Production Location

During the process of design development, it became clear that the original existing building identified for the fluid production plant would not be the optimal solution. The size and condition of the building and logistics of transporting the fluid from its location to the lower reservoir made it less practical and economic in comparison to building a dedicated temporary building closer to the lower reservoir. The design was adapted to suit with fluid to be transferred to the lower reservoir via a dedicated pipe rather than moved around the site in tankers as originally envisaged. This change allowed direct control of the fluid movement and greater flexibility for co-ordination with production.

Construction, Installation and Commissioning

Civil Works

Following a tender process, the main construction contract was initially awarded to a local marine contractor. However, late in contract negotiations, they disclosed that existing commitments meant they could not meet the delivery schedule required for the NZIP programme. RheEnergise therefore had to engage another contractor who could deliver to the build schedule at very short notice. The civil works design consultant, made an introduction to a Scottish contractor with an extensive experience in the hydropower industry. Despite being based at some distance from site, this contractor was able to commit to the programme and mobilised to site in June 2024.

Concurrent with the final main contract negotiations, RheEnergise engaged a local subcontractor to clear the site and set up safety fencing in preparation for works to start. This subcontractor became a key member of the project team, continuing to work with RheEnergise right through to the final operation of the system.

The main construction works took six months to complete, largely in line with the contract schedule. This was in spite of supplier delays on the main pipework manifold at the entrance to the powerhouse which slowed progress in the completion of the concrete works.

Figure 16 High Level Civil Works Plan

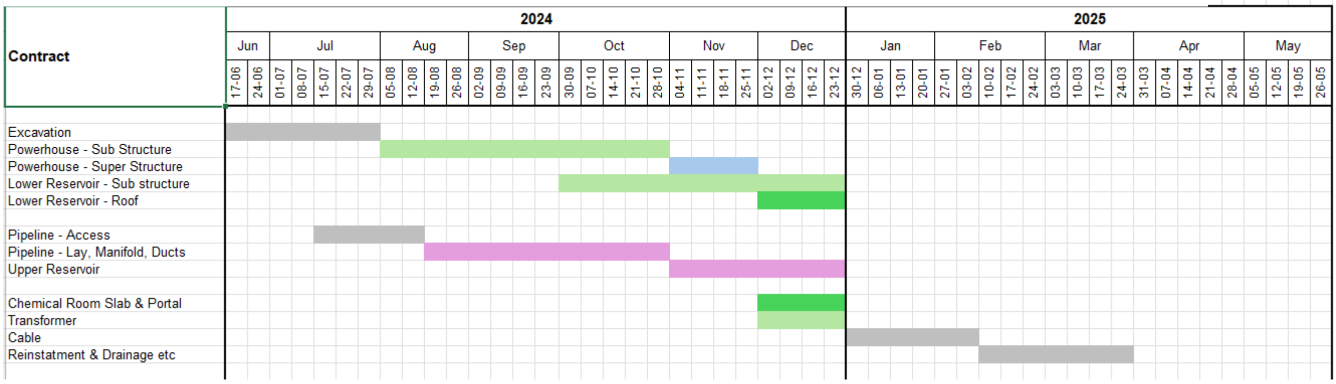


Figure 17 Upper reservoir construction

Figure 18 Lower reservoir and powerhouse construction

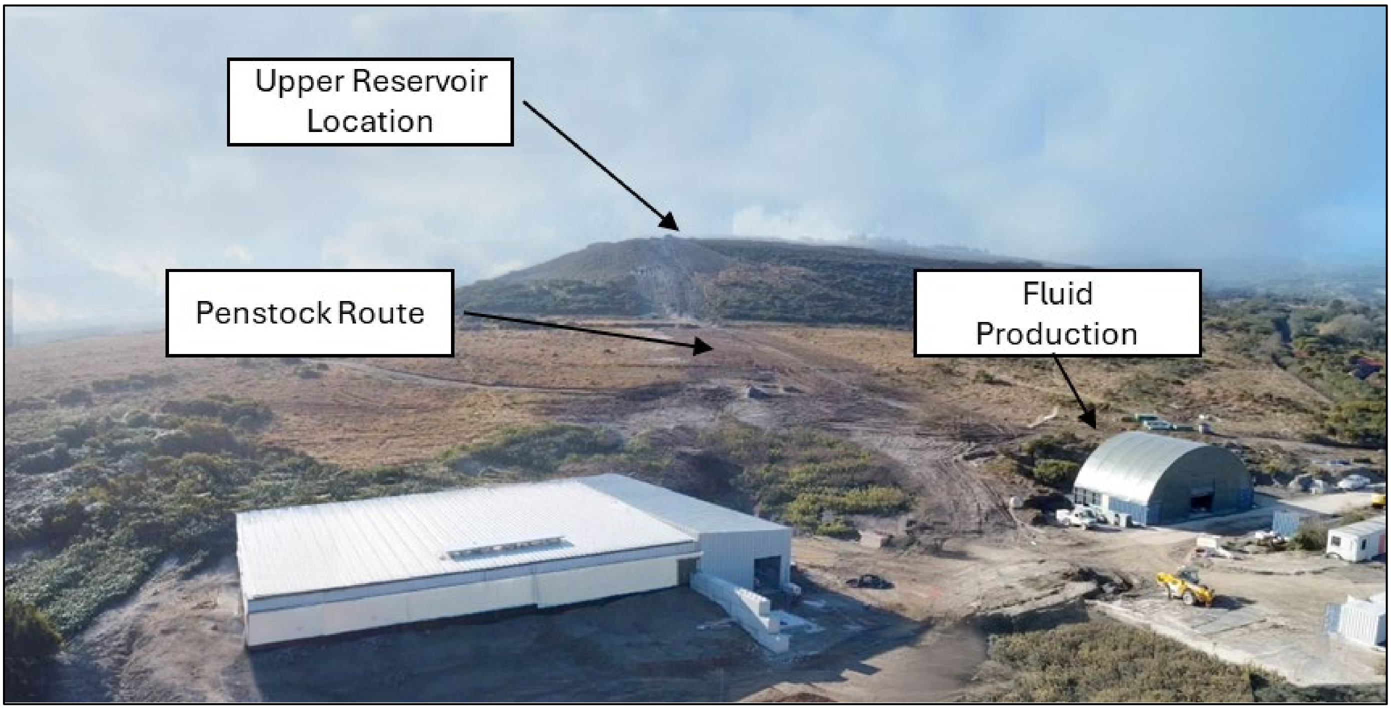
Generally, the civil works were of a good quality, but two major defects were missed during the routine site inspections by the Owner's Engineer, and having been identified at a later stage required swift rectification to avoid significant impacts on the programme.

Issues with a pipework joint in the upper reservoir: a full inspection of the upper reservoir GRP pipework was overlooked prior to the main contractor leaving site. Once completed, this revealed significant defects in a pipework joint. Repairs were made by specialist contractors nominated by the manufacturer. The root cause of the defect was identified as an installation error (insufficient tethering of the pipework during concrete pour) which may have been avoided with greater supervision by the client's engineer or the presence of a RheEnergise site engineer.

Incorrect pressure fittings in main penstock: having reviewed pressure testing results for the main penstock, it was identified by the RheEnergise team that pressure testing had been carried out at a value lower than expected. Having investigated this with the owner's engineer, it became clear that incorrect fittings had been installed in the lower half of the penstock (PN16 rated rather than PN25 as specified). Having explored different solutions, it was concluded that these fittings needed to be replaced and the penstock re-tested prior to full system operation. Discovering the issue at this point in the project meant returning the main contractor to site, uncovering the affected sections of buried pipework adding additional cost to the project. Fortunately, it was possible to carry out these works without a major impact on the overall programme.

In parallel with the main works, RheEnergise managed the construction of the temporary building to house the fluid production equipment. Having engaged D A MacDonald to provide the concrete foundations, the remaining construction was completed by end of December 2024.

Figure 19 Whole site layout



Powerhouse Fit Out

Fit out of the powerhouse began in early 2025 with the installation of stairs and walkways to enable safe access followed by the positioning of the main inlet valves and turbine.

Figure 20 Positioning of turbine and main inlet valve

Turbine and Pump Installation

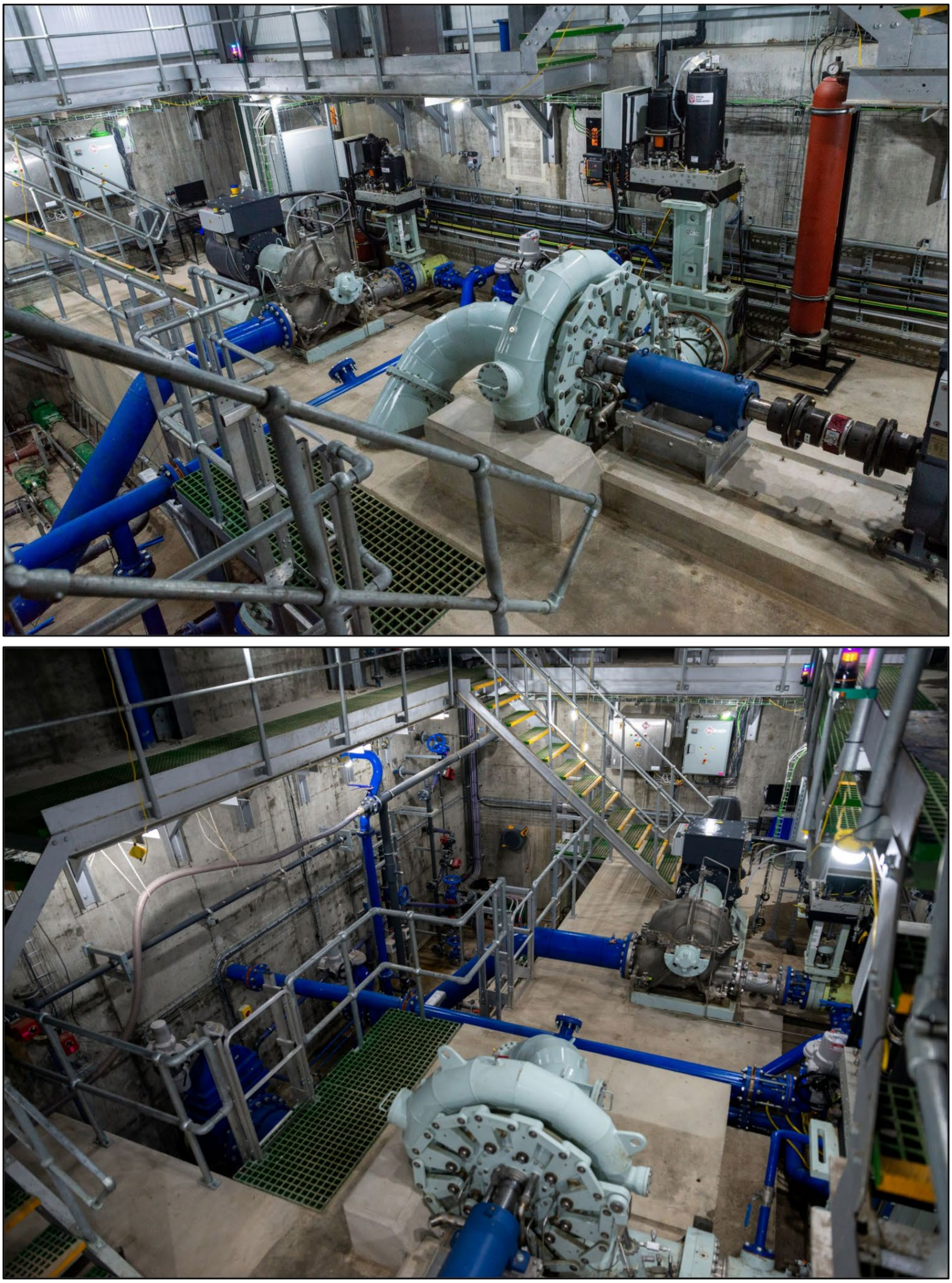
In February 2025 works began on the installation of the turbine and pump. A specialist contractor was brought in to complete the equipment installation. Substantial concrete works were required within the powerhouse to secure the equipment including some unforeseen alterations to the powerhouse floor. This led to the works being completed in two stages and being completed in April.

Mechanical and Low Voltage Electrical Works

RheEnergise directly contracted mechanical and electrical contractors (M&E) to deliver the equipment installation alongside their own in-house engineering team.

There were significant mechanical works to complete within the powerhouse with the installation of the Fluid Management System adding to the works undertaken in a standard pumped hydro scheme.

Figure 21 Powerhouse views of turbine pump and MIVs and towards FMS



High Voltage Works

Given the long lead times associated with high voltage (HV) equipment, RheEnergise engaged with an HV designer and contractor early in the project. Key items such as the transformer and ring main unit were delivered to the project in good time and construction works were completed in line with the overall programme. However, issues with establishing a sufficient site earth reading (influenced by local ground conditions) delayed the final high voltage connection by some weeks, with a corresponding delay to the low voltage commissioning in the powerhouse and in turn to the main power supply to the fluid production equipment.

Figure 22 Running the HV cable

Fluid Production System Fit Out, Testing and Commissioning

The large items of equipment were installed and connected in the Mud Mixing System (MMS) building in the first half of 2025. System integration and testing with the main control system took place in May followed by commissioning (both dry and with water) with fluid production beginning in early July.

One of the major uncertainties for the project was how the process of fluid production would progress when mixing greater volumes of high density fluid than had ever been previously produced. It was therefore not unexpected that issues would arise as the system came into operation.

Fluid Production Rate

Following the first weeks of operating the system, it became clear that although it was successful in producing a useable fluid, the production rate of the facility was not as predicted during the design phase.

Initial investigations suggested that there were multiple contributing factors and that some relatively quick improvements could be made to the system to try and alleviate the issues. As an initial step, the control system was upgraded, followed by the replacement of eductor components in the Mud Mixing system. Operation of the system was also refined, training up more operators to reduce reliance on RheEnergise's engineers and enabling the team to spend more time researching and making improvements to the system. However, without a more significant redesign it was unlikely that the original target mixing rate would be reached.

Figure 23 Fluid production equipment

Fluid Quality

Following the initial period of mixing, the first batch of fluid was transferred to the lower reservoir. Within a matter of days, signs of syneresis (separation) were observed in this fluid which suggested that there may be further issues with the fluid production.

Detailed sample testing and analysis in the Montreal facility showed that the properties of this first batch of fluid did not match the 'baseline design'. We discovered that the chemical properties of one of the additives did not match those in the version used for testing in spite of an understanding that an identical material had been ordered. Further enquiries revealed that this variation in the product was known to the manufacturer that but given that it does not impact common uses of the product, it had not been highlighted.

Change of Project Scope to Reach Minimum Viable Product

As the fluid production issues became clearer, it was recognised that given the constraints of the NZIP programme and the improvements that could be made in the short term, it would be very difficult to deliver the original volume of fluid proposed in the remaining time available.

Reducing the total volume of fluid from 1420m^3 to 540m^3 would reduce the total running time of the system to c. 15 minutes at full power, but it would still be possible to achieve a Minimum Viable Product (MVP).

Reaching the MVP would allow testing, full commissioning and operation of the integrated system. It would achieve TRL7 across the entire system, validating all control system features and functions, as well as sufficiently examining the actions of fluid. It would produce data such that the round trip efficiency of the system and levelised cost of storage for the system could be reliably forecasted.

Moving to MVP was a compromise to the original scope of the project but at this stage it was accepted that there was no other reasonable alternative.

Turbomachinery Commissioning

Commissioning of the system took place in three phases over approximately nine months with construction activities taking place in between.

Phase One - Dry Commissioning: verified the correct operation of individual components and subsystems, as well as their integration within the overall control architecture.

Phase Two – Water Commissioning: following experience in the fluid production and powerhouse clean-up required following a valve failure in the initial operation of the FMS with HDF, it was decided to include a stage of water commissioning ahead of introducing HDF into the system. This would also allow direct comparison of the turbine and pump performance with HDF versus water.

Phase Three – HDF Commissioning: carried out in December 2025, this confirmed stable and controlled operation of both pump and turbine with HDF across incremental operating points. Controlled shut down and safe response to a range of fault and emergency shutdowns was assessed and the process culminated in sustained operation at the design full power output of 500kW.

Performance Results

Following the latter two stages of commissioning, RheEnergise have been able to gather initial performance results from the turbine and pump allowing a comparison between operation with water and HDF. Most crucially the results could also be compared with the initial forecasts in order to validate the models used to predict the performance, vital when designing future projects.

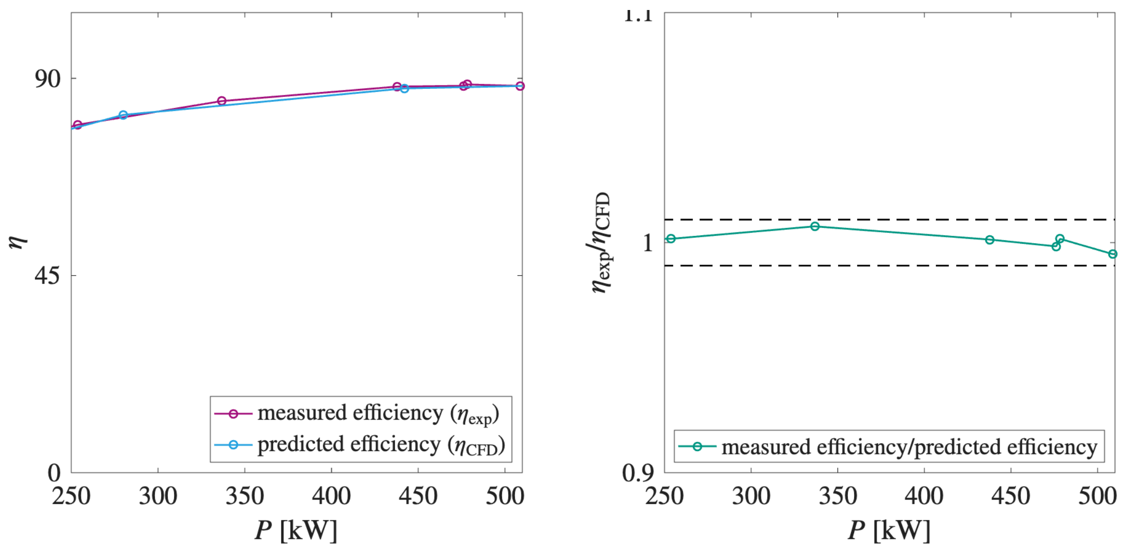
Turbomachinery Performance

The preliminary results from over 100 turbine-pump operations, have validated the turbine design and its operational compatibility with HDF. The system has been operated at full power over sustained periods and the turbine demonstrated excellent hydraulic performance, achieving a peak efficiency of 89.6% with water and 84.8% with HDF and a notably flat efficiency profile over a wide range of operating conditions. Allowing for system losses, this gives confidence that the target system efficiency for commercial projects is achievable once system designs have been further optimised.

Whilst there is a decrease in efficiency when operating with HDF, this can be explained as a combined effect of scale (Reynolds number) effects and the viscous dominance inherent in small-scale testing. In layman's terms, fluids flow more smoothly through larger machines. It is expected that as the small-scale demonstrator turbine is transitioned to a commercial-scale prototype (i.e. at 5MW), the efficiency with HDF is expected to approach the efficiency of water.

Figure 24 Hydraulic efficiency (%) vs power (kW) & measured vs predicted efficiency shows a comparison between the efficiency measured on site and the predicted results from CFD. Excellent agreement can be seen between the two, within c.1%

Figure 24 Turbine hydraulic efficiency (%) vs power (kW) & measured vs predicted efficiency



Crucially, after accounting for seal losses, the measured turbine runner efficiency showed excellent agreement with numerical data obtained through CFD, validating RheEnergise's in-house modelling capabilities.

Demonstrator Round Trip Efficiency

Table 2 gives a breakdown of the efficiency of different parts of the demonstrator system, showing a close agreement with the values provided by the computational modelling and measurements taken on site.

Table 2 Comparison of model and measured efficiency for the LoDES demonstrator

System Component	Model Efficiency	Measured Efficiency
Total Pumping	**70%**	**73%**
Pump Penstock	98%	98%
Pump Hydraulic	76%	78%
Pump Motor	97%	98%
Pump Variable Frequency Drive (VFD)	97%	98%
Turbine Overall	**79%**	**80%**
Turbine Penstock	98%	98%
Turbine Hydraulic (incl. seal losses)	86%	85%
Turbine Motor	97%	98%
Turbine VFD	97%	98%
RTE (excl. parasitic losses)	**56%**	**59%**

The figures given for RTE do not include parasitic losses. Measurement of parasitic losses is planned as part of further site testing but during modelling were estimated at 1.18% averaged over a year.

As previously mentioned, there are multiple areas for design optimisation but these results provide the RheEnergise team with confidence that our target round trip efficiency (RTE) of 80% for larger commercial projects is highly achievable.

From these results RheEnergise have been able to confidently conclude that at industrial scales, HDF will achieve efficiencies comparable to water, validating its viability as a medium for long-duration energy storage.

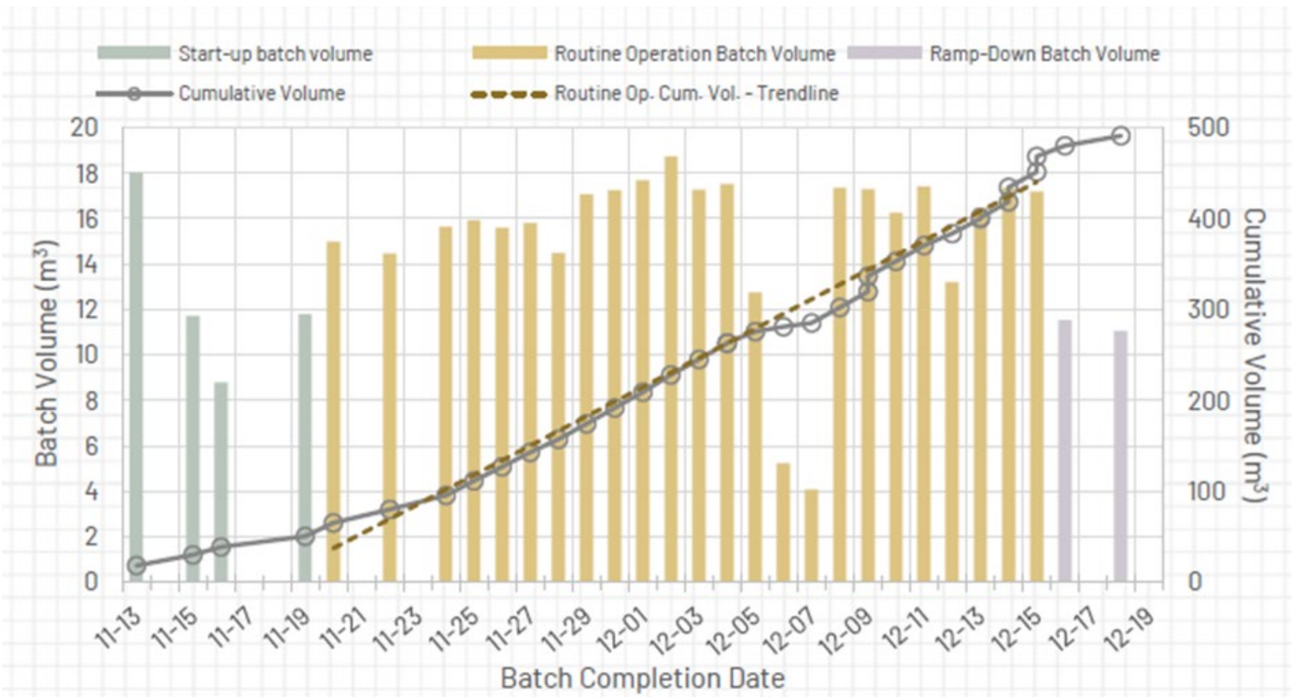
High Density Fluid Performance

Alongside the performance of the turbomachinery, the demonstrator project has provided vital experience and data for both the production and stability of the high density fluid formulation.

Fluid Production

The demonstrator project achieved the largest scale fluid production by the company to date. Following issues with the initial production, the team required three months to make improvements to the fluid formulation and troubleshoot equipment and system operation prior to restarting. Once production was running the team were able to mix 465m3 of HDF within the acceptable range of specific gravity, In just over five weeks, which successfully enabled full system testing.

Figure 25 Batch volumes and cumulative fluid output over the production period



The overall production rate was 1.09 m3/h. However, optimisations and operator experience resulted in an increase to 1.43m3/h in the latter stages. This represents 32% of the nominal rate from the design. Figure 25 shows the batch volumes during the production period.

The primary bottleneck was material handling, predominantly a slow barite powder feed, suspected to be due to moisture penetrating the bulk bags. It is also felt that assumptions made regarding batch sequence timing were optimistic. Many lessons have been learned which will inform the design of future commercial-scale systems.

Fluid Stability

Vitally important to the success of future projects is an understanding of the characteristics of the HDF and its stability during the long-term operation of the plant and an ability to test modifications of the original fluid management system. The demonstrator provides an invaluable facility for this. An initial period of testing during a period of FMS shutdown following the first system operation has already provided valuable data. It has indicated that although there was a reduction in in fluid density, the fluid has remained sufficiently stable such that it can be returned to a homogenised state. Building on this learning is an important next step for the team.

Budget

The original funding award was £8.2m. Managing budget overruns has been a significant challenge for the project for many reasons. Even with some additional funding awarded, the total funding fell short of the final total project spend which reached £10.2m versus a funding award of £9.8m.

There are several main reasons for changes to the original project budget.

- **Inflation**: this was identified as a potential project risk from the first monthly progress report and has continued to impact on budgets that were originally forecast in early 2022. Due to the delay in construction start, actual costs received from contractors have continued to exceed the original (and adjusted) forecasts.
- **R & D Cost Estimation-Related Factors**: the inherent complexity of R&D projects and the unknown unknowns that come with them make accurate cost estimations a challenge. While the original timelines and budget estimates for this project were based on information available to us at the time, as the project has progressed, we had to readjust some of these estimates (in some cases, multiple times) as our knowledge of this first-of-its-kind-globally energy storage prototype has expanded.
- **Extended Construction Programme**: the construction programme had been compressed from the original forecast of 16 months to 11 months to meet the original requirements of the funding programme. However, in December 2023, it became clear that it would be necessary to extend the programme to reach an expected completion date of end of May 2025 and then further to November 2025. Inherent to the extensions of the programme were further costs, to maintain the safe construction site, for project management and oversight and continued engineering efforts from the RheEnergise team.
- **New/Additional Scope**: due to the evolving project design, some items included in the revised project estimates were not originally budgeted (e.g. the inclusion of ‘bubble plates’ in the fluid management system, the provision of a building for the fluid processing (MMS) equipment and additional retaining walls).
- **Change to MVP** - In October 2025, due to the NZIP programme nearing closure, a change request was made to alter the scope of the project and reduce the volume of HDF to be manufactured to a volume sufficient to reach the Minimum Viable Product (MVP) with an intention to produce the remainder of the fluid later in 2026 when further refinement of the system will be complete. (More details in the section below). Consequently, there was a reduction in funding by £64.5k to reflect the lower volume of fluid being produced prior to project closure bringing the final funding to £9,806,109.

Project Successes

Moving to near-commercial scale

RheEnergise consider the scaling from laboratory to an operating near-commercial-scale system in an operational environment on these timescales as being highly successful. Given the complex nature of the technology being developed, the huge number of unknowns and major hurdles that the project had to overcome, it could not be viewed as anything other than a huge achievement.

Excellent turbine performance results

Achieving positive performance test results for the turbine and validating our internal modelling provides the confidence to develop our design as the technology scales further.

Developing a unique testing facility

RheEnergise now has a unique space in which to test and further develop HD Hydro. The demonstrator is key to proving to investors and others that the technology has progressed to TRL 6/7.[5] It has led directly to RheEnergise's securing Euro 2.5m European Innovation Council funding to develop technology further and is opening up conversations relating to other funding.

Intellectual Property

The project has delivered opportunities to register and protect intellectual property which strengthens our long-term strategic position. To date, 17 patent applications have been made with 3 granted and the team continue to explore further application opportunities.

Manufacturer Partnerships

Working closely with manufacturers as the team developed designs has had significant benefits. Unsurprisingly, the best engagement has come from those who have appreciated the potential to work with RheEnergise on future projects.

Team Development

The RheEnergise team have benefited enormously from the project and the opportunities that it has presented for both professional and personal development.

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[5] Using the European Commission definitions of TRLs for Industrial Processes where:
TRL6: Development of a pilot-scale testing plant or unit (1/100th of commercial scale)including engineering-scale equivalents of all the operations that will be required at scale. (The demonstrator is 1/10th the scale of a commercial project)
TRL7: Successful demonstration of the continuous operation of the pilot plant/unit during a relevant timeframe.

Lessons Learnt

There are numerous detailed technical improvements to be made across all areas that are too numerous to present here however some main themes and project delivery lessons are detailed below.

Approach to Construction Contracting

Incorporating everything into one main construction contract, although likely to be more expensive, could have reduced risk, time and issues for RheEnergise with co-ordinating works. However, it did have advantages given the research-based nature of the project. In areas where designs were not entirely developed, the team could remain closer to subcontractors and could ensure that changes were made in line with our requirements and with tighter control on costs.

Quality of design engineering services

RheEnergise chose a designer and owner's engineer with experience mainly in smaller scale conventional hydropower sites, which had a material impact on the project. Although this selection may have seemed aligned with the scale of the demonstrator, RheEnergise later felt that the project needed broader, deeper, and more specialist support.

The need for more in-house engineering and site engineering resource

RheEnergise worked extensively with consultants to support development of our detailed designs. Whilst this approach was very successful in some areas, such as the turbomachinery, in others, most particularly the main construction works it is felt that this could have been a more effective approach if RheEnergise had employed an in-house site engineer to interrogate design and construction work further. This may have avoided issues with over-specification, design coordination and the late detection of some major construction defects.

Sequencing of Works

Following the delays due to the change of site and need for major design changes, there was significant pressure on the project team to show progress in the construction. This led to some aspects of construction commencing when key aspects of design were being finalised. This created a complex array of overlapping work, and occasional confusion about engineering priorities. While some phasing (e.g. civil works moving to powerhouse works) or separation of clear project areas (e.g. MMS building vs. powerhouse) is reasonable, typical practice would be to complete and approve the design of each section of the project before commencing construction. While this may have delayed the start of some aspects of construction, a more streamlined/linear approach may have saved time overall.

Similarly, there was further overlap in the construction and commissioning stages of the works which would ideally be avoided in future projects.

Procurement Co-ordination and Insistence on Factory Test Reports

In some instances, sub-systems were separated into different procurement packages which were not well co-ordinated off site ahead of final installation. Spending more time integrating sub systems off site, rather than rushing to deliver equipment, is likely to have saved time overall.

Although Factory Acceptance Tests were carried out for major items of equipment, errors in more minor components also caused significant costs and delays at times. Manufacturing errors could have been detected earlier with a strict requirement for factory test reports and review prior to approving a component for shipping.

Design of Powerhouse Control Systems

Control systems for the sub systems within the powerhouse were either procured from separate vendors (valve actuators, TRS system) or developed in house by RheEnergise (Main Control System, FMS Control System). This has created interface and communications challenges. A common vendor and further sub-system control integration should be considered for future commercial-scale projects to simplify co-ordination and provide standardisation.

Fluid Management and Fluid Production – the need for more extensive pilot-testing

It is felt that further pilot-scale testing off site of sub-systems (particularly those designed in the latter stages of the project) would have been very beneficial. Under pressure to deliver on site, lessons were learnt at large scale with larger consequential costs in time and budget and this could have been alleviated.

Fluid Mixing System– dry material storage

Although efforts were made to store materials in the dry, the impact of moisture on the mixing process had been underestimated. Although it was possible to process the damp feedstock, it took about three times as long to mix. Storage conditions are a key consideration for future projects.

Fluid Mixing System – operational experience

The nature of the project precluded a fully automated MMS. However, the trade-off was heavy reliance on expert operation during HDF production. This allowed the team to build up a huge bank of experience but the HDF production process at scale will require a much higher level of automation. There were invaluable learnings regarding the robust processes for quality assurance that will be needed, and insights into recovery from process upsets.

Fluid Stability – poor mixing is worse than no mixing

Experience with HDF at this scale taught RheEnergise that poor/inadequate mixing is worse for fluid health than no mixing, as it breaks the gel structure on which stability depends. This will be a key consideration in the further development of reservoir designs, the fluid production and fluid management system designs.

Reflections on the NZIP funding scheme

The LoDES funding and framework of deliverables has been invaluable to the project, without it, the demonstrator is likely to have taken much longer to be constructed, if it got constructed at all. However, the funding time constraints both in absolute timing and specific deadlines at financial year ends, have presented significant challenges to the successful delivery of the project.

Future Plans

In the immediate future RheEnergise plan to use the demonstrator plant to further refine the design and operation of the system. We will be building up operational hours to provide further proof of the system's ability to sustain operation and perform in an industrial environment.

We will collaborate with the site owners to combine the operation of the plant with the on-site CHP and planned solar PV plants, demonstrating the potential for behind-the-meter energy supply flexibility and reliability.

We were recently awarded a European Innovation Council grant to take the lessons learnt from the demonstrator and develop the design for a 5MW, commercial scale, turbine.

Following this work we aim to deliver a 10MW, 6+ hour **First-of-a-Kind project** to scale from demonstrator to full deployment. To finance this development, we are actively pursuing further crowd funding in the short term and series A investment within the next six months.

In the longer term RheEnergise's commercialisation strategy targets global markets, starting with mines and quarries, data centres, and regions with high renewable penetration or grid constraints.

RheEnergise plan to operate as a service provider to future projects, offering consultancy, supply chain facilitation, and O&M services with recurring royalties.

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