CONNECTED PLACES CATAPULT (CPC)
HYDROGEN INNOVATION INITIATIVE (HII)
DEMONSTRATION 2025–2026

LIQUID HYDROGEN STORAGE, DISTRIBUTION, AND UTILISATION DEMONSTRATION: FINAL REPORT

08 April 2026

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Unitrove Innovation Limited – 7 Smithy Way, Shepshed
Loughborough, Leicestershire LE12 9TQ. United Kingdom
www.unitrove.com

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1 Executive Summary

1.1 Overview of the Demonstration

This project, delivered under the Connected Places Catapult (CPC) Hydrogen Innovation Initiative (HII) 2025–2026 programme, aimed to demonstrate an integrated liquid hydrogen (LH_2) value chain encompassing storage, distribution, and end-use applications.

The demonstration was led by Unitrove, with GeoPura and Steamology as project partners. The core objective was to validate the operational feasibility, safety, and performance of a modular LH_2 system using a 20-ft intermodal storage container, supplying hydrogen to downstream applications including electricity generation and turbine-based mechanical power systems.

The demonstration concept consisted of three interconnected elements:

- **Liquid hydrogen storage and vaporisation (Unitrove):** Deployment and commissioning of a 20-ft LH_2 intermodal tank with onboard vaporisation capability
- **Hydrogen-to-electrical-power conversion system (GeoPura):** Operation of a hydrogen power unit (HPU) using vaporised LH_2 to generate zero-emission electricity
- **Hydrogen-to-mechanical power conversion system (Steamology):** Development and testing of a hydrogen/oxygen-fuelled steam turbine system, including innovative vaporisation and energy recovery concepts

The project achieved substantial progress against its objectives, particularly in system development and preparation activities. However, the full integrated demonstration was not completed within the project timeline due to interdependencies across system elements, which extended the delivery programme beyond the end-of-March budget cycle. The integrated demonstration remains planned for future work.

Unitrove successfully completed the fabrication and assembly of the LH_2 storage skid in line with the planned scope. Commissioning of the LH_2 tank and associated filling operations could not be completed within the project timeframe due to programme timing and system interdependencies. As commissioning is a prerequisite for downstream operations, subsequent demonstration activities involving GeoPura's HPU were not executed within the project period. Nevertheless, the work completed provides a robust foundation and a clear pathway for completion in subsequent phases.

In contrast, Steamology successfully delivered its full defined scope of work, producing comprehensive technical outputs including vaporisation system concepts, system modelling, and turbine test preparation. These outputs establish a strong foundation for future system integration and demonstration activities.

1.2 Key Findings and Outcomes

Despite the partial completion of the physical demonstration, the project generated several important technical and operational insights.

- **System Development Progress**
  - Unitrove successfully designed and constructed a modular LH_2 storage skid, demonstrating readiness for deployment and integration
  - The project confirmed the feasibility of modular, transportable LH_2 infrastructure for distributed energy applications

- **Steamology Technical Deliverables (Completed Scope)**
  - Development of multiple LH_2 vaporisation system concepts (SVS1, SVS2, SVS3)
  - Identification of opportunities to utilise waste heat from turbine systems for hydrogen vaporisation
  - Energy modelling indicating potential efficiency gains, including estimated auxiliary energy savings through alternative pressurisation strategies
  - Preparation and partial commissioning of turbine testing systems

These outputs represent a significant contribution to understanding integrated hydrogen energy systems, particularly where thermal energy recovery can enhance system efficiency.

- **Integration and Execution Challenges**
  - Commissioning of cryogenic LH_2 systems was identified as a critical path activity with significant schedule sensitivity
  - The inability to complete LH_2 tank commissioning prevented validation of:
    - Storage performance (e.g., boil-off rate, holding time)
    - End-use system operation (GeoPura HPU)
  - The project highlighted the complexity of coordinating multi-partner demonstrations with interdependent system components

- **Data and Validation Limitations**
  - No operational LH_2 data was collected due to incomplete commissioning
  - System-level validation remains to be demonstrated in a future deployment

1.3 Relevance to the Hydrogen Industry or Subsector

This project is highly relevant to the advancement of the liquid hydrogen sector, particularly in the context of emerging hydrogen infrastructure and applications in the UK and globally.

- **Advancing Liquid Hydrogen Deployment**

  The project reinforces the strategic importance of LH_2 as a high-density energy carrier, especially for:

  - Heavy-duty transport
  - Remote and off-grid power generation
  - Industrial energy applications

  The modular 20-ft intermodal container approach demonstrated by Unitrove supports scalable and flexible hydrogen distribution models, which are critical for early-stage market adoption.

- **System Integration Insights**

  A key contribution of this project is the insight into the challenges of integrating:

  - Cryogenic storage systems
  - Vaporisation technologies
  - End-use applications (power and mechanical systems)

  These learnings are directly applicable to future LH_2 projects and highlight the need for staged validation and robust commissioning strategies.

- **Innovation in Energy Efficiency**

  Steamology's work demonstrates the potential to significantly improve system efficiency through:

  - Integration of waste heat recovery
  - Alternative vaporisation and pressurisation approaches
  - Coupling of thermal and mechanical energy systems

  This has important implications for reducing operational energy demand and improving overall system economics.

- **Implications for Commercialisation**

  Although the full demonstration was not completed in the timeframe, the project provides:

  - A strong technical foundation for future demonstrations
  - Evidence of subsystem readiness
  - Clear identification of risks and mitigation strategies for deployment

  These outcomes contribute to de-risking future LH_2 projects and accelerating progress toward commercial-scale implementation.

2 INTRODUCTION

2.1 PURPOSE OF THE REPORT

This report presents the outcomes, progress, and key learnings from the Connected Places Catapult (CPC) Hydrogen Innovation Initiative (HII) Demonstration Project 2025–2026, focused on liquid hydrogen (LH_2) storage, distribution, and utilisation.

The purpose of this document is to:

- Provide a transparent account of the demonstration activities undertaken by the Unitrove-led consortium, including contributions from GeoPura and Steamology
- Summarise technical progress, including completed and partially completed elements of the project
- Highlight key findings, challenges, and lessons learned from the development and attempted deployment of an integrated LH_2 system
- Share insights that can inform future hydrogen demonstration projects, infrastructure development, and system integration strategies

As this report is intended for public dissemination, it aims not only to document project outcomes but also to contribute to the broader hydrogen community by sharing practical experience and technical understanding gained during the project.

2.2 Brief Background on the Technology

Liquid hydrogen (LH_2) is increasingly recognised as a critical energy vector for enabling large-scale decarbonisation, particularly in sectors where high energy density and long-duration energy storage are required.

Compared to compressed gaseous hydrogen (CGH_2), LH_2 offers several key advantages:

- **Higher energy density:** Liquid hydrogen provides significantly greater energy per unit volume, making it suitable for heavy transport, marine applications, and space-constrained environments
- **Improved transport efficiency:** LH_2 enables bulk transport over longer distances, supporting the development of regional and international hydrogen supply chains
- **High purity:** The liquefaction process removes impurities, making LH_2 suitable for sensitive applications such as fuel cells and industrial processes

However, LH_2 systems also introduce technical challenges, including:

- Cryogenic storage requirements at extremely low temperatures (approximately –253°C)
- Boil-off losses and pressure management within storage systems
- Complexities associated with vaporisation and integration with end-use technologies

This demonstration project was designed to address these challenges by exploring a **modular, integrated LH_2 solution**, combining storage, vaporisation, and utilisation within a single operational framework.

The project brings together complementary technologies across the hydrogen value chain:

- **Unitrove:** Modular LH_2 storage and distribution using a 20-ft intermodal container
- **GeoPura:** Hydrogen power units (HPUs) for converting hydrogen into electricity
- **Steamology:** Hydrogen-based turbine systems, including innovative approaches to vaporisation and energy recovery

Together, these technologies represent a potential pathway toward scalable, flexible, and efficient hydrogen infrastructure.

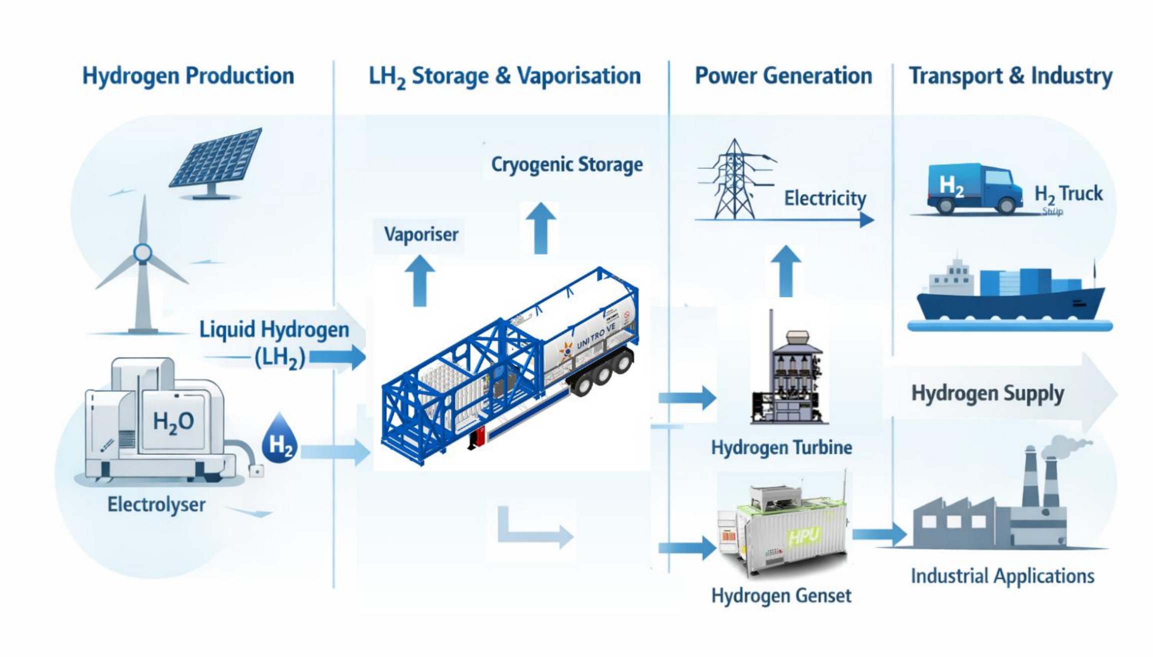


Figure 1 – Overview of hydrogen energy systems including storage, vaporisation, and end-use applications.

2.3 Objectives of the Demonstration

The primary objective of the project was to demonstrate the technical feasibility and operational performance of an integrated liquid hydrogen system, covering key stages of the hydrogen value chain from storage to end-use.

Core Objectives

- **Demonstrate Liquid Hydrogen Storage**
  - Deploy and commission a 20-ft LH_2 intermodal storage container
  - Validate storage performance, including holding time, pressure behaviour, and operational safety

- **Validate Hydrogen Vaporisation and Supply**
  - Convert LH_2 into gaseous hydrogen using onboard and integrated vaporisation systems
  - Ensure compatibility with downstream applications

- **Demonstrate End-Use Applications**
  - Supply vaporised hydrogen to a GeoPura hydrogen power unit (HPU) for electricity generation
  - Support Steamology's turbine system development for mechanical power applications

- **Evaluate System Integration**
  - Demonstrate interoperability between storage, vaporisation, and end-use systems
  - Identify challenges associated with multi-system integration and operation

- **Generate Operational and Technical Data**
  - Collect data on system performance, efficiency, and safety
  - Support future design improvements and technology development

Secondary Objectives

- Advance the technology readiness level (TRL) of LH_2 storage and utilisation systems
- Demonstrate the potential for modular, transportable hydrogen infrastructure
- Explore innovative approaches to improving system efficiency, including waste heat utilisation
- Provide insights to support future commercial deployment of LH_2 systems

3 Project Description

3.1 Description of the Hydrogen Technology Being Demonstrated and the Preceding Development

The project was designed to demonstrate an integrated liquid hydrogen (LH_2) system, combining storage, vaporisation, and end-use applications within a modular and transportable framework. The core technology centred around the deployment of a **20-ft intermodal LH_2 storage unit**, enabling flexible and scalable hydrogen distribution.

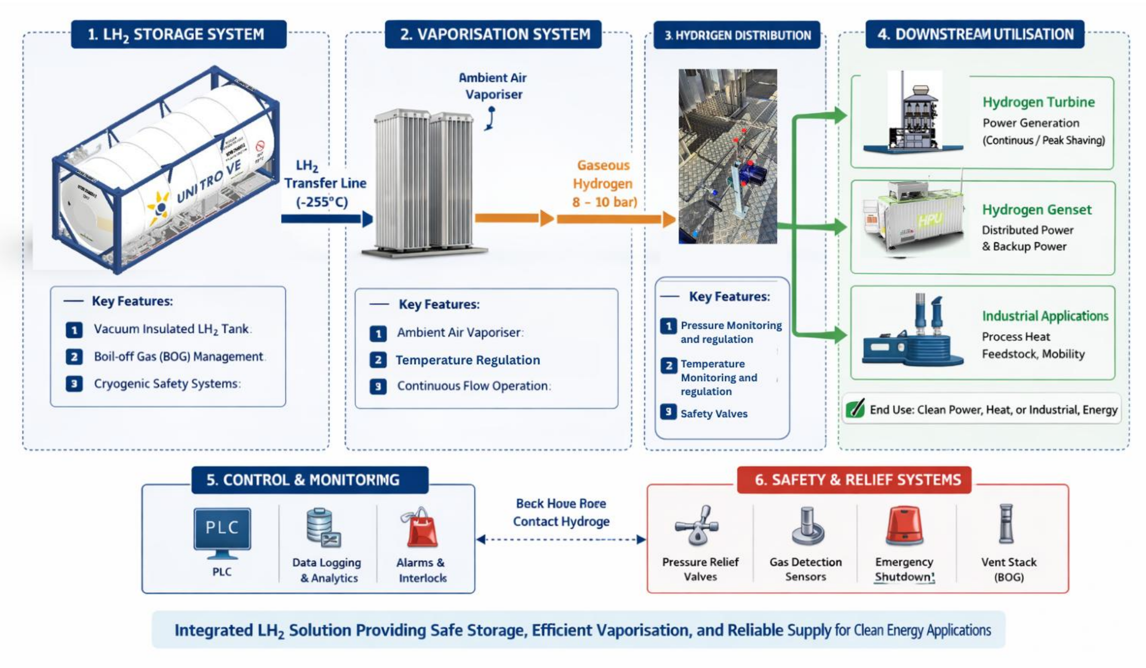


Figure 2 – Integrated system architecture showing LH_2 storage, vaporisation, and downstream utilisation.

3.1.1 Liquid Hydrogen Storage and Distribution (Unitrove)

At the core of the demonstration was Unitrove's liquid hydrogen (LH_2) storage and distribution system, designed as a fully integrated, containerised solution. The system consists of a cryogenic storage tank housed within a standard 20-ft skid, enabling the storage of hydrogen in liquid form at extremely low temperatures (approximately –253 °C). Storing hydrogen in liquid form significantly increases its energy density compared to compressed gas, making it more suitable for applications where space, transport efficiency, and energy capacity are critical.

A key function of the system is to maintain stable storage conditions while minimising hydrogen losses. This is achieved through advanced vacuum insulation and tank design, which reduce heat ingress and limit boil-off. Maintaining pressure within safe and operational limits is essential for both system integrity and efficient downstream utilisation. The ability to control these parameters is particularly important in real-world deployments, where storage duration and operational flexibility directly impact system performance and economics.

The system is also designed to enable controlled withdrawal of liquid hydrogen and its subsequent conversion into gaseous hydrogen for downstream applications. This ensures a consistent and reliable hydrogen supply that can be matched to the requirements of end-use systems such as power generation or industrial processes. The integration of storage and controlled distribution within a single skid simplifies system architecture and reduces the need for complex on-site infrastructure.

A defining feature of the Unitrove solution is its containerised, modular design. By integrating all key components within a compact footprint, the system can be rapidly deployed across a range of sites without extensive civil works. This approach also allows compatibility with existing transport and logistics networks, enabling easier handling and relocation. Furthermore, the modular architecture supports scalability, where multiple units can be deployed in parallel to increase storage and supply capacity in line with demand. This flexibility is particularly valuable for early-stage hydrogen adoption, where requirements may evolve over time.

Preceding Development

Prior to the demonstration phase, Unitrove had progressed the system through key stages of development, including conceptual design, engineering validation, and detailed system integration. Critical cryogenic components were procured, and the LH_2 storage skid was successfully fabricated and assembled. These activities ensured that the system reached a high level of technical readiness, positioning it for commissioning and operational validation during the demonstration phase. Representing a significant step toward operational deployment. However, final commissioning of the LH_2 tank, including filling and operational validation, remained outstanding at the end of the project timeline.

3.1.2 Hydrogen Vaporisation and Energy Integration (Steamology)

Steamology's core technology is based on the controlled reaction of hydrogen with oxygen to generate high-temperature steam, which is then used to drive a turbine for mechanical and electrical power generation. Unlike conventional combustion systems that rely on air, this approach uses a controlled supply of both hydrogen and oxygen, enabling a cleaner and more efficient energy conversion process with water as the primary by-product. This method allows for precise control of reaction conditions and can deliver high-quality steam suitable for efficient turbine operation.

Within this context, hydrogen must be supplied in gaseous form at controlled pressure and temperature conditions to ensure consistent reaction behaviour and reliable system performance. As hydrogen is stored in liquid form at cryogenic temperatures, the vaporisation stage becomes a critical enabling step in the overall system. The effectiveness of vaporisation directly influences hydrogen flow stability, which in turn impacts steam generation, turbine efficiency, and operational responsiveness. This makes the design and optimisation of vaporisation systems a key focus of the demonstration.

A central aspect of Steamology's work in this project was the development and evaluation of multiple hydrogen vaporisation system configurations, referred to as SVS1, SVS2, and SVS3. These configurations were designed to explore different approaches to converting liquid hydrogen into gaseous form under varying operating conditions and integration strategies. The configurations included ambient air-based vaporisation, steam-assisted vaporisation, and hybrid approaches that combine multiple heat sources.

The use of multiple configurations was intended to assess the trade-offs between system simplicity, efficiency, and operational flexibility. Ambient air vaporisation offers a relatively simple and low-cost solution with minimal integration requirements, but its performance can be influenced by environmental conditions and may limit responsiveness under varying demand. Steam-assisted vaporisation, on the other hand, provides a more controlled and consistent heat source, improving hydrogen flow stability and enabling better integration with the downstream steam cycle, but at the cost of increased system complexity. Hybrid configurations aim to combine the advantages of both approaches, offering improved reliability and adaptability across a wider range of operating scenarios.

These vaporisation systems were designed to integrate directly with Steamology's hydrogen–oxygen reaction process, ensuring that hydrogen is delivered at the required pressure range (typically 8–10 bar) and suitable thermal conditions for efficient steam generation. The integration between vaporisation and energy conversion is critical, as fluctuations in hydrogen supply can directly affect combustion stability and turbine performance. As such, the project focused on understanding how different vaporisation strategies influence overall system behaviour and identifying the most suitable configurations for scalable deployment.

Preceding Development

Steamology's work in this project builds upon prior development in hydrogen-based energy systems, including hydrogen-fuelled turbine concepts, controlled oxygen–hydrogen reaction processes, and thermal integration methodologies for efficient energy recovery. Previous work has demonstrated the feasibility of generating high-temperature steam from hydrogen and oxygen reactions, as well as the importance of precise control over reactant supply and thermal conditions. The current project extends this foundation by focusing specifically on the integration of liquid hydrogen storage with vaporisation and downstream energy conversion, addressing practical challenges associated with system coupling, operational stability, and deployment readiness.

Project Activities and Development Approach

Within the project, Steamology undertook a structured programme of design, modelling, and system integration activities aimed at advancing the readiness of the technology. This included the development of detailed system models to simulate hydrogen flow, vaporisation performance, and steam generation under different operating conditions. Based on these models, multiple vaporisation configurations were designed and assessed to understand their impact on system efficiency and controllability.

In parallel, engineering work was carried out to define system layouts, integration interfaces, and operating parameters for coupling the vaporisation systems with the hydrogen–oxygen reaction and turbine components. Steamology also progressed the preparation of turbine testing infrastructure, including partial commissioning activities, to enable future validation of the integrated system. These efforts were aimed at de-risking the technology by identifying optimal system configurations and ensuring that key components could be effectively integrated into a coherent and scalable energy solution.

3.1.3 Hydrogen-to-Power Conversion (GeoPura)

GeoPura's role in the project was to demonstrate the use of hydrogen for zero-emission electricity generation through its Hydrogen Power Unit (HPU).
The HPU is designed to:

- Convert hydrogen into electricity using fuel cell technology
- Provide reliable, off-grid or grid-support power
- Replace diesel generators in temporary and remote applications

Preceding Development:

GeoPura has previously deployed HPUs in commercial and pilot applications, demonstrating:

- Operational reliability
- Scalability of hydrogen-based power systems

In this project, the HPU was intended to operate using vaporised LH_2 supplied by the Unitrove system, completing the end-to-end demonstration of the hydrogen value chain. However, due to the lack of LH_2 system commissioning, this integration and demonstration could not be executed.

3.1.4 Integrated System Concept

The overall system architecture was designed as a fully integrated hydrogen value chain, bringing together hydrogen storage, conditioning, and end-use applications into a single, coordinated system. The objective of this integrated approach was to demonstrate how liquid hydrogen can be stored, processed, and utilised efficiently across multiple applications within a real-world deployment scenario.

At the upstream stage, liquid hydrogen is stored within Unitrove's cryogenic storage system, where it is maintained at extremely low temperatures in a compact, containerised format. From this storage system, hydrogen is withdrawn and converted into gaseous form through the vaporisation process, ensuring that it is delivered at the required pressure (typically 8–10 bar) and suitable temperature for downstream use. This intermediate stage acts as a critical link between storage and utilisation, as it determines the stability and quality of hydrogen supplied to end-use systems.

The conditioned hydrogen is then distributed to two primary end-use pathways within the demonstration. The first pathway involves power generation using GeoPura's Hydrogen Power Unit (HPU), which converts hydrogen into electricity to support off-grid or low-emission energy applications. The second pathway involves Steamology's turbine-based system, where hydrogen reacts with oxygen to generate high-temperature steam for mechanical or electrical power generation. These parallel use cases were selected to demonstrate the versatility of hydrogen as an energy carrier across different technologies and operational requirements.

The integration of these subsystems was designed to evaluate how effectively hydrogen can be managed across interfaces, from storage through to end use. This includes ensuring compatibility in terms of pressure, flow rate, and operational control, as well as maintaining system stability under varying demand conditions. Demonstrating interoperability between independently developed systems is a key requirement for scaling hydrogen technologies, as real-world deployments often involve multiple vendors and components working together.

In addition to technical compatibility, the integrated system concept also aimed to assess the practical feasibility of deployment. This includes considerations such as modularity, ease of installation, transportability, and the ability to operate within existing site and regulatory constraints. By adopting a containerised and modular design approach, the system was intended to support flexible deployment across a range of applications and locations.

While full system validation was not achieved due to external constraints, substantial progress was made in the development and integration planning of the individual subsystems. The project successfully established a clear system architecture, defined interface requirements, and demonstrated the readiness of key components for integration. These outcomes provide a strong foundation for future demonstration and deployment of integrated hydrogen systems.

3.2 Location and Partners Involved

Project Partners

The project was delivered through a collaborative consortium comprising:

- **Unitrove (Project Lead):** Responsible for LH_2 storage system design, fabrication, and overall system integration
- **GeoPura (Partner):** Provider of hydrogen power units for electricity generation
- **Steamology (Partner):** Developer of hydrogen-based turbine and vaporisation technologies

Each partner contributed specialised expertise across different segments of the hydrogen value chain, enabling a comprehensive demonstration concept.

3.3 Demonstration Location

The demonstration was planned to be conducted at a suitable UK-based site capable of supporting:

- Installation of cryogenic hydrogen storage infrastructure
- Safe handling and operation of LH_2 systems
- Integration with power generation and turbine equipment

The selected location was required to meet:

- Safety and regulatory requirements for hydrogen handling
- Space and infrastructure constraints for containerised deployment
- Operational accessibility for all project partners

Due to the incomplete commissioning of the LH_2 system, full on-site demonstration activities were not carried out. However, subsystem development and preparation activities were conducted at partner facilities.

3.4 Timeline of the Demonstration

The project was executed over a compressed timeline under the CPC HII programme, with key phases outlined below:

Project Timeline

- **November 2025 – Project Initiation**
  - Consortium formation and project kickoff
  - Finalisation of technical scope and responsibilities

- **December 2025 – Design and Procurement**
  - Detailed engineering design of LH2 system
  - Procurement of critical components
  - Development of vaporisation and turbine concepts

- **January 2026 – Fabrication and System Preparation**
  - Construction and assembly of Unitrove LH2 skid
  - Steamology system development and test preparation
  - Integration planning across partners

- **February 2026 – Planned Demonstration Phase**
  - Intended commissioning of LH2 tank
  - Planned integrated system demonstration
  - Execution of performance testing

- **March 2026 – Reporting and Close-Out**
  - Documentation of project outcomes
  - Analysis of completed and incomplete activities
  - Identification of lessons learned and next steps

4 Demonstration Activity

4.1 Equipment and Infrastructure Used

The demonstration was designed around an integrated liquid hydrogen (LH_2) system, incorporating cryogenic storage, vaporisation, and end-use technologies. The infrastructure comprised modular and transportable components to enable flexible deployment.

4.1.1 LH_2 Storage and Handling System (Unitrove)

The primary infrastructure element was a 20-ft intermodal LH_2 storage skid, designed for cryogenic hydrogen storage and controlled gas delivery.

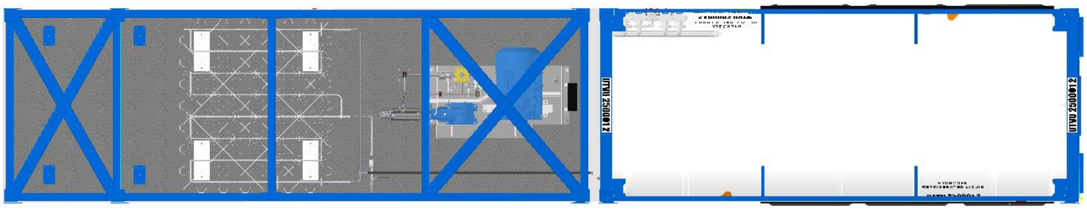
Key components included:

- **Cryogenic LH_2 Tank**
  - Vacuum-insulated vessel designed for storage at ~–253°C
  - Multi-layer insulation (MLI) to minimise heat ingress
  - Pressure relief and venting systems for boil-off management

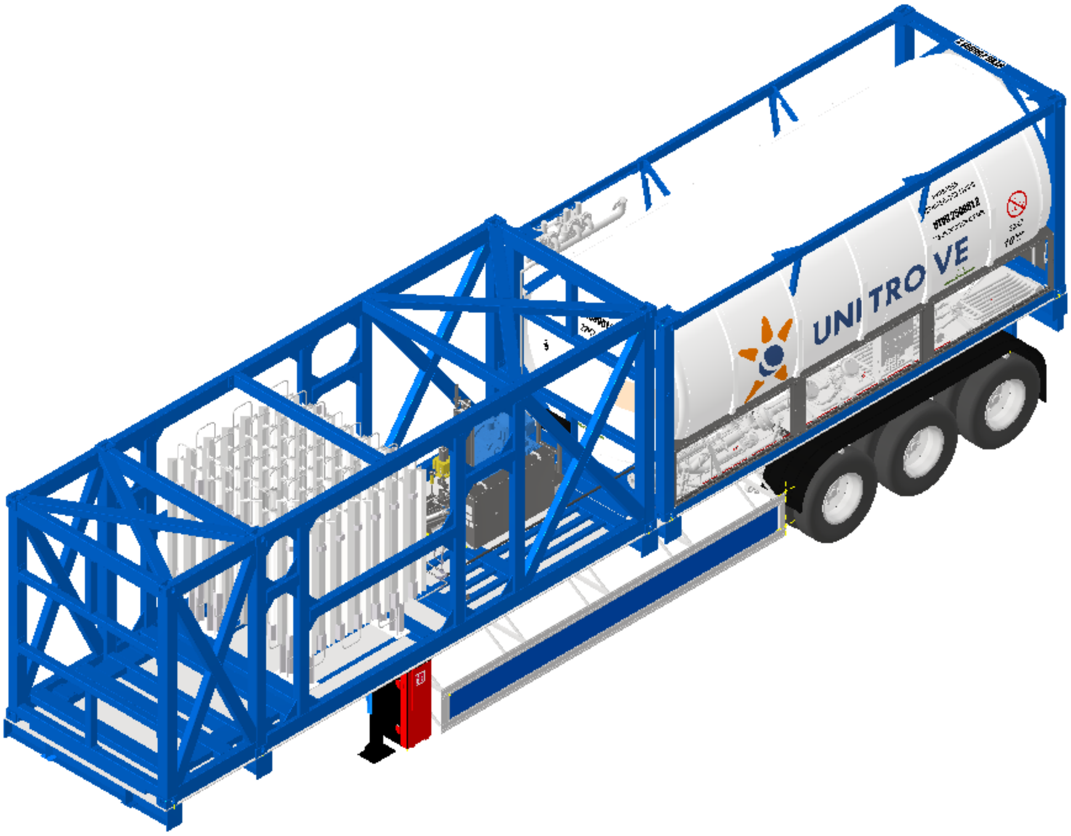
- **Piping and Valving System**
  - Cryogenic-rated piping and valves
  - Pressure regulation and isolation systems
  - Emergency shutdown (ESD) valves

- **Vaporisation Interface**
  - Connection points for external or integrated vaporisers
  - Provision for controlled phase transition from liquid to gas

- **Instrumentation and Control**
  - Pressure and temperature sensors
  - Level measurement systems
  - Data logging interface (planned)



Top View



Isometric View

Figure 3 – Unitrove LH_2 Storage Skid Assembly: 3D model

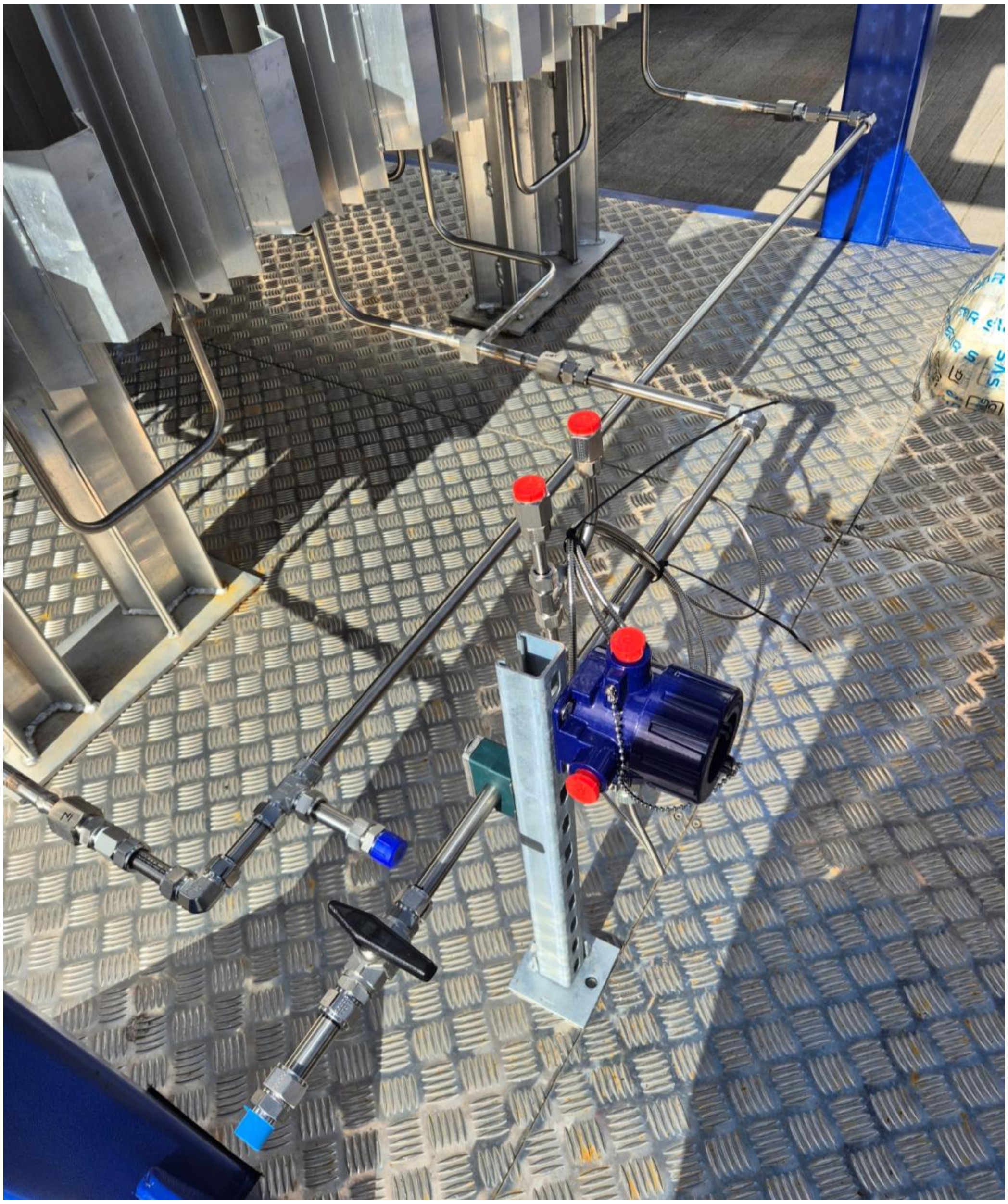


Figure 4 – Unitrove LH_2 Storage Skid Assembly-Manufactured Pipe work and valves

Figure 5 – Unitrove LH_2 Storage Tank

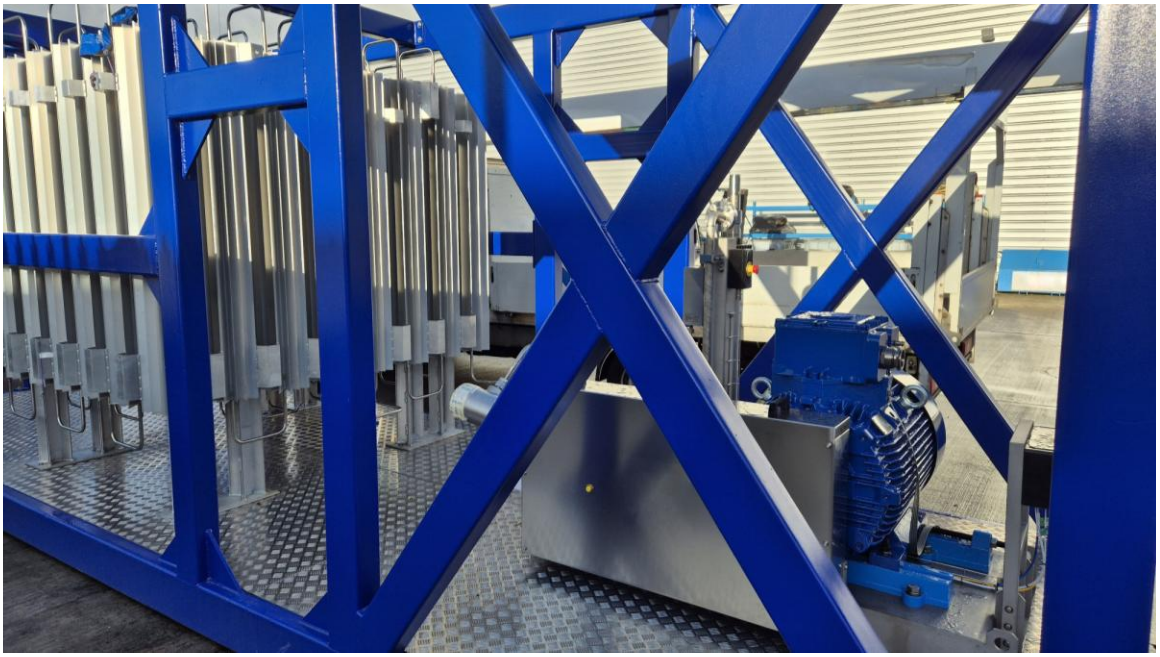


Figure 6 – Rest of the Unitrove LH_2 Storage & Distribution skid

4.1.2 Vaporisation and Thermal Integration System (Steamology)

The Steamology system was designed to integrate hydrogen vaporisation with thermal energy generation and recovery, forming a closed-loop approach to maximise overall system efficiency. At a high level, liquid hydrogen is first converted into gaseous form through a vaporisation process, after which it is supplied along with oxygen to a controlled reaction system that generates high-temperature steam. This steam is then expanded through a turbine to produce mechanical or electrical power. A key feature of the system is the recovery and reuse of thermal energy from the turbine exhaust to support upstream processes such as hydrogen vaporisation.

To evaluate the most effective approach for hydrogen conditioning, multiple vaporisation system configurations (SVS1, SVS2, and SVS3) were developed and assessed. These configurations represent different strategies for supplying the heat required to convert liquid hydrogen into gas, and each offers distinct advantages and limitations.

- **Liquid Hydrogen Vaporisation System Concepts**

  - **Concept SVS1**

    This concept assumes using the existing Unitrove hydrogen storage and vaporisation system is used on the liquid hydrogen fuelling side. On the oxygen fuelling side a steam heated vaporiser is used to vaporise the liquid oxygen. The P&ID below outlines the key components required to enable system function.

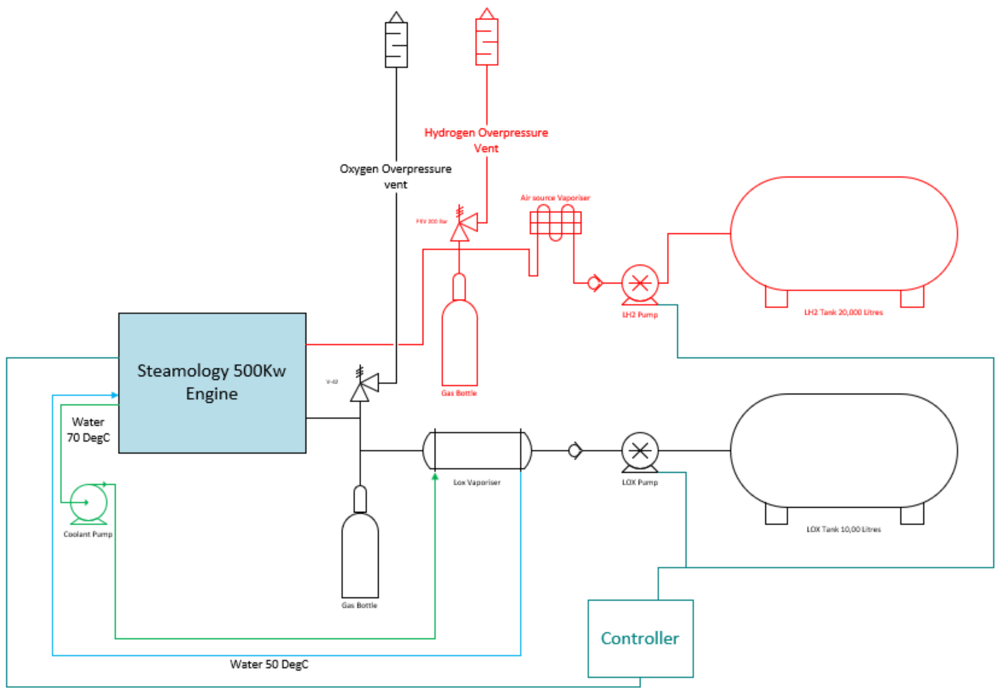


Figure 7 – SVS1 Concept P&ID

- **Concept SVS2**

This concept has been further developed to replace the air source LH_2 vaporiser with a steam heated LH_2 vaporiser similar to the oxygen system. The system is then represented by the P&ID below (SVS2):

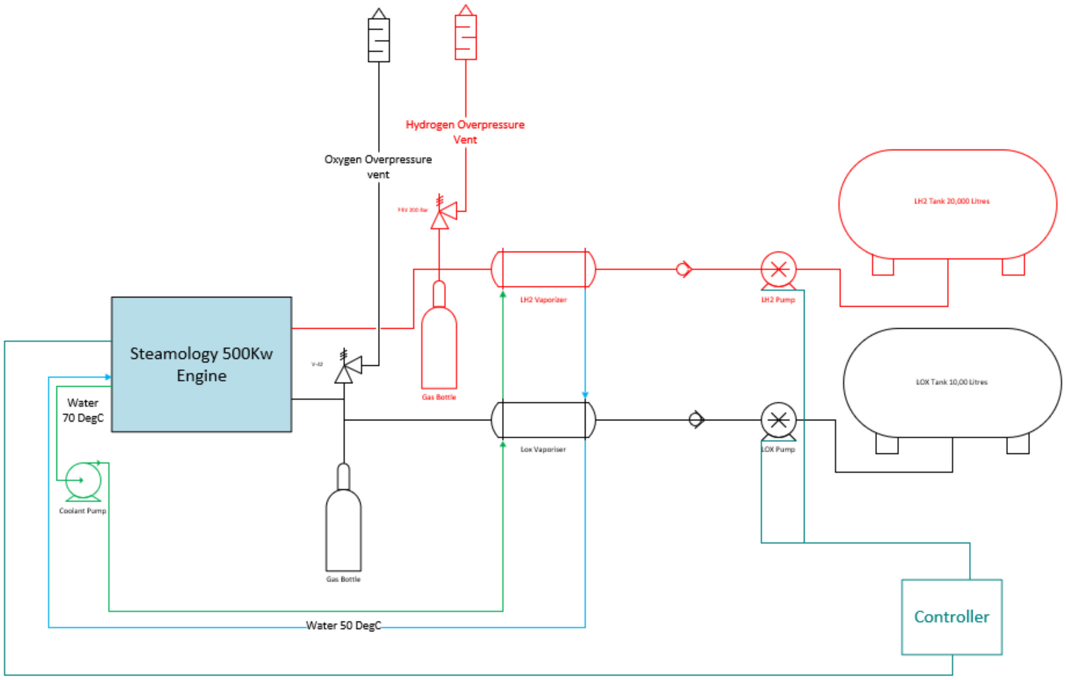


Figure 8 – SVS2 Concept P&ID

This concept saves significant space when viewing the overall system volume. Showing a more attractive power/storage to volume ratio, a key factor in heavy transport applications.

- **Concept SVS3**

In an effort to further reduce the volume and increase system total efficiency a third concept which removes the cryogenic gas pumps in place for pressurising the liquid storage tanks as a means for extracting the liquid into the vaporiser.

To do this, a second heat exchanger has been added to both the hydrogen and oxygen storage systems which allows steam to vaporise liquid fuel and recirculate the vaporised gas back into the liquid storage container.

This proposed system is very similar to currently used liquid pressurisation systems which enable filing and emptying of cryogenic liquid vessels. This method of pressurising the liquid tank would require a high-pressure cryogenic tank to be manufactured. Steamology estimates a max working pressure of 60–70 bar would be required.

This enables the excess heat from the steam turbine exhaust to be used to maintain a tank pressure rather than spending generated electrical energy powering the cryogenic pumps. In the concept shown this would equate to roughly a 50 kW energy saving on a 500 kW electrical generator set.

The P&ID of this concept is shown below:

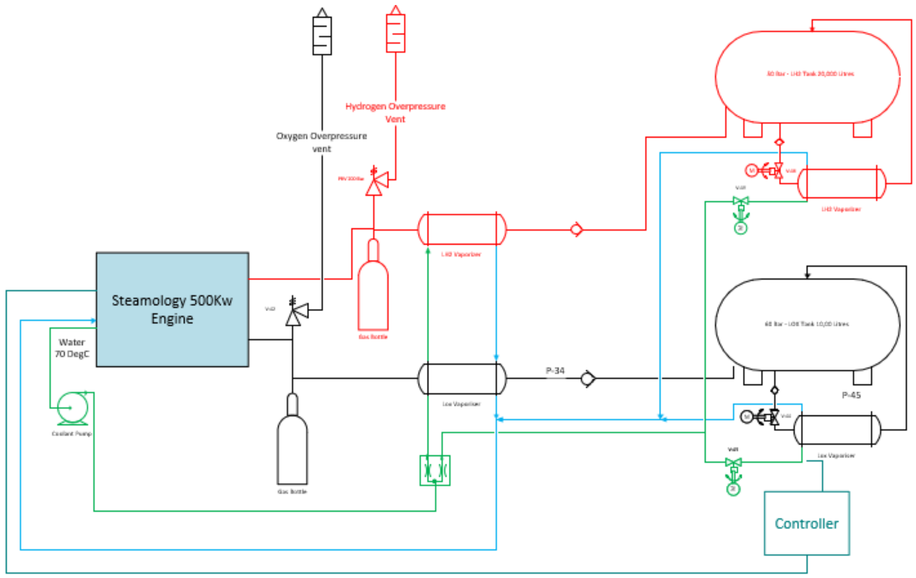


Figure 9 – Steam vaporisation and pressurisation concept P&ID

The comparison of these configurations highlights key trade-offs between simplicity, efficiency, and integration complexity. While SVS1 offers ease of deployment and lower cost, SVS3 provides the highest potential efficiency through thermal integration, with SVS2 acting as an intermediate solution that balances performance and practicality. The evaluation of these approaches was intended to identify the most suitable configuration for different deployment scenarios, depending on factors such as scale, operating environment, and system integration requirements.

- **Thermal Energy Recovery System**

  In addition to vaporisation, the system incorporates a thermal energy recovery framework designed to capture and reuse waste heat generated during operation. Heat from the turbine exhaust is recovered through dedicated heat exchangers and can be redirected to support hydrogen vaporisation or other thermal processes within the system. This integration reduces overall energy losses and enhances system efficiency, particularly in configurations where thermal coupling is maximised.

  At the core of the system is the hydrogen–oxygen combustion chamber, where gaseous hydrogen reacts with oxygen under controlled conditions to produce high-temperature steam. This process enables precise control over steam quality and operating conditions, which is essential for efficient turbine performance. The generated steam is then directed to a turbine system, where thermal energy is converted into mechanical energy and, where applicable, electrical output via a coupled generator.

  Steamology's approach demonstrates how vaporisation, energy conversion, and thermal recovery can be integrated into a cohesive system. By linking these elements, the system aims to maximise efficiency, improve hydrogen utilisation, and support scalable deployment of hydrogen-based power solutions.

- **Vaporisation Concepts – Space model comparison**

  3D modelling of the vaporisation concepts has proved an interesting exercise. As shown below the Steamology system incorporating steam driven vaporisers has a compatible to reduced size of currently available fuel cell systems including the volume required to store liquid oxygen.

A diagram outlining the three models is shown below:

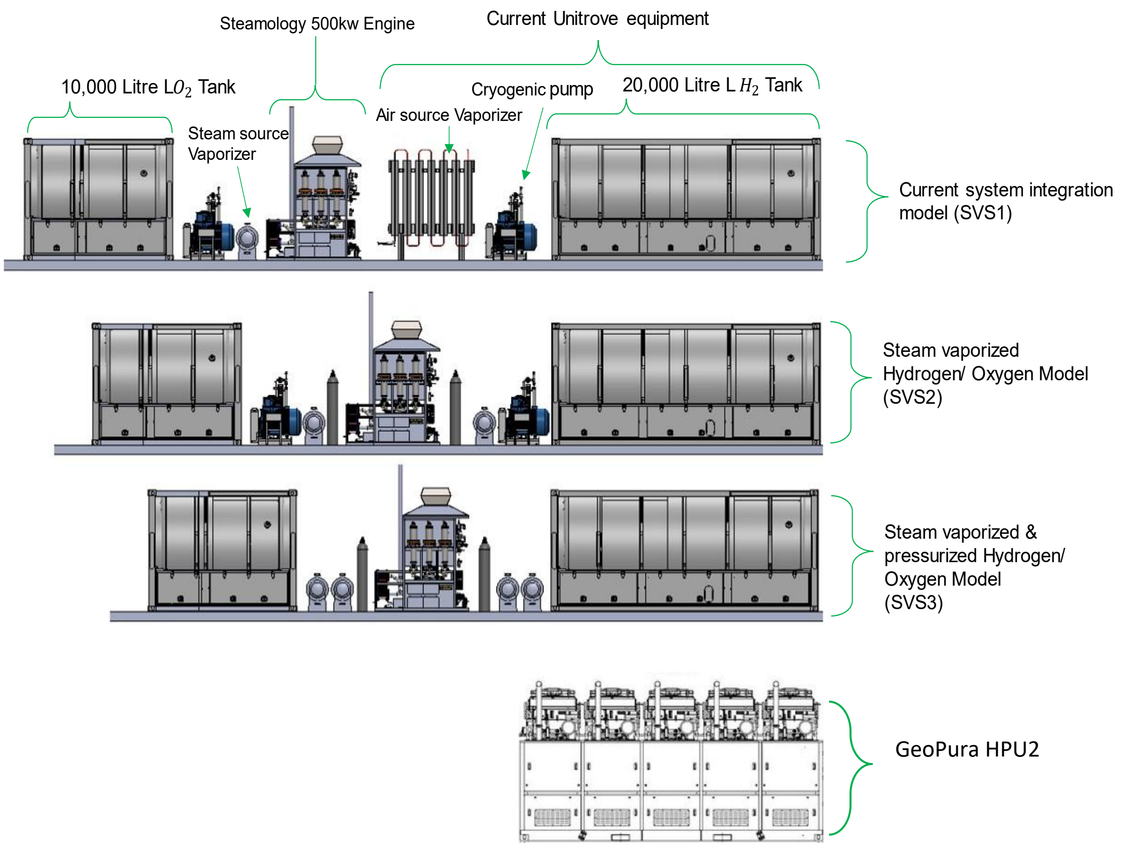


Figure 10 – Vaporisation Concepts: Space model comparison

- **Implications and Trade-offs**
  - Ambient/forced vaporisation (SVS1) requires a larger footprint due to reliance on external heat exchange but offers lower complexity and easier deployment.
  - Hybrid systems (SVS2) reduce footprint and improve performance by supplementing heat input, at the cost of moderate system complexity.
  - Fully integrated systems using turbine waste heat (SVS3) provide the most compact and efficient solution but require higher levels of system integration and control.
  - The comparison highlights a key trade-off between simplicity and deploy ability versus efficiency and compact system design, depending on site constraints and operational requirements.

4.1.3 Hydrogen Power Unit (GeoPura)

The GeoPura Hydrogen Power Unit (HPU) was intended to provide end-use validation through electricity generation.

Key components included:

- Fuel Cell System
    - Conversion of hydrogen gas into electricity
    - Zero-emission operation

- Balance of Plant
    - Hydrogen supply interface
    - Cooling and control systems

- Electrical Output System
    - Power conditioning and distribution

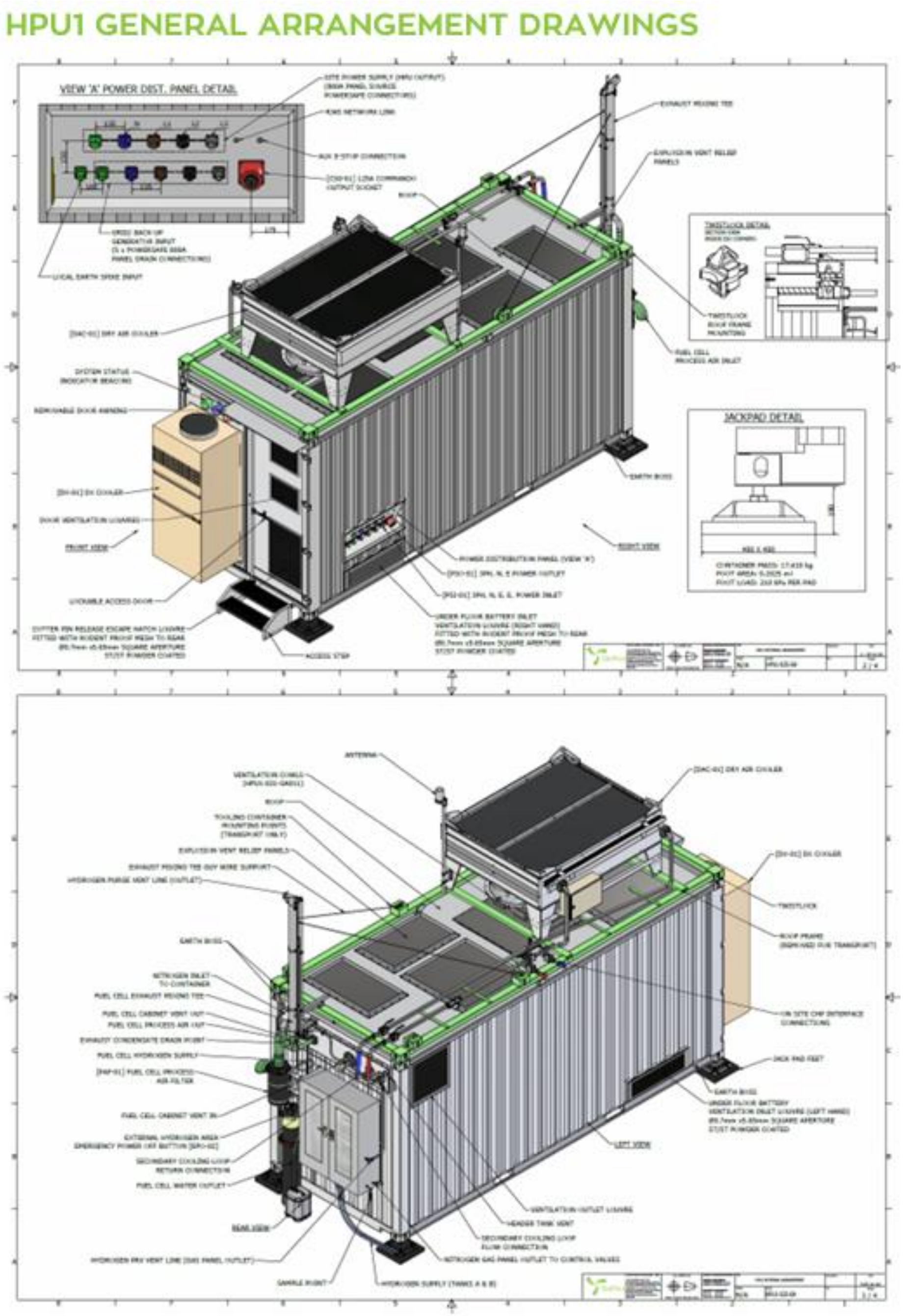


Figure 11 – GeoPura HPU System

4.2 Site Infrastructure (Planned)

The demonstration site was intended to include:

- Designated cryogenic storage zone
- Safety exclusion zones and barriers
- Electrical and control system interfaces
- Monitoring and data acquisition setup

Due to incomplete commissioning, full site deployment was not realised; however, infrastructure planning and subsystem preparation were completed.

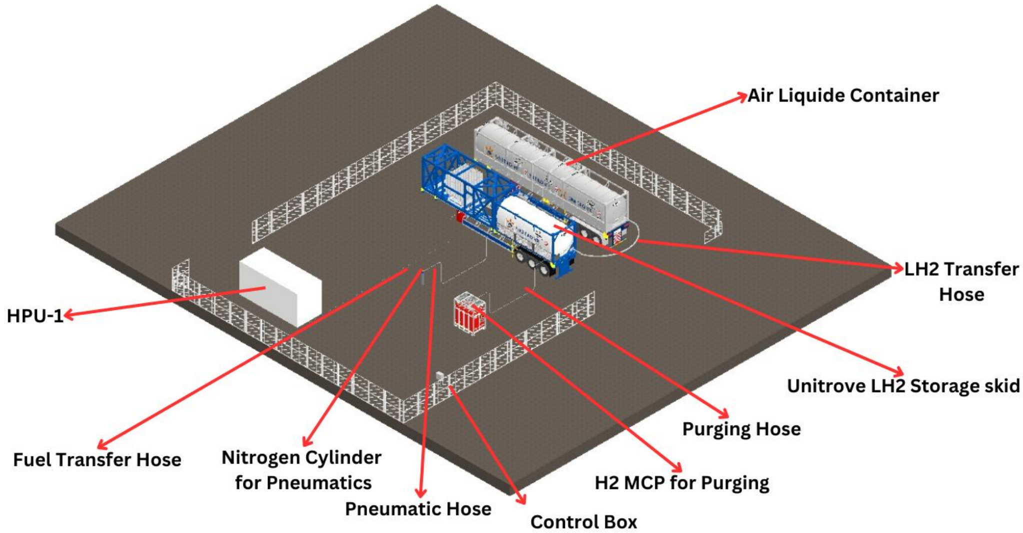


Figure 12 – Proposed Site Layout: 3D rendering

4.3 Methodology and Procedures

The demonstration methodology was structured to validate the integrated operation of LH_2 storage, vaporisation, and utilisation systems under controlled conditions.

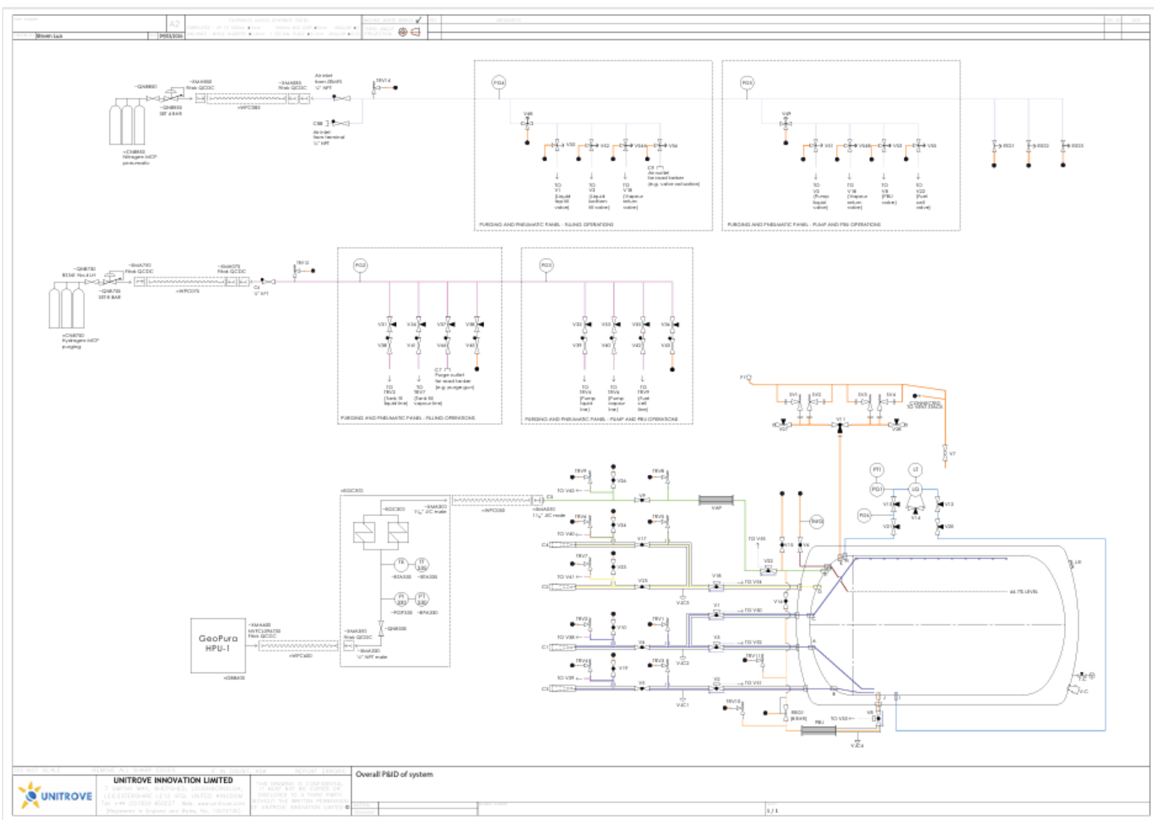


Figure 13 – Process flow diagram illustrating hydrogen transfer, vaporisation, and utilisation pathways

4.3.1 Commissioning Procedure (Planned)

- Pre-commissioning inspection of LH_2 tank and piping
- Leak testing using inert gas (e.g., helium/nitrogen)
- Cool-down procedure for cryogenic system
- Controlled filling of LH_2 tank
- Stabilisation of pressure and temperature conditions

4.3.2 Operational Procedure (Planned)

Once commissioned, the system would operate as follows:

a) **LH_2 Storage**
   - Maintain cryogenic conditions within tank
   - Monitor boil-off and pressure

b) **Hydrogen Withdrawal and Vaporisation**
   - Controlled extraction of LH_2
   - Phase change via vaporisation system
   - Pressure and temperature conditioning

c) **End-Use Supply**
   - Delivery of gaseous hydrogen to:
     - GeoPura HPU
     - Steamology turbine system

d) **System Integration Testing**
   - Continuous operation under steady-state conditions
   - Load variation testing
   - Performance evaluation

4.3.3 Actual Implementation

- LH_2 skid fabrication and assembly were completed
- Steamology systems were developed and partially tested independently
- Full commissioning and integrated operation were not executed due to incomplete LH_2 tank readiness

4.4 Safety, Risk Management, and Regulatory Considerations

Given the use of liquid hydrogen, the project incorporated stringent safety and risk management protocols aligned with industry standards

4.4.1 Key Safety Risks Identified

- Cryogenic hazards (extreme low temperatures)
- Hydrogen flammability and explosion risk
- Overpressure due to boil-off
- Leakage in cryogenic systems

4.4.2 Risk Mitigation Measures

- **Engineering Controls**
  - Vacuum-insulated tank design
  - Pressure relief valves (PRVs)
  - Emergency shutdown systems
- **Operational Controls**
  - Defined operating procedures
  - Controlled access to demonstration area
  - Trained personnel for LH_2 handling
- **Detection and Monitoring**
  - Hydrogen leak detection systems (planned)
  - Continuous pressure and temperature monitoring

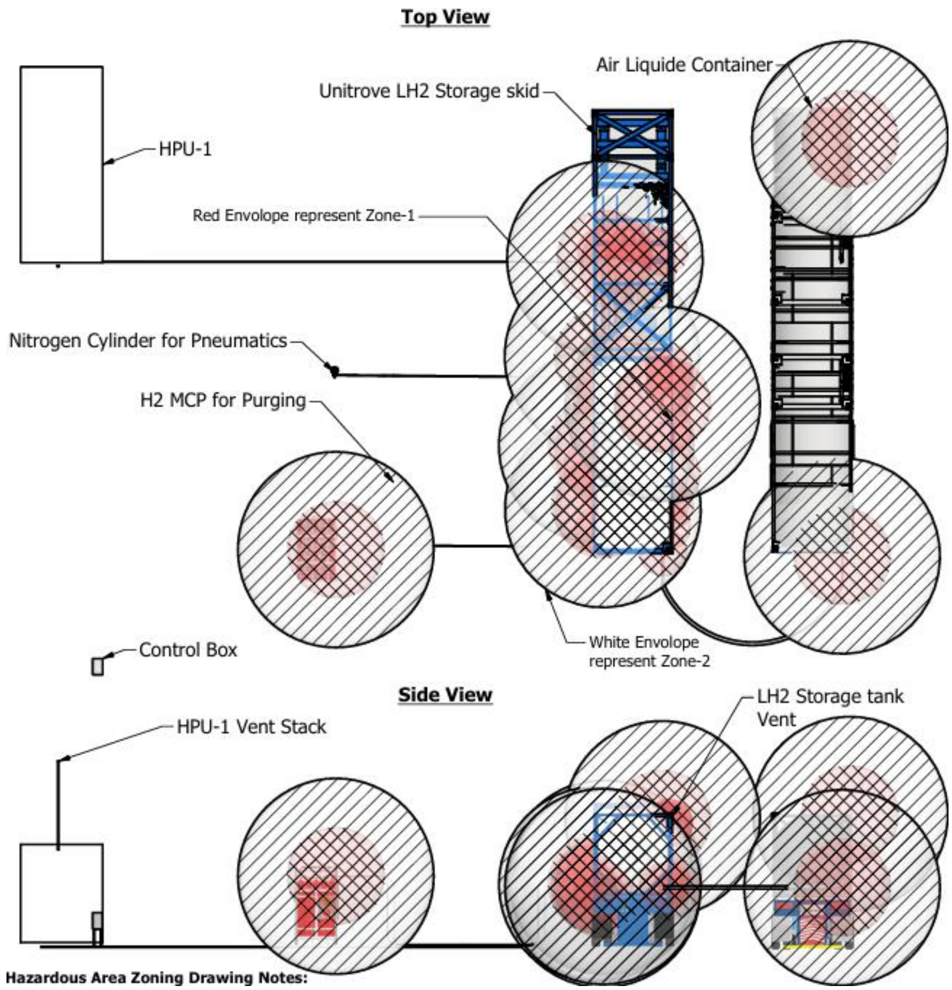


Figure 14 – Proposed Site Layout: Hazardous Area Classification

4.4.3 Regulatory Compliance

The demonstration was designed to align with:

- UK hydrogen safety regulations
- Pressure systems safety standards
- Cryogenic storage and handling guidelines
- Site-specific risk assessment and permitting requirements

Due to the incomplete commissioning phase, full regulatory validation through live operation was not conducted.

4.5 Data Collection and Monitoring Methods

4.5.1 Planned Data Collection Parameters

The demonstration aimed to collect high-resolution operational data across the system, including:

- **LH_2 Storage Metrics**
  - Tank pressure and temperature
  - Liquid level and boil-off rate
  - Holding time and losses
- **Vaporisation Performance**
  - Heat input vs hydrogen flow rate
  - Efficiency of vaporisation systems
  - Energy consumption
- **End-Use Performance**
  - Power output (GeoPura HPU)
  - Turbine efficiency (Steamology)
  - System response under varying loads

4.5.2 Instrumentation and Monitoring Systems

- Cryogenic-rated sensors for pressure, temperature, and level
- Data acquisition system (DAQ) for real-time monitoring
- Logging systems for post-analysis

4.5.3 Data Collection Outcome

Due to the incomplete commissioning of the LH_2 storage and integrated system, no live operational data was obtained from full system trials. However, a structured programme of analytical modelling and subsystem-level testing was carried out by Steamology to generate representative performance data relevant to the intended system.

A key component of this work was the development of a high-power energy flow calculation model, designed to simulate the interaction between hydrogen fuel storage, combustion, steam generation, and turbine operation. The model evaluates how system parameters—such as fuel consumption, storage volume, and energy output—scale with increasing power demand. This enabled the assessment of different system configurations under varying operational scenarios, including part-load and cyclic operation. The structure and outputs of this model are illustrated in Figure 15.

- **High-power energy flow calculation model**

In parallel, turbine system testing and commissioning activities were undertaken at subsystem level. These activities focused on validating key functional elements, including hydrogen–oxygen combustion behaviour, steam generation characteristics, and integration readiness of the turbine system. Testing was conducted under controlled conditions to replicate expected operating environments as closely as possible in the absence of LH_2 supply. The subsystem testing configuration and setup are shown in Figure 16.

Steamology engine data	Value	Units
Volume occupied	8.8	m3
electrical Power output	500	Kw
Heat power output	1500	kw
Heat Power density	170.4545455	kw/m3
Electrical Power density (500kw concep	56.81818182	kw/m3
total power density	227.2727273	kw/m3

fuel to energy data	Value	Units
required electrical energy capacity	3600	kwh
heat energy capacity	10800	kwh
H2 consumption	75	kg/h
H2 storage mass	540	kg
O2 Consumption	600	kg/hr
O2 Storage mass	4374	kg

Gen level Data	Value	Units
Number of generators	5	Qty
Power per generator	100	kw
generator h2 consumption	250	g/min

Geopura HPU2	Value	Units
Volume occupied	43.1636	m3
electrical Power output	500	Kw
Electrical Power density	11.58383453	kw/m3

fuel to energy data	Value	Units
required electrical energy capacity	16050	kwh
H2 consumption	42	kg/h
H2 storage mass	1348.2	kg

energy available lhv	2475	1386
effeciency	20%	36%
heat and electric effeciency	61%	

amology engine fuel consumption & required stor

Storage Margin	5%

Liquid storage	Units 1		Units 2		Units 2 Plus Margin	
Liquid h2 consumption	1.06	m3/hr	17.66	Litres/min	18.54	Litres/min
Liquid O2 Consumption	0.53	m3/hr	8.77	Litres/min	9.21	Litres/min
Liquid H2 storage volume	7.63	m3	7627.12	litres	8008.47	litres
Liquid O2 storage volume	3.84	m3	3836.84	litres	4028.68	litres
Liquid h2 consumption	0.59	m3/hr	9.89	Litres/min	10.38	Litres/min
Liquid H2 storage volume	19.04	m3	19042.37	litres	19994.49	litres

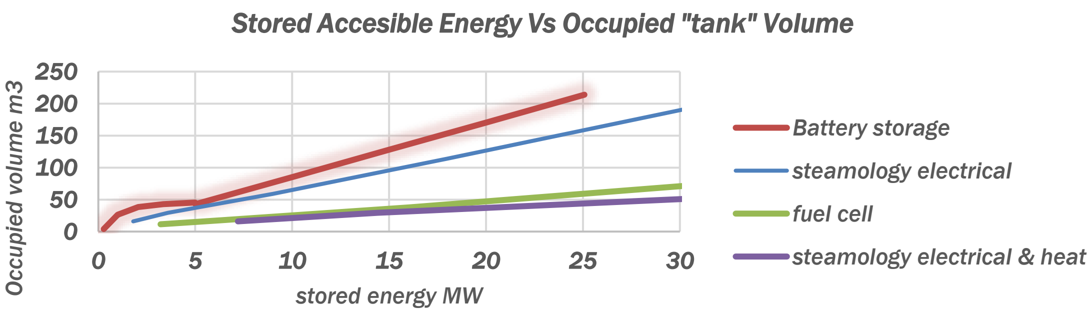


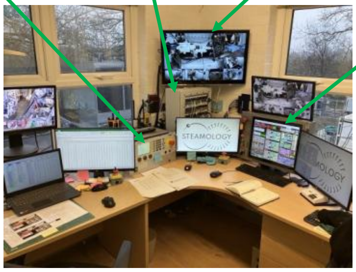
Figure 15 – High Power Energy Flow Calculation Model illustrating system-level energy interactions and scaling behaviour

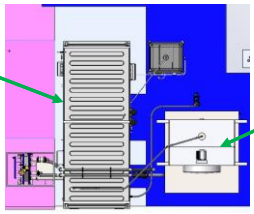
- **Steam Turbine Testing and Commissioning**

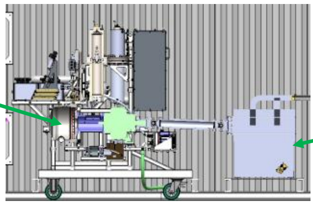
Steam Turbine Dynamometer

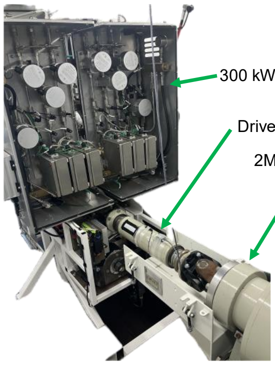
300kW Engine Dyno Setup

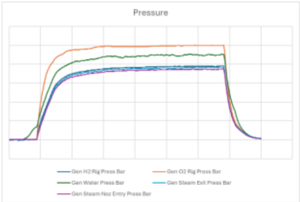
Steamology has setup and tested a 300kw engine coupled to a 2MW dynamometer. The dyno setup is capable of logging and recording over 250 sensors in Realtime during turbine tests. Through in house developed software, tests can be configured and controlled in a variety of ways. If a new functionality or test type is needed this can be added to the test software and trialed seamlessly.

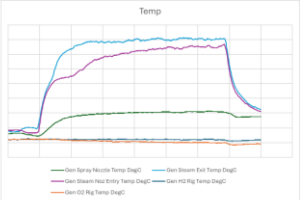


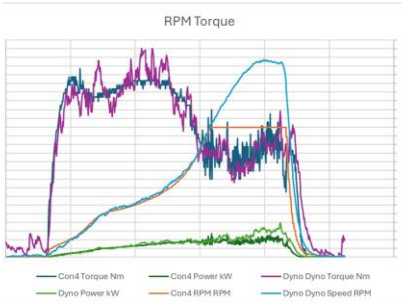












Steamology Turbine

The turbine is a high torque delivery device. Steamology has improved the control of the dynamometer control system that is primarily designed at traditional diesel engine response. Alongside developing the data set to inform the steam nozzle and steam entry and exit conditions for effective steam turbine operation.

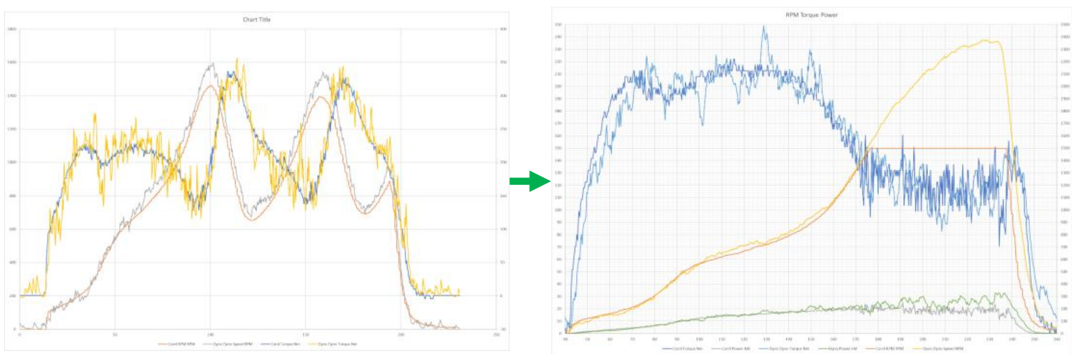
Closed loop operation

The Steamology system operates in closed loop. The turbine operating in the dynamometer test cell is fully data logging and is fully recirculating. The test programme has improved the overall system dynamics.

Steam Turbine Dynamometer

Dyno Setup and Tuning for 300kW Engine

The 300kW engine has a maximum output speed of around 2500rpm whereas the standard dyno programming is setup to control an en gine at 6000 rpm. Steamology has developed the PID Control loop that controls the dynamometer to this new rpm range. On the left the dyno controllers response to power is shown. This shows hysteresis in the torque and power due to incorrectly tuned PID loop. The graph on the right sh ows the Dynamometer response after tuning. The results show stable and consistent adjustment to a varying power and the ability to trade torque f or rpm with a constant power delivery output.



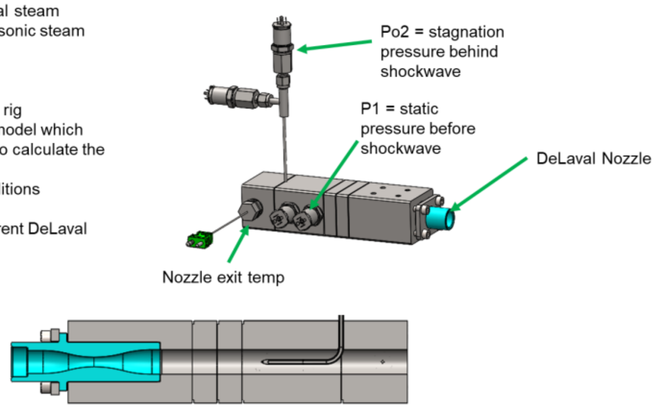
Steam Turbine Development

Steam Velocity Testing

Steamology has been developing its DeLaval steam nozzles which supply the turbine with supersonic steam used to drive the turbine.

This has involved a number of key stages:

- Design and build of supersonic pitot test rig
- Development of iterative mathematical model which uses the supersonic Rayleigh equation to calculate the Mach number of steam
- Setup and testing of pitot test rig at conditions optimised for the 300 Kw Turbine
- Analysis of data to confirm or adjust current DeLaval nozzle design calculations.



Pitot Tube Test conditions
Hydrogen mass flow : 180 g/min
Oxygen mass flow: 1458 g/min
Water Flow rate : 6.32 L/min
Total mass flow rate: 10kg/min
Nozzle inlet temp : 400 ˚C

Rayleigh Equation

$$\frac{p_{o_2}}{p_1} = \frac{p_{o_2}}{p_2}\frac{p_2}{p_1} = \left(\frac{(\gamma+1)^2 M_1^2}{4\gamma M_1^2 - 2(\gamma-1)}\right)^{\gamma/(\gamma-1)} \frac{1-\gamma+2\gamma M_1^2}{\gamma+1}$$

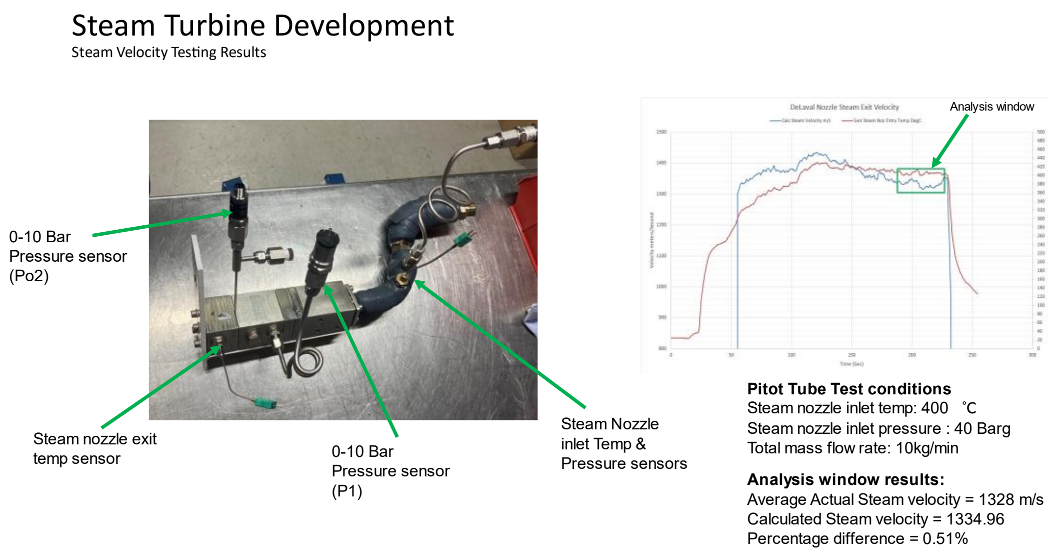


Figure 16 – Various images for steam turbine testing and commissioning

Together, the modelling and testing activities generated a dataset that supports evaluation of:

- Energy flow and system efficiency under different configurations.
- Thermal integration opportunities, including waste heat utilisation.
- Operational behaviour of the turbine system under hydrogen-based combustion.

These outputs form the analytical basis for the performance assessment presented in Section 5.1.

5 Results and Analysis

5.1 Performance of the Technology

5.1.1 Vaporisation System Performance (Steamology)

Steamology evaluated multiple vaporisation system configurations (SVS1, SVS2, SVS3) through thermodynamic modelling and system-level analysis to assess their performance under different operating and integration scenarios. The evaluation focused on hydrogen temperature control, pressure stability, and energy input requirements for vaporisation.

The configurations were analysed using heat and mass balance models, incorporating different heat sources including ambient air, supplementary heating, and recovered thermal energy from downstream processes. These models enabled comparison of system efficiency and auxiliary energy demand across configurations.

The analysis showed that systems incorporating thermal integration—particularly those utilising recovered heat—significantly reduce the need for external energy input during vaporisation. This results in improved overall thermal efficiency and reduced auxiliary power consumption.

In contrast, simpler ambient-based vaporisation systems were found to be more sensitive to environmental conditions, leading to variability in hydrogen temperature and pressure. This variability can affect downstream processes that require stable hydrogen delivery conditions.

Further modelling of pressurisation strategies demonstrated that optimised system design can reduce electrical input requirements for hydrogen delivery, contributing to lower overall system energy demand.

These findings were established through the combination of:

- Thermodynamic modelling of vaporisation processes
- Comparative analysis of multiple system configurations
- Evaluation of energy flows and auxiliary load requirements

The results indicate that vaporisation is a critical component of the overall system, with direct implications for efficiency and operational stability. In an integrated system, the use of thermal energy recovery enables more consistent hydrogen supply and improves overall system performance.

5.1.2 Turbine System Performance (Steamology)

The analytical modelling and subsystem-level testing described in Section 4.5.3 provide insight into the expected performance of Steamology's hydrogen–oxygen combustion turbine system.

Key findings derived from this work include:

- **Combustion and steam generation viability**: The analytical outputs confirm that hydrogen–oxygen combustion can reliably generate high-temperature steam suitable for turbine operation, supporting the feasibility of the proposed thermodynamic cycle.

- **Efficiency through thermal integration**: The integration of waste heat recovery into the system significantly improves overall energy efficiency by reducing the external energy required for hydrogen vaporisation.

- **System responsiveness and flexibility**: The modelling indicates that the system is well-suited for applications requiring variable load operation and rapid response, particularly in distributed energy environments.

- **Implications for integrated system performance**: These findings demonstrate that, when combined with a stable hydrogen supply from the LH_2 storage system, the turbine subsystem can form part of an efficient and scalable hydrogen-based power solution.

5.1.3 LH_2 Storage System Performance (Unitrove)

Operational performance data for the LH_2 storage system—such as boil-off rate, pressure stability, and holding time—was not obtained due to incomplete commissioning of the liquid hydrogen tank.

However, the system was designed against defined performance targets based on industry standards and engineering design criteria for cryogenic hydrogen storage systems. These targets provide a benchmark for future validation and indicate the expected operational performance of the system.

Key target performance parameters include:

- **Boil-off rate:** The system is designed to achieve an expected boil-off rate of approximately 10 kg per day, enabled through vacuum-insulated cryogenic tank design and minimisation of thermal ingress.
- **Pressure stability:** The storage system is designed to maintain a stable operating pressure in the range of 8 to 9 bar, ensuring compatibility with downstream vaporisation and hydrogen utilisation systems.

- **Holding time:** Based on manufacturer specifications, the tank is expected to achieve a holding time of up to 11 days without significant loss of stored hydrogen. Validation of this parameter was a key objective for Unitrove within the demonstration.
- **Controlled withdrawal capability:** The system is designed to support a hydrogen mass flow rate of approximately 8.26 kg/h, enabling consistent supply to downstream vaporisation and energy conversion systems under expected operating conditions.

The system incorporates cryogenic storage, insulation, and process interfaces required for integration with downstream vaporisation and utilisation systems.

These outcomes confirm:

- Engineering feasibility of the modular LH_2 storage approach
- Readiness of the system for commissioning and operational validation
- Compatibility with the integrated hydrogen system architecture

While performance validation could not be completed during this phase, the defined design targets establish a clear basis for future testing. Once commissioned, the system will be evaluated against these parameters to confirm operational performance under real-world conditions.

The availability of a fully fabricated and integrated skid significantly reduces risk for future demonstration phases and supports rapid progression to operational validation.

5.2 Validation Against Design or Models

5.2.1 Subsystem Validation (Steamology)

Steamology's modelling and analytical work provide partial validation of system performance against design expectations:

- Vaporisation system behaviour aligns with thermodynamic predictions
- Heat recovery integration demonstrates expected efficiency improvements
- System configurations perform consistently with assumptions under simulated conditions

These results support the technical feasibility of the proposed system configurations at a conceptual and subsystem level.

5.2.2 Integrated System Validation

Full validation of the integrated system (LH_2 storage → vaporisation → end-use) was not achieved due to the absence of operational LH_2 supply. The validation status of key system components is summarised below:

System Component	Validation Status
LH_2 Storage System	Not validated (commissioning not completed)
Vaporisation System	Conceptual and modelling validation completed
Turbine System	Subsystem validation completed
Hydrogen Power Unit Integration	Not validated

This highlights that while individual subsystems have demonstrated readiness, system-level integration and performance remain to be validated in future work.

5.3 Economic Analysis

A full economic assessment of the demonstrated system was limited by the inability to complete on-site operations and collect real-time performance data. However, based on system design, fabrication outcomes, and supporting analysis from project partners, an indicative economic evaluation has been undertaken to assess the potential viability of the technology.

The primary capital expenditure (CAPEX) components of the system are associated with the liquid hydrogen (LH_2) storage skid, including the cryogenic storage vessel, vacuum insulation systems, and associated piping and control infrastructure. Additional capital costs arise from the ambient air vaporiser, gas distribution system, and integration with downstream applications. The modular and containerised design approach adopted by Unitrove is expected to reduce installation and engineering costs, particularly in comparison to fixed, large-scale hydrogen infrastructure.

Operational expenditure (OPEX) for the system is expected to be relatively low. The use of ambient air vaporisation eliminates the need for external energy input for phase change, significantly reducing operating costs compared to electrically heated or steam-based vaporisation systems. Routine operational costs are primarily associated with system monitoring, maintenance of cryogenic components, and periodic inspection of safety systems. The use of a PLC-based control system further enables efficient operation with minimal manual intervention.

From a supply chain perspective, the cost and availability of liquid hydrogen represent a key economic variable. As observed during the project, reliance on third-party LH_2 delivery introduces logistical and commercial dependencies that can impact both project timelines and operating costs. As the hydrogen supply ecosystem matures, improvements in production scale and distribution infrastructure are expected to reduce LH_2 costs and enhance overall project economics.

The modular architecture of the system provides a significant economic advantage in terms of scalability. Capacity can be increased incrementally through the deployment of additional modules, allowing capital investment to be phased in line with demand. This reduces upfront financial risk and improves the economic feasibility for early-stage hydrogen adoption, particularly in distributed energy and industrial applications.

Although detailed cost-per-unit hydrogen delivery metrics could not be validated within the scope of this demonstration, the system design indicates strong potential for cost competitiveness in applications where high energy density, transport efficiency, and flexible deployment are critical. Compared to compressed hydrogen systems, LH_2 offers advantages in storage density and reduced footprint, which can translate into cost savings in transport and site infrastructure.

Overall, the economic assessment suggests that the demonstrated technology is well-positioned for cost-effective deployment in emerging hydrogen markets, particularly as supply chain maturity and demand scale improve.

5.4 Environmental Impact

5.4.1 Emissions Reduction Potential

The system is designed to operate as a zero-emission solution at the point of use, with:

- Hydrogen serving as a clean energy carrier
- No direct carbon dioxide (CO_2) emissions during operation
- Water vapour as the primary by-product in combustion-based processes

This provides a direct pathway for replacing fossil fuel-based systems such as diesel generators in relevant applications.

5.4.2 Efficiency and Environmental Performance

- Improved vaporisation efficiency reduces overall energy consumption
- Reduced auxiliary energy demand contributes to lower indirect emissions, depending on electricity source

5.4.3 Limitations

- No direct emissions measurements were recorded
- Full lifecycle environmental impacts (including hydrogen production and liquefaction) were not assessed within the scope of this project

5.5 Comparison with Existing or Alternative Technologies

5.5.1 Liquid Hydrogen vs Compressed Hydrogen

Parameter	Liquid Hydrogen (LH_2)	Compressed Hydrogen (CGH_2)
Volumetric Energy Density	High	Lower
Storage Footprint	Compact	Larger
Transport Efficiency	Higher for bulk transport	Lower
System Complexity	High (cryogenic)	Moderate

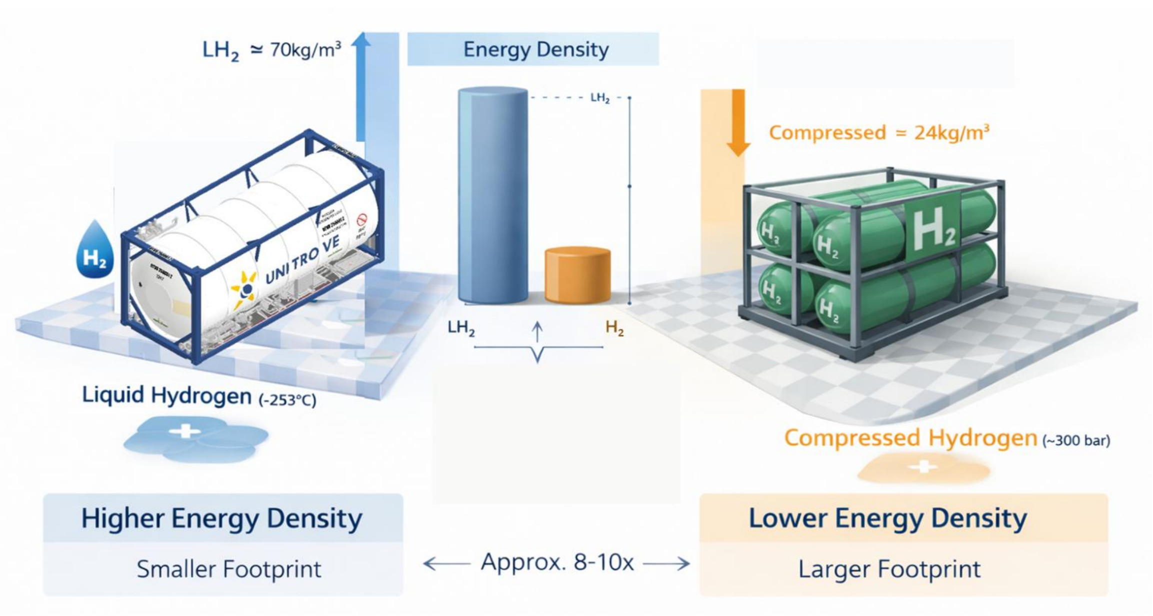


Figure 17 – Comparison of LH_2 and CGH_2 storage in terms of energy density and footprint

Insight: LH_2 provides clear advantages for high-demand and space-constrained applications, though it introduces additional complexity in storage and handling.

5.5.2 Integrated System vs Conventional Hydrogen Systems

Aspect	Conventional Systems	Integrated System (Project Concept)
Vaporisation	Standalone, energy-intensive	Integrated with thermal recovery
Energy Efficiency	Moderate	Potentially higher
System Integration	Limited	High
Operational Complexity	Lower	Higher

Insight: The integrated approach explored in this project demonstrates potential for improved efficiency, particularly through thermal energy recovery, but requires further validation.

5.5.3 Hydrogen Systems Hydrogen Systems vs Diesel-Based Systems

Parameter	Hydrogen-Based System	Diesel-Based System
Emissions	Zero at point of use	High CO_2 emissions
Environmental Impact	Low	High
Fuel Source	Renewable (potentially)	Fossil fuel
Noise and Air Quality	Improved	Poorer

Insight: Hydrogen systems provide a clear pathway to decarbonisation, particularly for applications currently reliant on diesel generation.

6 Challenges and Solutions

6.1 Technical Issues Encountered

No major technical issues were encountered in the development and preparation of the core equipment for the demonstration.

All primary system components, particularly the liquid hydrogen (LH_2) storage and handling system developed by Unitrove, were successfully:

- Designed, fabricated, and assembled
- Integrated into a modular skid-based configuration
- Prepared for commissioning and operational deployment

Similarly, Steamology completed its scope of work, including system design, modelling, and subsystem validation activities.

From a technical standpoint, the project demonstrated that:

- The proposed system architecture is feasible and implementable
- Key subsystems can be developed and prepared independently
- Equipment readiness was achieved in line with design objectives

As such, technical readiness was not a limiting factor in the delivery of the demonstration.

6.2 Operational or Logistical Challenges

While technical development progressed successfully, several external and project delivery-related challenges impacted the ability to complete the full demonstration.

6.2.1 Liquid Hydrogen Supply Constraints

The demonstration was dependent on the timely delivery of LH_2 from the fuel supplier.
Challenges included:

- Scheduling and coordination of LH_2 delivery within the project timeframe
- Alignment between system readiness and supplier availability
- Dependencies on external logistics outside the direct control of the project partners

The delay in LH_2 delivery prevented final commissioning and operational testing of the integrated system.

6.2.2 Liquid Hydrogen Supply Constraints

The deployment of LH_2 systems required appropriate insurance coverage and compliance approvals prior to operation. Challenges included:

- Time required to secure insurance for cryogenic hydrogen operations
- Coordination between multiple stakeholders to meet compliance requirements
- Alignment of documentation and risk assessments with insurer expectations

These processes extended beyond initial planning assumptions and contributed to delays in project execution.

6.2.3 Site Finalisation and Readiness

Finalisation of the demonstration site and its readiness for LH_2 operations was a critical dependency. Challenges included:

- Delays in confirming the final deployment location
- Additional time required to ensure site compliance with hydrogen safety requirements
- Coordination between infrastructure readiness and system deployment

6.2.4 Documentation and Coordination Dependencies

The project required timely exchange of technical documentation between partners to support integration and site preparation. Challenges included:

- Delays in submission of required technical documentation to GeoPura
- Impact on downstream activities such as site preparation and system integration planning
- Increased coordination complexity across multiple stakeholders

While these challenges were manageable, they contributed to cumulative delays affecting the overall demonstration timeline.

6.3 Mitigation Strategies and Solutions

Despite the challenges encountered, several measures were implemented to ensure that project objectives were progressed as far as possible within the available timeframe.

6.3.1 Full Technical Readiness of Equipment

All major equipment, particularly the Unitrove LH_2 storage and handling system, was brought to a state of readiness for commissioning. This ensures that:

- The system is fully prepared for future demonstration activities
- No additional major technical development is required prior to operation
- The project can be progressed with minimal additional engineering effort

6.3.2 Advancement of Subsystem Work

In parallel with site and supply challenges:

- Steamology completed system design, modelling, and subsystem validation
- Key technical insights were generated independent of full system operation

This approach ensured that valuable technical outcomes were still achieved, even in the absence of full demonstration.

6.3.3 Improved Understanding of Deployment Dependencies

The project highlighted critical dependencies that can inform future demonstrations:

- Early alignment with LH_2 suppliers
- Advance planning for insurance
- Timely submission and coordination of technical documentation
- Early confirmation of deployment site and infrastructure readiness

6.3.4 Recommendations for Future Implementation

Based on the experience gained, the following measures are recommended:

- **Early engagement with hydrogen suppliers** to secure delivery schedules
- **Pre-arranged insurance frameworks** for hydrogen demonstration projects
- **Phased project execution**, separating equipment readiness from fuel supply logistics
- **Stronger coordination protocols** for documentation between project partners
- **Advance site selection and preparation** prior to equipment deployment

7 KEY LEARNINGS

7.1 TECHNICAL LESSONS LEARNED – UNITROVE

A key outcome of the project from Unitrove's perspective is the demonstrated readiness of modular liquid hydrogen (LH_2) storage and handling systems. The successful completion of design, fabrication, and skid assembly confirms that containerised LH_2 infrastructure can be developed as a transportable and scalable solution suitable for deployment across a range of applications. This reinforces the practicality of modular approaches in reducing on-site complexity and enabling more flexible deployment models.

The project also highlights the importance of aligning technical readiness with external project dependencies. While the LH_2 system was fully prepared for commissioning, the inability to progress to operational demonstration emphasises that infrastructure development must be closely coordinated with fuel supply, site readiness, and compliance processes. This learning is critical for future deployments, where ensuring synchronisation between equipment readiness and operational enablers will be essential to achieving successful outcomes.

7.2 TECHNICAL LESSONS LEARNED – STEAMOLOGY

Steamology's work within the project provides important insights into hydrogen vaporisation and integrated thermal system design. The modelling and system development activities demonstrate that significant efficiency improvements can be achieved through the integration of waste heat into the hydrogen vaporisation process. This reduces reliance on external energy sources and enhances overall system performance, highlighting the value of adopting a system-level optimisation approach.

The evaluation of multiple vaporisation configurations also provides a strong technical basis for selecting appropriate system designs based on application requirements. In addition, the development and validation of hydrogen-based thermal power concepts at subsystem level confirm the feasibility of integrating hydrogen combustion, steam generation, and power production. These findings support the development of more efficient and integrated hydrogen energy systems in future applications.

7.3 System Integration and Design Considerations

A key learning from the project is the critical role of system integration in hydrogen technologies. The work undertaken demonstrates that even when individual subsystems are technically complete, successful deployment depends on how effectively these components are integrated. Parameters such as pressure, temperature, and flow conditions must be aligned across system boundaries, and these considerations should be incorporated early in the design phase.

The project also reinforces the value of modular system architectures, while highlighting the need for standardised interfaces to simplify integration. This is particularly important in multi-partner projects, where different organisations are responsible for different parts of the system.

7.4 Policy and Regulatory Insights

The project provides useful insights into the regulatory and compliance landscape associated with hydrogen demonstration projects. It highlights the importance of early engagement with insurers, regulatory bodies, and site operators, particularly for systems involving LH_2. Approval processes and insurance requirements can have a significant impact on project timelines and should be treated as key elements of project planning.

There is also an opportunity to develop more streamlined and standardised approval pathways for hydrogen demonstrations. Such improvements would reduce uncertainty, accelerate project delivery, and support the broader adoption of emerging hydrogen technologies.

7.5 Market and Industry Implications

The outcomes of the project reinforce the growing importance of LH_2 as an energy carrier, particularly in applications where high energy density and compact storage are required. Compared to alternative storage methods, LH_2 offers advantages in transport efficiency and footprint, making it well suited to specific use cases such as mobile or space-constrained energy systems.

The project also demonstrates the value of integrated hydrogen energy solutions, where storage, conditioning, and end-use systems are designed as part of a cohesive architecture. This integrated approach has the potential to improve efficiency and performance, supporting the transition towards more advanced hydrogen-based energy systems within the industry.

7.6 Best Practice for Running Demonstrations

The experience gained highlights several important considerations for the successful delivery of demonstration projects. Early identification and management of critical dependencies is essential, particularly for elements such as fuel supply, site readiness, and regulatory approvals. These factors should be incorporated into project planning with appropriate contingencies.

The project also demonstrates the benefits of adopting a phased approach, where subsystem development and validation can be progressed independently of full system integration. This allows technical progress to be maintained even when external factors impact later stages of the project. Strong coordination and communication between project partners is also essential to ensure alignment and timely delivery of interdependent activities.

7.7 Recommendations for Future Demonstration Projects

Future hydrogen demonstration projects should place greater emphasis on aligning technical development with external enabling factors. Early engagement with suppliers, insurers, and regulatory bodies will be critical to reducing delays and ensuring smoother project execution. Greater use of modelling and simulation can also support design validation and optimisation prior to deployment.

In addition, continued focus on modular, scalable system design will support repeatability and facilitate the transition from demonstration to commercial deployment. Strengthening coordination between project partners and establishing clear processes for information sharing will further enhance the effectiveness of multi-partner projects.

8 IMPLICATIONS FOR THE HYDROGEN INDUSTRY

8.1 RELEVANCE TO CURRENT INDUSTRY TRENDS

The findings from this project align closely with current industry trends towards the development of integrated hydrogen energy systems. Across the sector, there is increasing recognition that hydrogen technologies must move beyond standalone components and towards fully integrated solutions encompassing storage, conditioning, and end-use applications.

The analysis conducted by Steamology reinforces this trend, particularly through the evaluation of vaporisation and thermal integration strategies. The results demonstrate that system performance is significantly enhanced when hydrogen processing is integrated with downstream energy systems, rather than treated as a separate function. This reflects a broader industry shift towards optimising whole-system efficiency rather than individual component performance.

In addition, the exploration of hydrogen–oxygen combustion and turbine-based energy conversion aligns with growing interest in **diversifying hydrogen end-use technologies**. While fuel cells remain a dominant pathway, the findings from this project highlight the relevance of alternative approaches capable of delivering high power output and operational flexibility.

The system-level modelling further supports industry trends focused on **space efficiency and scalability**, particularly in applications where battery-based solutions may be constrained. Overall, the project findings are consistent with the direction of travel within the hydrogen sector, emphasising integration, flexibility, and application-specific system design.

8.2 Role in Decarbonisation and Energy Transition

The project demonstrates the potential role of integrated hydrogen systems in supporting decarbonisation, particularly in applications where direct electrification may be insufficient or impractical.

The Steamology analysis shows that hydrogen-based systems, when combined with thermal integration, can achieve improved overall energy efficiency by utilising both electrical and thermal outputs. This increases the effective utilisation of energy input and reduces overall system losses, contributing to lower emissions across the energy value chain.

The ability to generate high-temperature steam through hydrogen–oxygen combustion and convert it into mechanical or electrical output provides a pathway for decarbonising energy-intensive processes. This is particularly relevant for industrial applications, temporary power generation, and off-grid energy systems, where conventional low-carbon alternatives may be limited.

Furthermore, the modelling results indicate that hydrogen systems can offer advantages in energy density and storage flexibility compared to purely electrical solutions. This supports their role in enabling the transition to low-carbon energy systems, particularly in scenarios requiring high energy capacity or long-duration storage.

Overall, the findings reinforce the position of hydrogen as a critical component of the energy transition, particularly when deployed as part of integrated and optimised energy systems.

8.3 Potential for Commercialisation and Scalability

The project provides important insights into the commercial potential and scalability of integrated hydrogen systems, despite the absence of full system demonstration.

From a technical perspective, the modelling and subsystem testing conducted by Steamology demonstrate that the core components of the system—hydrogen vaporisation, thermal integration, and turbine-based energy conversion—are feasible and can be scaled to meet higher energy demands. The high-power energy flow model, in particular, indicates that hydrogen-based systems can scale more favourably than battery-based alternatives in terms of system footprint, especially when both electrical and thermal outputs are considered.

The modular LH_2 storage approach developed by Unitrove further supports scalability, enabling deployment across different sites and applications with minimal infrastructure constraints. This modularity is consistent with industry requirements for flexible and rapidly deployable energy solutions.

However, the project also highlights key challenges that must be addressed to enable commercial deployment. These include the need for reliable hydrogen supply infrastructure, effective system integration, and successful validation under real operating conditions.

Despite these challenges, the combined findings suggest that integrated hydrogen systems have strong potential for commercialisation in applications where space, flexibility, and high energy output are critical factors.

Figure 18 – Concept diagram: Scalable deployment model for modular hydrogen systems.

8.4 Recommendations for the Industry

Based on the findings of this project, several recommendations can be made to support the continued development and deployment of hydrogen technologies.

Firstly, there should be a stronger focus on **system-level integration** in both design and demonstration activities. The results clearly show that significant performance improvements can be achieved by integrating hydrogen storage, vaporisation, and energy conversion processes, particularly through the use of thermal energy recovery.

Secondly, the industry should prioritise the development of **robust hydrogen conditioning and delivery systems**, as stable pressure, temperature, and flow are essential for reliable operation of downstream technologies. Greater attention to these aspects will be critical in enabling high-performance hydrogen applications.

Thirdly, further exploration of **alternative hydrogen utilisation pathways**, such as hydrogen–oxygen combustion and turbine-based systems, is recommended. These technologies offer complementary benefits to existing solutions and may be better suited to specific applications requiring high power output or operational flexibility.

Finally, continued investment in **demonstration projects and real-world validation** is essential. While modelling and subsystem testing provide valuable insight, full system integration and operational data are required to confirm performance, reduce technical risk, and accelerate commercial adoption.

9 CONCLUSION

9.1 SUMMARY OF KEY FINDINGS

This project has demonstrated the feasibility and value of developing an integrated hydrogen energy system, combining liquid hydrogen storage, controlled vaporisation, and downstream energy utilisation technologies. Although full system commissioning was not achieved, significant progress was made across system design, subsystem validation, and performance analysis.

A key finding from the project is the importance of **thermal integration in hydrogen systems**, as identified through Steamology's modelling and concept development. The evaluation of multiple vaporisation configurations (SVS1, SVS2, SVS3) showed that systems incorporating waste heat recovery can substantially reduce auxiliary energy demand and improve overall system efficiency. This highlights the benefit of designing hydrogen infrastructure as an integrated energy system rather than a series of standalone components.

The project also demonstrated the feasibility of **hydrogen–oxygen combustion for high-temperature steam generation**, providing a viable pathway for turbine-based power generation. Subsystem-level analysis confirmed that this approach can support efficient energy conversion, particularly when coupled with thermal energy recovery.

In addition, system-level modelling indicated that integrated hydrogen systems can offer advantages in terms of **energy density and system footprint**, especially in applications where space constraints or high energy demand limit the practicality of alternative solutions.

From the Unitrove perspective, the successful fabrication and integration of the modular LH_2 storage system confirmed the engineering viability of containerised hydrogen storage solutions, designed for flexible deployment and compatibility with downstream systems.

Together, these findings provide a strong technical foundation for the continued development of integrated hydrogen energy systems.

9.2 Impact on Future Hydrogen Projects

The outcomes of this project have important implications for the design and delivery of future hydrogen projects. In particular, the findings reinforce the need to adopt a **system-level approach**, where storage, conditioning, and utilisation technologies are developed and optimised as part of a single integrated solution.

The insights generated by Steamology highlight that **vaporisation and thermal management are critical enablers of system performance**, rather than secondary processes. Future projects should therefore place greater emphasis on these areas, ensuring that hydrogen delivery conditions are aligned with the requirements of downstream applications.

The demonstration of hydrogen–oxygen combustion and turbine-based energy conversion also expands the range of viable hydrogen utilisation pathways. This provides future projects with greater flexibility in selecting technologies based on application requirements, particularly in scenarios requiring high power output, rapid response, or combined heat and power capability.

Furthermore, the project underscores the importance of **modular and scalable system design**, as demonstrated by the Unitrove LH_2 storage solution. This approach supports deployment across diverse locations and use cases, reducing barriers to adoption and enabling more flexible hydrogen infrastructure.

Overall, the findings from this project contribute to a more informed and integrated approach to hydrogen system design, supporting the transition from pilot-scale demonstrations to commercially viable solutions.

9.3 Next Steps and Future Development Areas

Building on the progress achieved in this project, several key areas for future development have been identified.

The primary priority is the **full commissioning and operational validation of the integrated system**, including the LH_2 storage, vaporisation, and downstream energy conversion components. This will enable the collection of real-world performance data, including system efficiency, operational stability, and hydrogen consumption.

Further development of **thermally integrated vaporisation systems** is also recommended, building on the findings from the SVS configurations. This includes optimisation of heat recovery mechanisms, refinement of system control strategies, and validation under varying load conditions.

For Steamology's technology, continued advancement of the **hydrogen–oxygen combustion and turbine system** is a key focus area. This includes extended testing, performance validation, and further integration with hydrogen supply systems to demonstrate full operational capability.

In addition, refinement of **system modelling tools**, such as the high-power energy flow model, will support improved system design and scalability assessment. These tools can be used to evaluate performance across different applications and operating scenarios, informing future deployment strategies.

Finally, future projects should prioritise **integrated demonstration and data-driven validation**, ensuring that system-level performance can be demonstrated under real operating conditions. This will be critical in reducing technical risk, building confidence in hydrogen technologies, and accelerating their commercial adoption.