Solid State Hydrogen Storage

Reporting on DESNZ funded projects under the Low Carbon Hydrogen Supply 2 and the Industrial Hydrogen Accelerator programmes

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Executive Summary

This report details the development of the H2GO solid state hydrogen storage technology through the deployment of Department of Energy and Net Zero (DESNZ) funded programmes. The main body of the report focuses on the deployment of the Low Carbon Hydrogen Supply 2 project entitled SHyLO: Solid Hydrogen at Low pressures. Additionally, a further project delivered through the Industrial Hydrogen Accelerator programme entitled SHyGaN: Smart Hydrogen Gas Networks is presented in the appendix.

The projects were focused on delivering the deployment of innovative hydrogen storage methods using metal hydrides along with developing a platform (HyAI) for the optimisation and management of hydrogen assets using machine learning. The SHyLO project built a hydrogen storage demonstrator which was deployed at a Kiwa Energy site in Cheltenham. The SHyGaN project completed the design of a power to heat system that was intended to be deployed at Northern Gas Networks' Net Zero Research Village (NeRV) near Newcastle-upon-Tyne. Both systems had a capability to store 38kg of hydrogen gas in H2GO's proprietary materials-based hydrogen storage system, and in addition the SHyGaN project included 100kW of electrolysis and a 45kW industrial hydrogen boiler supplied by Baxi.

This report details the work done on each of the projects and illustrates the benefits that materials-based hydrogen storage can bring when compared with alternative methods of hydrogen storage. Specifically, these include safety benefits that lead to reduced exclusion zones around storage, and hence storage density benefits, reduced risk profiles for the deployment site, the ability to store larger volumes of hydrogen and theoretically not trigger regulatory requirements, (e.g. COMAH). Work is presented on the benefits that the technology can bring when used in industrial applications and demonstrates how storage efficiencies can be increased to over 90%. The presented costs show, with scaling and commercial maturity, that the technology has the potential to be competitive with, and potentially lower than the cost of the conventional hydrogen storage method (compressed gas).

Both projects were terminated before completion as H2GO were unable to raise funds to continue operations as a company and scale the technologies. However, both projects delivered significant learnings. SHyLO was in the closing stages with demonstration started and SHyGaN was ready for build. This report serves to demonstrate the main findings of the work performed until termination and H2GO Power hopes that the provided information supports the future advancement of the hydrogen sector.

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Abbreviations

2FA	Two-factor authentication	ACOPs	Approved Codes of Practice
ALARP	As Low As Reasonably Practicable	AEM	Anion exchange membrane
AI	Artificial Intelligence	API	Application Programming Interface
ATEX	Atmospheres Explosibles	CAPEX	Capital expenditures
COMAH	Control of Major Accident Hazards	ConOps	Concept of Operations
COTS	Commercial off the Shelf	DCS	Distributed Control System
DESNZ	Department for Energy Security and Net Zero	DfM	Design for Manufacture
DSEAR	Dangerous Substances and Explosive Atmosphere Regulations	EMS	Engineering Management Systems
ET	Event Tree	FAP	Forward Action Plan
FAT	Factory Acceptance Test	FEED	Front End Engineering Design
FERA	Fire & Explosion Risk Assessment	FSM	Finite State Machine
FT	Fault Tree	GHGs	Greenhouse Gases
GKE	Google Kubernetes Engine	HAZAN	Hazard Analysis
HAZID	Hazard Identification	HAZLOG	Hazard Log
HAZOP	Hazard and Operational	HMI	Human Machine Interface
HSE	Health and Safety Executive	KPIs	Key Performance Indicators
LOPA	Layers of Protection	LCOH	Levelised Cost of Hydrogen
LCOS	Levelised Cost of Storage	ML	Machine Learning

MHx	Metal Hydrides	OPC UA	Open Platform Communications Unified Architecture
MtCO2e	Megatons of Carbon Dioxide Equivalent	PCT	Pressure-Temperature-Composition
OPEX	Operating Expenses	PFD	Process Flow Diagram
PEM	Proton Exchange Membrane	RMR	Risk Management Report
PLC	Programmable Logic Controller	SCADA	Supervisory Control and Data Acquisition
SAT	Site Acceptance Test	SME	Small and Medium-Sized Enterprise
SIL	Safety Integrity Level	SMS	Safety Management System
SMR	Steam Methane Reforming	SSHS	Solid State Hydrogen Storage
SR	Safety Requirements	TCL	Thermal Control Loop
VPN	Virtual Private Network		

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1.0 Introduction

1.1 Company information

H2GO Power is a UK based and pioneering cleantech SME founded in 2014. An award-winning spinout company from the University of Cambridge and further supported by Imperial College London. Our mission is to develop hydrogen-based solutions for renewable energy storage for zero emission, safe and reliable power supply. Our technology after years of development and deployment at scale, addresses the overall operation of hydrogen-based systems including the most underdeveloped value chain element - storage.

Our solution integrates two separate yet interconnected technologies:

I. a breakthrough solid state hydrogen storage technology demonstrating high efficiencies, cost-effectiveness, and safety, and
II. an AI-enabled software platform (HyAI) for actively managing hydrogen systems.

Our patented technology portfolio is highly scalable, widely applicable across the hydrogen value chain, and can bring a profitable social and environmental impact to its users and society in general. H2GO is a woman led company founded by CEO Enass Abo Hamed, also a Fellow at the Royal Academy of Engineering. The company has 31 employees with its R&D base in West London.

Unfortunately, H2GO ceased trading in late 2024 due to difficult market conditions. It's important to note that H2GO still believe strongly that the technology has a place to play to enable the green hydrogen transition. However, over the course of many conversations with possible investors the stumbling block was always the absence of a current viable market for the product. H2GO Power's view is that the market will need to develop significantly before green hydrogen can play a role in a sustainable energy/fuel mix.

1.2 DESNZ supported programmes

H2GO were funding recipients from two Department of Energy and Net Zero (DESNZ) programmes. The main body of the report focuses on the deployment of the Low Carbon Hydrogen Supply 2 project entitled SHyLO: Solid Hydrogen at Low pressures. Additionally, a further project delivered through the Industrial Hydrogen Accelerator programme entitled SHyGaN: Smart Hydrogen Gas Networks is presented in the appendix.

However as previously stated, due to the unfortunate situation and inability to secure funding for the company's next stage of growth, both projects were terminated before they could be finalised. The SHyLO project was terminated with approximately 3 months of duration remaining and the SHyGaN project with approximately 7 months remaining. H2GO Power hopes that this report will support innovators in the future to advance the hydrogen sector and contribute to establishing a much needed green hydrogen market and the decarbonisation of hard to abate sectors.

1.3 H2GO hydrogen technologies

1.3.1 Storage

Hydrogen storage is the hydrogen value chain's most under researched part, and critical to achieve scalable decarbonisation targets, while green hydrogen deployment remains low due to high associated costs and limited efficiency.

H2GO Power's storage technology applies specialised materials that absorb hydrogen and bind it through potent chemical bonds allowing for solid state storage at ambient and completely safe conditions, unlike conventional storage methods (compressed gas and cryogenic storage) that need to maintain special conditions associated with higher costs, prohibitive regulation and safety. Furthermore, the technology demonstrates higher cost-effectiveness and overall efficiency than state of art. The applied materials are stored in proprietary modular reactors which are integrated into containerised systems that allow the controlled charge and release of hydrogen, following a modular design approach that allows for satisfying storage demand at any scale.

The H2GO storage technology stores hydrogen through metal hydrides (MHx), using a chemical bond to lock hydrogen away, as opposed to high pressures or cryogenic temperatures to achieve high energy densities. The storage process operates at benign temperature and pressure conditions, overcoming any safety concerns encountered within conventional storage methods (compressed gas and cryogenic storage).

1.3.1.1 Benefits

Firstly, this allows deployment in locations where compressed hydrogen storage may be prohibitive due to the need of managing on-site risks, or due to the infeasibility of securing the necessary safety distances for managing those risks. These conditions for example, would be typical in applications where increased interaction with personnel is likely or near critical infrastructures. The H2GO technology has been proven to be lower risk through independent safety studies, assessing the risks of deployments. Work conducted has shown reduction of risks, as the associated exclusion zones were in the region of 5 times smaller compared to the ones for 200 bar compressed hydrogen, with benefits being further pronounced when compared with higher pressures.

Secondly, the technology allows a more efficient and lower-cost storage compared to conventional technologies. Energy losses through the thermochemical reaction are similar to what can be achieved at the higher end of compressed storage, however there are added efficiency gains that can be achieved where heat recuperation is available; work presented on the SHyGaN project illustrates how over 90% efficiency can be achieved. As many hydrogen applications require hydrogen at low pressures, compression is purely a requirement of storing the gas at a reasonable energy density. Removing the need for compression removes the need for compressors and compression, which impacts upfront and operational costs.

H2GO deploys fully automated plug and play solid state storage products that can store hydrogen, equivalent to ~1500 bar, at pressures in the region of 10 bar. The solid-state storage is more efficient and lower cost as it avoids the energy losses and infrastructure required in the case of compression or cryogenic cooling. It's safer as hydrogen is stored typically at 2% of the pressure of compressed gas and there is no risk of boil off. It's a volumetrically denser way of storing through the chemical bonds holding the hydrogen molecules together. H2GO Power's modular reactor units are designed to be stacked and contained in containerised solutions, to achieve scale and capacity.

1.3.2 HyAI - energy management optimisation

1.3.2.1 Background

Green hydrogen is increasingly recognised as a critical component for the energy transition. Globally, over 230 GW of electrolysis capacity has been announced for deployment by 2030 [1], with substantial further growth forecasted in subsequent decades. However, the green hydrogen value chain is a multi-step process involving production, storage and distribution, which is further complicated by the intermittency of renewable generation. Accordingly, the optimised design and operation of green hydrogen systems and storage assets is essential to their economic and logistical viability. Nonetheless, existing energy management software solutions primarily focus on the optimisation of battery storage. Hardware assets in hydrogen systems, such as electrolysers and compressors, have very different operating characteristics to batteries, rendering these existing technologies unsuitable. There is therefore a clear need for a software product that specialises in hydrogen system optimisation.

1.3.2.2 The HyAI Solution

HyAI is an AI-powered tool for optimizing the design and real-time control of green hydrogen systems. It leverages state-of-the-art machine learning and optimisation algorithms to create a customised Virtual Hydrogen System for each site, which maximises profitability and minimises carbon footprint. At the design stage (i.e. pre-FEED/FEED study), HyAI provides a systematic and data-driven approach to asset sizing, technology selection and project financing for green hydrogen developments. In addition to economic considerations, HyAI can estimate and explicitly optimise for decarbonisation metrics, ensuring capital is invested efficiently to abate emissions. Once hardware is on the ground and operational, the cloud-based HyAI platform can securely integrate with and control it. Scheduling decisions are made to increase revenue and reduce OPEX, while accounting for operational constraints (e.g. offtake agreements) and multiple sources of variability and uncertainty (e.g.

renewable generation, electricity pricing, curtailment, hydrogen consumption). Data from the assets is regularly collected, so the digital model continually improves and adapts over the lifetime of the site. Model-based decisions are displayed on a user-friendly interactive dashboard. The collection, storage and transfer of data follow best security practices all along the process.

The SHyLO and SHyGaN projects supported the development of HyAI with the primary objective of transforming it from a prototype, that had only been tested within the controlled environment of H2GO Power laboratory, into a fully operational product seamlessly integrated into real-world industrial settings.

1.3.2.3 Economic & Environmental Impact

By optimising the design of green hydrogen systems, HyAI can significantly reduce carbon abatement costs, thereby accelerating the adoption of these technologies in hard-to-decarbonise sectors. In a completed project for the National Grid (UK-based gas and electricity grid operator), H2GO Power utilised HyAI to optimise the design of a green hydrogen system and decarbonise compressor stations. HyAI was able to reduce the system's carbon abatement costs system by 20%, with a projected reduction of over 35,000 tCO_2e per site. Moreover, real-time optimisation of hydrogen production and storage, can reduce operating costs and energy wastage considerably. This results in a more competitive levelised cost of green hydrogen, with the additional benefit of mitigating the curtailment of renewable generation at affected sites. For example, pilot trials at a hydrogen production plant in Scotland indicate that HyAI can increase gross profit by over 25%, relative to a reactive control baseline.

2.0 Solid Hydrogen at Low pressures (SHyLO)

2.1 The Low Carbon Hydrogen Supply 2 and the SHyLO Project

In 2021, the Department for Business, Energy & Industrial Strategy (BEIS) – now renamed into Department for Energy Security and Net Zero (DESNZ) launched the NZIP Low Carbon Hydrogen Supply 2 Competition.

H2GO Power having already developed a prototype of its hydrogen storage technology, in partnership with the European Marine Energy Centre (EMEC), Abbot Risk Consulting (ARC), the Manufacturing Technology Centre (MTC) and HSSMI, submitted the SHyLO proposal for a demonstration project, which was successful and allowed the initiation of the project.

2.2 Consortium information

The SHyLO project was supported by 4 consortium partners: MTC, EMEC, HSSMI, and ARC. SHyLO was an ambitious project including various types of interrelated activities. Thus, it required an efficient management and organisational structure that could handle the project's complexity and assure smooth coordination, implementation and achievement of the project's goals. The roles of the consortium partners were as follows:

HSSMI are a sustainable manufacturing consultancy.

HSSMI led the H2GO technology scale up activities to prepare the work done and development for the next stage of growth at H2GO, along with project management support.

Abbot Risk Consulting (ARC) offer a full complement of Safety, Engineering and Risk Management consultancy services.

ARC led on safety and specifically addressed regulatory uncertainties. Supporting and advising at all stages of the project: design commissioning and, testing, ensuring that necessary hazard controls are embedded in the final system design to achieve certification.

MTC is a leading research and technology organisation at the forefront of manufacturing innovation who are surrounded by world-leading facilities and industry-leading minds. Above all, they're united in our shared curiosity and creativity, with an appetite to restlessly and repeatedly reimagine what progress looks like.

MTC were responsible for leading the build of the system and supported on certain aspects of the design work.

EMEC is a not-for-profit innovation catalyst pioneering the transition to a clean energy future.

EMEC is the world's leading accredited test laboratory and inspection body for demonstrating ocean energy technologies in the sea, spanning components and subsystems testing to full-scale demonstration. EMEC also operates a green hydrogen production and storage R&D facility.

The centre's strategic R&D focus areas in hydrogen are innovation to increase renewable integration, and hydrogen and hydrogen based e-fuels in the aviation and maritime sectors.

In 2017, EMEC generated the world's first tidal-powered hydrogen.

2.3 SHyLO project background

The UK government identified the opportunity for the use of hydrogen as a NetZero energy source [2], replacing the use of natural gas as a fuel. The key challenges surrounding NetZero energy sources include the intermittency of its availability, which highlights energy storage is more important than ever [3]. Low-pressure solid-state hydrogen storage provides an interesting alternative to other methods, such as compressed gas storage.

Green hydrogen can be produced during periods of high renewable electricity generation; therefore, it is unlikely that hydrogen can be produced at the same rate as is commercially required for hydrogen as fuel gas or other energy storage requirement. Therefore, a storage method is required to store hydrogen for periods of low generation to provide a buffer.

Currently, compressed gas technologies are being deployed across the UK as a relatively easy method of storing gas for medium to long durations, utilising underground geological facilities and pressurised vessels. The ease of its input/output of gas makes it a reliable method of gas storage, however, this method comes with its own challenges. Pressurised vessels on operational sites pose safety challenges, efficiency limitations, high costs at scale associated with compression, and require large areas of land to store.

The project designed and built a modular hydrogen storage solution with the H2GO Power reactor, which is proven and certified, storing almost 2 kg of hydrogen. The H2GO product provides a solution in cases where compressed gas storage is not feasible. This report demonstrates that the technology can achieve volumetric storage densities of up to 50-100gH2/L (section 7.3), which is higher than liquid hydrogen and equivalent to 1500 bar compressed equivalent, thus needing less floor space for storage [4]. Additionally, as the technology stores hydrogen at ambient temperatures and pressures, this report demonstrates how it makes hydrogen storage safer (section 7.4), lower cost (section 7.2), and a more efficient alternative to other storage solutions (section 10.3). This has significant cost savings (removing compression or cryogenic cooling costs), space savings as it carries lower risks ; removing or reducing many regulatory requirements, and hydrogen can be stored in periods of days to months providing the security of supply required [5].

This first construction of a modular prototype is critical for the technology evaluation at scale to establish a viable solution and a market offering in the future. The program of works investigated integrating 30 kg (~1MWh) of hydrogen in the H2GO storage reactors into a shipping container with the associated heat management and process safety controls to confirm the solution. This solution was initially intended to be integrated into the EMEC network of hydrogen assets to assess its performance and commercial viability; however, as explained elsewhere in the report it was necessary to change the location to an alternative site in Cheltenham.

2.4 Project overview

2.4.1 Aims and objectives

The aim of the project was to demonstrate and trial the H2GO technology at commercial scale, integrating a 1MWh containerised solution with the existing hydrogen infrastructure, to demonstrate a large-scale power-to-gas system. By measuring and validating a series of performance characteristics to determine the viability of the technology as a method of storing hydrogen. The full list of aims are set out in the conclusions in section 8.0 along with the progress against each.

Perceived safety concerns with large-scale production, storage, and use, are major barriers limiting the development of hydrogen economy, alongside challenges related to achieving certification. H2GO's system offers inherently lower risks than other large-scale hydrogen storage solutions and the project was developed to demonstrate this, ensuring that legislative challenges are addressed throughout. The following safety features/advantages and project components would facilitate this development of low carbon hydrogen:

- H2GO's system does not utilise high pressure storage, the main aspect of hydrogen storage that may lead to safety or regulatory issues.
- Demonstrating H2GO's solution and disseminating the results would address the public's perception of large-scale hydrogen storage being dangerous. In this solution, if a vessel was to rupture, the hydrogen would leak out slowly rather than be released instantly, which although with sound engineering and appropriate risk management has been demonstrated to be safe way to store hydrogen for decades, can be a major safety concern for compressed gas solutions.
- It can be rolled out across a diverse range of sites due to its lower operating pressure. Sites such as urban environments, inside buildings, oil and gas platforms. All are suitable locations for this technology, widening the opportunities for utilising low carbon hydrogen

- The solution requires less spacing between storage systems and other functions (production, use etc.), enabling deployment in space critical sites, key for accelerating the development of large-scale refuelling stations, industrial heat or heavy industry applications, for example.

The H2GO solution also results in a more commercially viable storage solution which facilitates the deployment of large-scale hydrogen systems:

- The project set out to demonstrate that the system can provide hydrogen at cost parity to its competitors, increasing the commercial accessibility of green hydrogen.
- By operating assets intelligently, the HyAI component, maximises the monetisation of hydrogen systems, thereby improving the commercial viability of large-scale green hydrogen projects and reducing the price of green hydrogen.
- Hydrogen production and storage hardware have unique positioning requirements (e.g. electrolyser start-up time), so better planning improves their operation. Moreover, these assets have longer operational horizons than other storage technologies such as lithium-ion batteries, meaning predicting further into the future is necessary for smart decision-making.

2.4.2 Schedule

The SHyLO project was initially planned to be delivered over a 24-month period. During delivery it was identified that the initial timelines were not possible to be achieved due to delays experienced throughout the project. These were mainly a result of technical difficulties encountered. As a consequence, 2 extensions were requested: 1 request for an extension of 6 months and a further for an extension of 3 months, resulting in a total project duration of 33 months. The schedules are presented in Appendix 2 showing the as planned project plan and the as demonstrated plan at the end of the project.

2.4.3 Deliverables

The project was broken down into 9 work packages (WP) of which each containing multiple deliverables. The work packages are presented in Table 1 with further details of the content of each presented in Appendix 3.

Table 1. Work package breakdown for the SHyLO project

WP	Title	Lead	Support	Status at end of project*
1	Project Management	HSSMI	H2GO	Complete
2	Safety Assurance	ARC	All	Incomplete
3	Design and Development	H2GO	MTC	Complete

4	Build	MTC	H2GO	Complete
5	Demonstration and Test	EMEC**	H2GO	Incomplete
6	HyAI Integration, Demonstration and Trials	H2GO	EMEC	Incomplete
7	Manufacturing Scale-up Strategy	HSSMI	H2GO	Complete
8	Technology Feasibility Review & Cost Benefit Analysis	H2GO	-	Not started
9	Dissemination and Exploitation	H2GO	All	Incomplete
*The project was terminated before completion as identified in the introduction to this report. **Subsequent issues experienced with the EMEC site resulted in the demonstration site being changed to Kiwa Energy and H2GO leading the WP. See challenges section.				

2.4.4 Financial information including baseline cost and actual spend

The total spend for the project was £4,114,063.47.

2.4.5 Dissemination

A large number of dissemination events took place throughout the duration of the project. These are presented in Appendix 1Appendix 6.

3.0 Design of the SHyLO system

At commencement of the project, the H2GO reactors had not been integrated before into a large unit and had only been scaled as a system to the size of a 300g hydrogen gas storage system. The challenge existed to design this system from the ground up and be able to navigate the complexities of ensuring the development was safe with a limited regulatory framework due to the novelty of the technology. Parallel work streams that covered safety, design and scale up commenced.

3.1 System description

The specification of the system that was developed is presented in Appendix 1. The SHyLO system comprised of:

- A 'hydrogen room' with 21 storage reactors each filled with metal hydride (MHx) powder stacked in a 3(W) x 7(H) frame; each reactor could store up to approximately 1.8 kg of hydrogen.
- An 'electrical room' with 2 electrical cabinets and 1 junction box for all electrical components and controls.
- A 'balance of plant' (BoP) room containing the heater and pump for the coolant liquid flow.
- An external chiller connected to the BoP room.

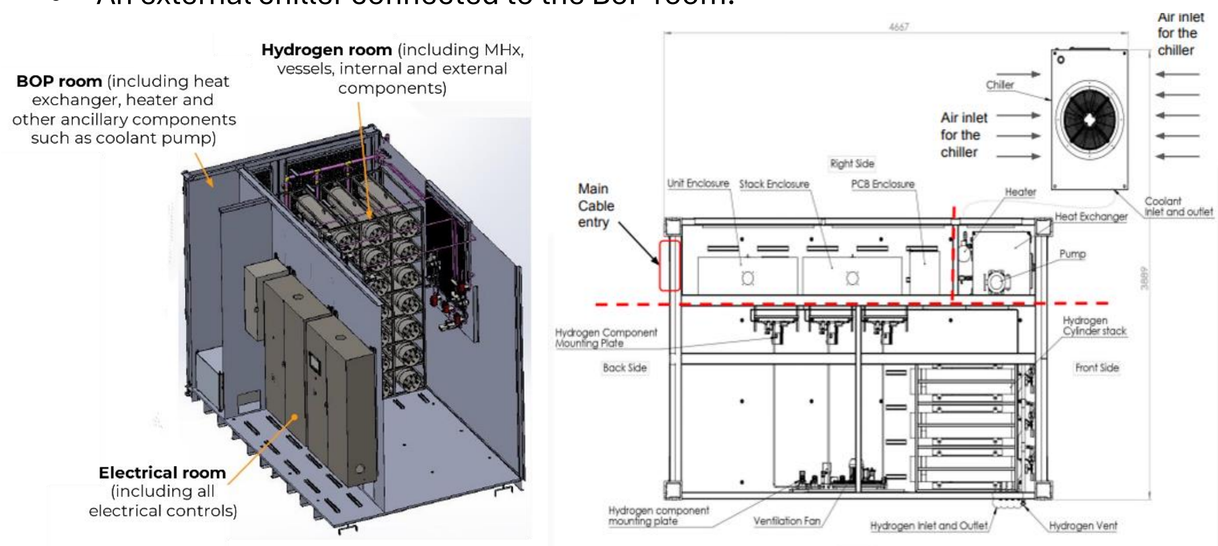


Figure 1 SHyLO Container design

The system configuration was expected to remain similar for future iterations of commercial products. However, the overall system complexity was expected to be reduced, particularly around the piping, control instrumentation and wiring. Moreover, the expectation was to significantly improve the stack frame design, increasing the stacking density and allowing for more reactors to be inserted into the container.

3.2 Safety

3.2.1 Design, implementation, operation accountability and responsibility

H2GO Power had the ultimate accountability for the design of the overall SHyLO project system. However, the design responsibility for some sub-systems and operations were delegated to EMEC, HSSMI, Kiwa and the MTC. The following accountability and responsibility relationships were in place:

- SSHS System - H2GO had the ultimate accountability for the design and installation of the SSHS systems at the Kiwa site. Activities assigned:
    - HSSMI as project manager, as well as working on future developments around the long-term manufacturing scale up strategy for the technology.
    - MTC to undertake mechanical and thermal fluid system design and system assembly.
- H2GO retained accountability for the following:
    - Supply chain management.
    - Staff competency. NB: this was assumed to be covered for the other project partners through the consortium founding process and external assessment during the grant application process.
- Hydrogen generation and hydrogen transfer - Kiwa had the ultimate responsibility to H2GO for these elements. Kiwa would generate and transfer all hydrogen supply for the SHyLO project at the Kiwa site. Kiwa checked the site's infrastructure adequacy for the SSHS systems and then ensured that any iterations or developments required to accommodate the system were completed.
- Interfaces with hydrogen artificial intelligence (HyAI) – This was to be managed by H2GO and was considered part of the overall software assurance approach covering both safety and cybersecurity considerations.
- Interfaces with utility supply - Kiwa had the responsibility, being accountable to H2GO, for the interfaces with the Kiwa test site. Kiwa would supply, or arrange supply for, all utilities at the Kiwa site, e.g., power and water supplies.
- Interfaces with HSE, ARC, and standards - H2GO had accountability for the relationships with HSE, ARC, and standards bodies during the design, development, and operations of the SHyLO project.

3.2.2 Safety activities

Within the development of the Safety Management System (SMS) for the SHyLO project, the following safety assurance activities were conducted:

- HAZID Workshops:
    - Initial HAZID.
    - Manufacturing and Integration HAZID.
    - Piping and Control Integration HAZID.
- Health & Safety Legislation Register development
- HAZAN Activities:
    - Dangerous Substances and Explosive Atmosphere Regulations (DSEAR)
- Assessment
    - Consequence Modelling.
    - LOPA and SIL Assessment.
- HAZLOG Development and Update
- Safety Review meetings:

- Weekly team meetings.
    - Safety input to Design reviews.
    - MTC H&S Meetings.
- Arising Activities
    - Review of DFMEA.
    - Review of Control Philosophy.
    - Input to Test Plan Development.
    - AI/ML Cybersecurity workshop.
    - HAZID review of Kiwa site.
    - Assessment of system design against COMAH.
    - Assessment of bounding case for 10 bar releases and site interactions.
    - FAP Development and Update

The relationship between these activities is presented in Figure 2. Safety activities and their relationships, and are described in greater detail below.

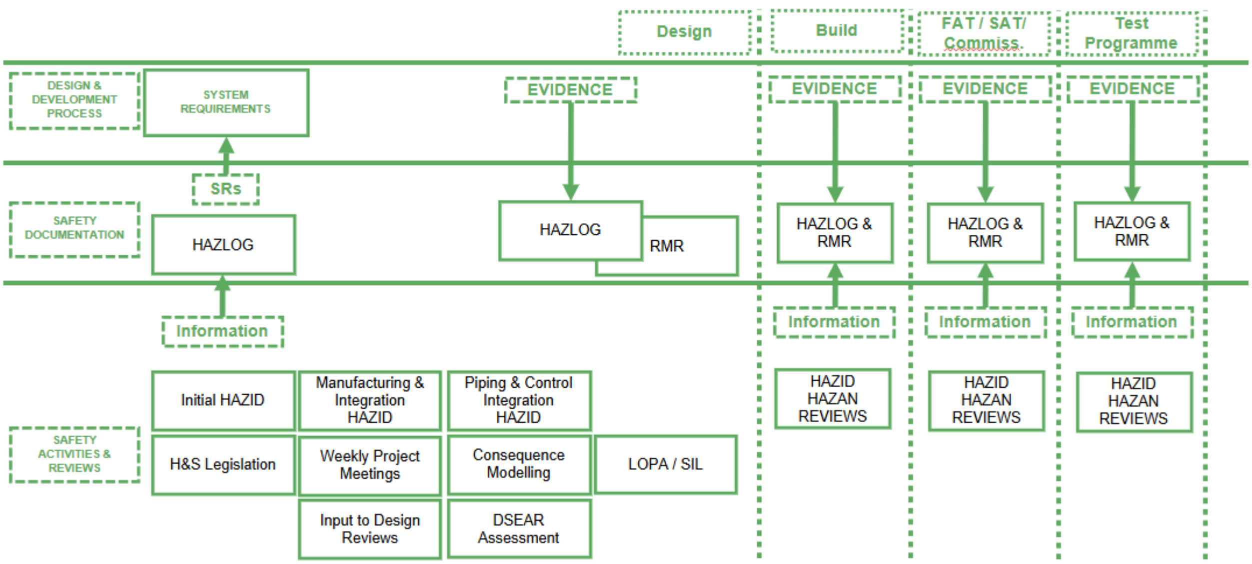


Figure 2. Safety activities and their relationships

3.2.3 DSEAR and ventilation design

The Dangerous Substances and Explosive Atmosphere Regulations 2022 (DSEAR) assessment sets minimum requirements for preventing or limiting the harmful effects of fires, explosions and similar energy-release events and corrosion to metals. DSEAR are goal-setting regulations and are supported by Approved Codes of Practice (ACOPs) that provide practical advice on how to comply with them. The DSEAR assessment was to determine the type and extent of hazardous zones that needed to be managed during operation of the deployment and would provide recommendations on how to reduce or eliminate any risks identified.

A desktop Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) assessment was carried out to determine:

- Common Assumptions - the fundamentals of the use case that bound the subsequence assessment.
- System Configuration - the system elements, interfaces, and operating parameters that all other system deployments would be variations of.
- System Layout - the system layout that was assessed.
- System Operations - an overview of the operational activities that would be undertaken with the system.
- Assessment Conclusions - the outcomes of the assessment, including any identified Atmosphères Explosible (ATEX) zones and follow-on actions to be considered or implemented in future developments.

An early decision for following a conservative approach was taken, by classifying the system as a zone 2 atmosphere, where a release and a build-up of hydrogen would be expected under normal operation, in the absence of any evidence to the contrary, and to allow procurement to begin for zone 2 rated components.

However, during the project, testing of the reactor technology and development of the system it was determined that:

- **Ventilation:** calculations for passive ventilation provided high dilution factors and with the addition of forced ventilation into the design this was significantly increased.
- **Release rates:** as the stored hydrogen was to be chemically bonded, its release rates were governed by reaction kinetics meaning that hydrogen would be released gradually over time, reducing the rate at which hydrogen could escape from a leak
- **Self-inhibiting reactions:** it is not possible to have a runaway reaction and uncontrolled release of hydrogen. This arises from the nature of the pressure-composition isotherms, which define the equilibrium between the hydrogen stored in the material and the surrounding environment. Specifically, in a closed hydrogen storage system, an increase in temperature promotes hydrogen dissociation from the storage medium, leading to a gradual increase in internal pressure, as hydrogen gas is released. However, once the internal pressure reaches the system's equilibrium point, no further hydrogen release occurs. This balance is a function of the isotherm curve, where pressure and hydrogen concentration in the storage material reach a stable equilibrium at a given temperature. This results in a highly stable system that remain safe under varying temperature conditions, without the risk of abrupt hydrogen discharge.
- **Hydrogen detection:** hydrogen detection included as part of the safety system.

Therefore, as part of the DSEAR assessment it was determined that:

- **Release type:** any release inside the container would be classed as a secondary grade release; secondary grade releases are not expected to release in normal operation.
- **Summation of releases:** as releases were not expected in normal operation, given it is unlikely one secondary source would release at any one time, only the largest secondary release should be considered.
- **Classification:** the ATEX Zone Extent inside the container was deemed n/a due to Zone 2 NE.

In conclusion zoning the internals of the system zone 2 NE reduced future complexities of the design and hence cost. The only areas of the system that required zoning were the ones where there was the potential for high pressure hydrogen to be feeding the system at the inlet and at the vent stack, where hydrogen could occasionally be expected to vent during normal operations. The zoning of the SHyLO system is shown in Figure 3 with the hatched areas indicating where a hazardous area is likely to occur.

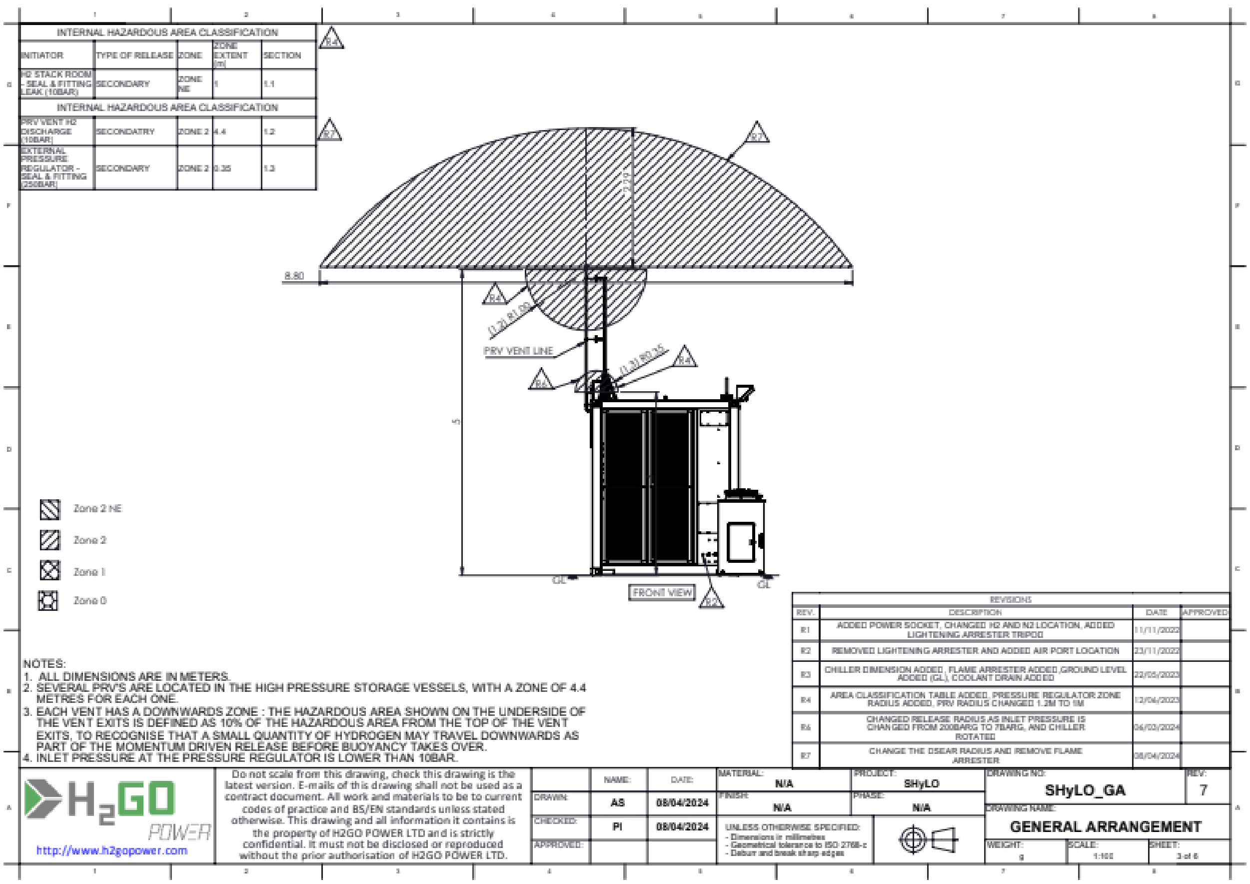


Figure 3. Hazardous area drawing extract for the SHyLO system

3.3 Electrical system

The power system in the SHyLO system was comprised of several voltage buses:

- The system power supply is connected to a single 415VAC supply from the host plant. This incoming supply is used to power 3 phase AC loads such as a heater and chiller for the thermal process control loop to control the hydrogen reactor operation.
- 230V buses are created using the individual phases of the 415VAC supply and used to power smaller protective and indicator components for the system (such as lamps).
- Two isolated 24VDC buses are generated via switched mode power supplies, one in the unit domain, and one in the stack domain. These 2 DC buses share a common ground potential.
- The 24VDC bus in the unit domain is used to power hydrogen sensing, controllers such as the system PLC, the H2GO Power XC boards and process control components such as solenoid valves and pressure transducers.
- The 24VDC bus in the stack domain is used to power all HSXC boards and all 24V sensors and actuators in all domains except for the unit domain.

A shunt trip device was fitted to the unit level incomer circuit breaker, which would be used to interrupt (disconnect) the 415VAC host input power supply to the SHyLO system if a hydrogen leak was detected - an operator would activate the emergency stop button, or it would be activated automatically if a critical fault was detected with the system power supply. In the case of a device interrupting the safety interlock circuit, the device that would be responsible for the power interruption would visually indicate this on its corresponding contactor. The PLC would also be able to read the states of the contactors on the interlock circuit and be able to deduce which protective device induced the power down.

3.4 Control logic development

3.4.1 Technology control background

The system requires control of the process to heat or cool based on the operation mode; heating to release hydrogen and cooling to store hydrogen, the rate of which depends on the release rates required. The technology was developed to enable fast cooling or heating enabling fast flow rates of hydrogen in or out of the system.

3.4.2 System control

The SHyLO system was split into several layers known as 'domains' each of which was responsible for a different function of the system. Each domain was also responsible for the safety of the sensors, actuators and controllers within its domain boundary. The functions across these domains worked together to create the product features.

Five data networks were used in the system. RS232 was used for communication between the Module Controllers and the hydrogen mass flow controllers. RS485 was used for communication between the Stack Controller, through an RS232 to RS485 data converter and the chiller unit used in the thermal control loop. The system CAN bus was used for all communication between Module, Bank and Stack and the PLC system via a data converter. PROFINET was used to communicate between the Unit Controller and the host system.

The controller hardware was designed as a single control hardware which could be used to control any domain in the system. The hardware differentiation is employed via software during flashing. Each controller would be configured after software download to be assigned to a domain (i.e. unit, stack, bank, or module), and the position of control within this domain (i.e. Module 1 or Bank 2).

3.5 Procurement and fabrication activities

Procurement was primarily handled by H2GO for the majority of hydrogen storage system:

- Hydrogen storage reactors including hydrogen storage materials
- Supporting balance of plant: e.g. pipework, controls, electromechanical equipment, ISO container, electrical infrastructure.

3.6 SHyLO unit deployment

Under the original work programme, the aim was to integrate the SHyLO system into the EMEC network of hydrogen assets at EMEC's Caldale tidal test site on the island of Eday, to assess performance and commercial viability. However, significant delays were encountered at the Caldale site, with regards to the commissioning and handover of the electrolyser which furnished under a separate project. This impacted the site readiness for integrating the SHyLO equipment and moved the schedule for system validation outside of H2GO Power's viable timeframe. This subsequently, led to the decision of moving demonstration and testing of the H2GO hardware to Kiwa 's inspection & test facilities at Cheltenham.

The Kiwa's hydrogen production plant (HPP) and technology demonstration facility has been purpose designed and built to provide pipeline quality hydrogen to its test labs at 65mbarg pressure, whilst simultaneously providing a demonstration facility for technology developers requiring access to pure hydrogen at up to 6barg pressure. It is currently operating and providing hydrogen to Kiwa's test laboratories.

The move to Kiwa was chosen as it aligned with H2GO demonstration objectives and required minimal site integration works. As the H2GO solid state storage is a low-pressure solution, it meant that integration was simpler and negated the need for compression and complex control systems; production and storage is pressure driven. Due to time and budget constraints, the decision was made to reduce the complexity of the integration further by manually controlling the charging and discharging of the SHyLO system, with limitations being the need for a clearly defined test schedule to be agreed with Kiwa and physically implemented by an operative. Figure 4 shows the delivery for the completed system to Kiwa Energy.

Figure 4. The SHyLO system being delivered to Kiwa Energy

4.0 HyAI development

HyAI had been developed to optimise both the design and real-time operation of hydrogen systems. For the SHyLO and SHyGaN projects, the primary focus was to develop and productionise functionalities that enable HyAI to control and optimise an operational hydrogen system in real time.

4.1 Architecture

HyAI was a modular software product that consisted of multiple independent components:

- Third-party data pipeline: responsible for retrieving data from third-party APIs and pre-processing it.
- Forecasting component: responsible for the creation of the forecasted quantities needed to generate the optimised schedule for the different assets of a hydrogen system.
- Telemetry data pipeline: responsible for retrieving data from the deployed hydrogen system and pre-processing it.
- Optimisation component: responsible for the creation of a discretised hydrogen system schedule. A schedule consists of all the operations of the different system assets.
- Calibration component: responsible for adaptively calibrating the model parameters that specify the system operation dynamics using live telemetry data from the deployed assets.
- Web-application: this component is the user interface that puts together all relevant information about the forecasting and the optimisation components. It displays the status of the hydrogen system and how HyAI impacts the system KPIs.

When HyAI was to be used for the optimisation of live plant operations, all components worked as part of a pipeline that run at a regular frequency (e.g., 15 minutes) to produce an updated schedule for the operation of the system assets. This pipeline is schematically depicted in Figure 5. However, each component could also be used independently. For example, for the optimisation of the plant design, the optimisation component could be used as a standalone component.

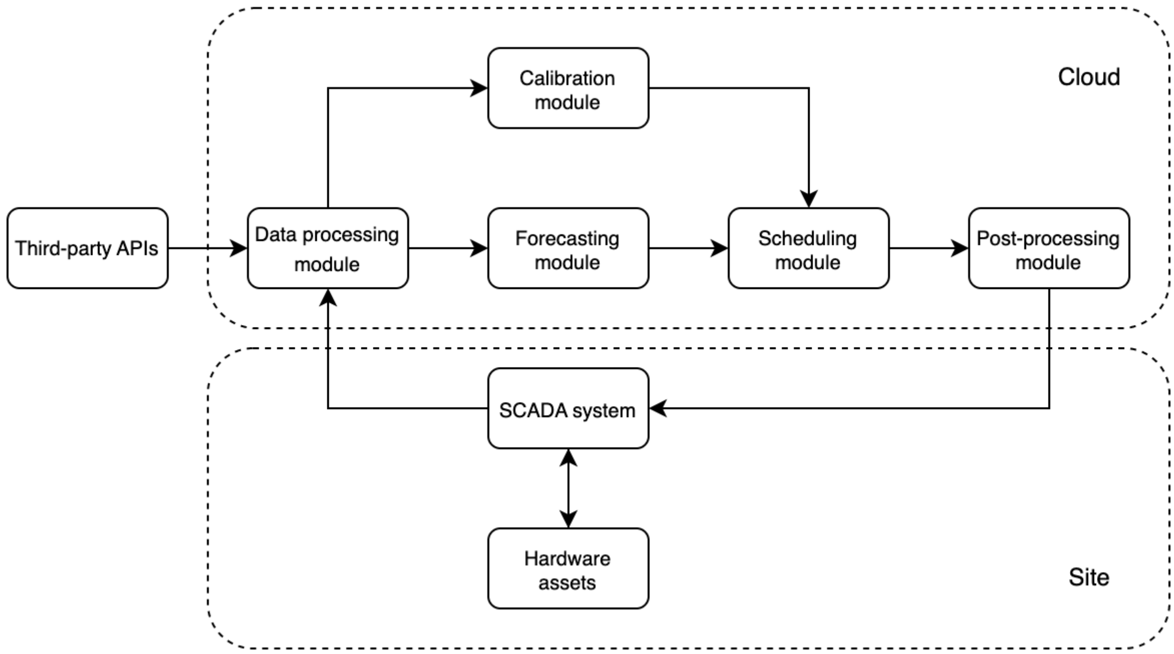


Figure 5: Schematic of optimisation workflow for live plant operation

The modularity of HyAI provided many benefits: it allowed easier management and maintainability of each component and enabled scalability at a granular level as each component could be scaled independently based on demand. It also improved the overall system performance as resource allocation could be tuned independently for each component. Fault isolation was another benefit provided by modularity, as issues or failures within one component were contained within that component. Finally, modularity simplified integration with external systems and services as each component could interact with them via well-defined and specific APIs and interfaces.

4.2 Deployment

HyAI was deployed on Google Cloud Platform (GCP) using a variety of services:

- Google Kubernetes Engine (GKE) for container orchestration (each container represented a different HyAI's component)
- BigQuery as a data warehouse

- Firestore and Cloud SQL as databases
- Cloud Storage for long term storage of data and model artifacts

Each project was deployed independently with dedicated resources (where needed) to guarantee isolation between different projects. GKEs ensured that resources for each project could scale seamlessly to satisfy any requirements. The overall infrastructure was built to handle any number of projects.

The provisioning of the GCP infrastructure was automated using Terraform, allowing for consistent management and scaling of resources through infrastructure-as-code practices. The deployment on GCP is automated using pipeline implemented as GitHub Actions. These pipelines included continuous integration and testing, ensuring that every code change was thoroughly inspected and seamlessly integrated into the production environment.

The usage of multiple environments (development, staging and production) ensured that new HyAI features and functionalities were tested thoroughly before being released.

4.3 Cybersecurity

In order to ensure the security of HyAI and the hydrogen systems it managed, H2GO Power employed a variety of security measures that include:

- A layered defence, where multiple and diverse layers of security were in place to prevent cyber-attacks from penetrating the systems (e.g., web application firewalls, virtual private networks etc.)
- Isolated components and segmented networks, to prevent exposed components from affecting other components.
- Strict user access control, employing measures such as 2FA, role-based access and principle of least privilege.
- Data encryption, during transmission and for sensitive data at rest.
- Continuous monitoring and logging, to detect suspicious activities and respond promptly to security incidents.
- Penetration testing, to increase awareness of the system vulnerabilities and minimise the impact of potential attacks.

For the optimisation of live plant operations, the final schedule layer is decoupled, which consists of the optimised schedule created by HyAI, from a security layer that independently assessed the validity and safety of the decisions made by HyAI. This prevented voluntary and/or accidental unsafe decisions from being implemented.

The ultimate goal around HyAI‘s cybersecurity was to achieve the IEC 62443 certification, a globally recognised standard for ensuring cybersecurity in industrial automation and control systems. This certification would provide assurance that systems, processes and components meet stringent security requirements designed to address the unique challenges of operational technology environments. The security measures already implemented for HyAI demonstrated a strong alignment with the foundational principles of IEC 62443, which focus on layered protections, system integrity and operational resilience. Additionally, specific steps, such as segmenting networks and introducing validation layers to safeguard decision-making processes, reflected a proactive approach for ensuring safety and mitigating risks. Collectively, these efforts established a robust security framework that was well-suited to support the certification process.

4.4 Web application

The web application, also referred to as the HyAI dashboard, was used to provide users with information about the status of their hydrogen system. It put together all relevant information about the forecasting and optimisation components, displaying the schedule created by HyAI and making it clear why specific operation decisions are made. It also displayed all relevant KPIs for the system and how they could evolve over time.

The web application consisted of two sub-components:

1. The backend, which included databases and the application logic, and handled tasks such as processing user requests, executing calculations, interacting with databases, and returning responses to the frontend.
2. The frontend, which referred to the client-side portion of the web application that users interact with directly. It involved the presentation layer, which included the user interface and user experience elements.

The HyAI dashboard could be used as part of two use cases:

1. As a reporting tool: when HyAI was integrated for autonomous control, the dashboard served as a visual interface that kept users informed about the decisions made by HyAI.
2. As an advisory tool: when HyAI would not directly control hydrogen storage assets, the web application would function as an advisory tool, providing guidance on the optimal actions to implement manually.

Figure 6 shows the dashboard developed for the EMEC site. The dashboard displays data from various assets at EMEC, including readings from a tidal turbine, wind farm, grid electricity supply, a battery, hydrogen compressor, electrolyser, hydrogen offtake and hydrogen storage. The dashboard was initially used as a reporting tool and was then intended to serve as an advisory tool during live operation, however, as detailed in section 5.0, the demonstration was moved away from EMEC.

Figure 6: Screenshot showing the dashboard for the EMEC site displaying the assets under data acquisition

4.5 Kiwa HyAI integration

4.5.1 HyBridge

The main area of integration work performed for the SHyLO unit deployed at Kiwa involved the research, development and testing of HyBridge: the proprietary H2GO software used to facilitate communication between HyAI and hardware systems, including but not limited to the SHyLO system. HyBridge was used to collect data from the deployed hardware assets, which HyAI used to create optimised schedules. HyBridge would then be responsible for communicating these schedules back to the assets.

HyBridge was functionally split into host and remote parts as depicted in Figure 7 below. This was to facilitate structured cross-environment communication while accommodating for different requirements in the cloud and site environments.

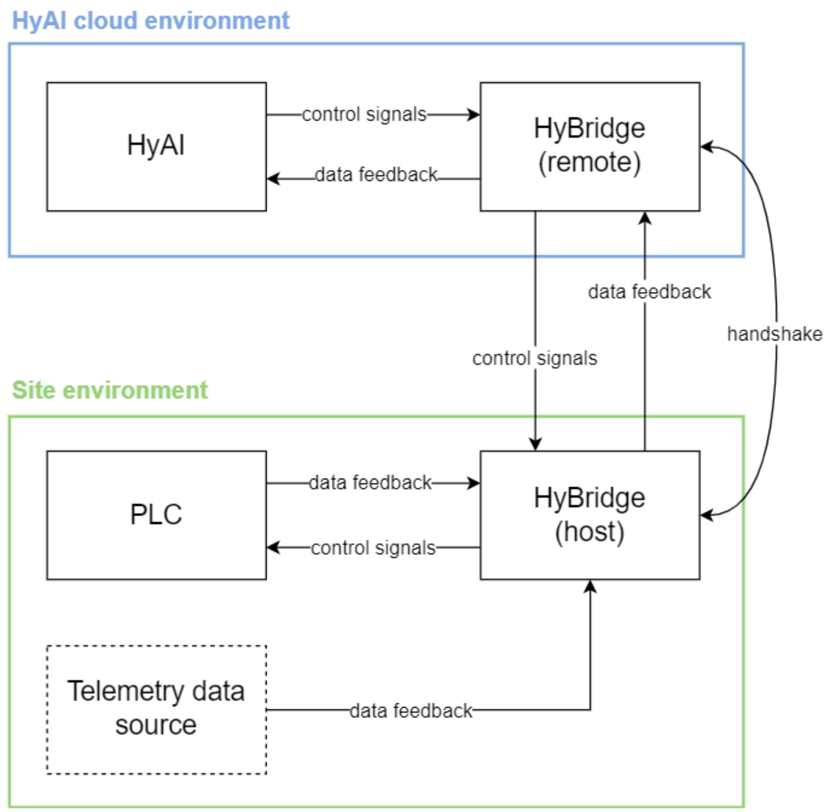


Figure 7. Summary diagram of HyBridge installation. Note that the site environment is indicative but may be different in practice.

The two HyBridge components each had an independent finite state machine (FSM) that was tightly coupled to its counterpart. This provided a highly systematic, predictable and well-defined logic flow between the pair and constrains the behaviour of the host to closely follow that of the remote, and vice versa. This allowed for safer operation by minimising opportunities for divergences in behaviour across environments. It also allowed logic to be carefully implemented and isolated in a finite number of operational states.

4.5.1.1 Operational flow

A typical operational flow is described below:

1. HyBridge Host continually reads telemetry data from the host system and transmits it to HyAI via a private OPC UA connection
2. Operator on site requests a HyAI remote control session. This may be initiated through a SCADA system or an HMI.
3. Remote control request is registered in a PLC (or another site controller) that communicates with HyBridge Host.
    1. Typically, the PLC is configured to host an OPC UA server and HyBridge uses an OPC client to communicate with the PLC (over local ethernet connection)
4. HyBridge host initiates handshake with remote

5. If the handshake initiation succeeds, a remote-control session is created. Else, an error is fed back to the host hardware system.
6. HyAI monitors the state of hardware system and as dictated by the control policy, issues control signals that get passed to HyBridge Remote which checks the signal and, if possible and safe to do so, passes it to its host counterpart
7. HyBridge Host relays control signal to PLC which actions the signal
8. Operator stops remote session

4.5.1.2 Versatile hardware interfacing

The HyBridge host component was designed in a modular and extensible fashion that allowed interfacing with a variety of hardware devices and other data sources operating on protocols such as OPC UA, Modbus TCP, serial protocols such as RS232, and more.

4.5.2 Kiwa deployment

The HySTOR deployment in SHyLO presented the first opportunity to test HyAI on a tangible, full-scale hardware system. Prior to this, the software had proven extremely useful in feasibility studies and projects by providing highly flexible and detailed simulations of energy systems. The clear next step was to use the software to control actual field assets and compare simulated and real control behaviour and performance. The missing piece of this puzzle, however, was the ability for HyAI to communicate with H2GO Power’s hardware in a secure and structured fashion. This led to the inception and development of HyBridge.

4.5.3 HyBridge software

As discussed above, the entire HyBridge system was architected and developed from the ground up during the SHyLO project. Initial development work included:

- Architecture and development of all application software.
- Design and algorithm implementation of novel handshake protocol for secure communication.
- Setup of all cloud resources, including databases, services and communications, to realise the cloud-based part of the system.
- Setup of VPN services for end-to-end encryption of remote communications.

4.5.4 HyAI validation testing

A test rig shown in Figure 8, was developed in order to test and de-risk HyBridge before deploying it at the Kiwa site. The concept was to use the same electrical and software architecture as SHyLO, to safely simulate its operation on a smaller scale. This test rig comprised a scaled-down version of the SHyLO system with only a single storage reactor.

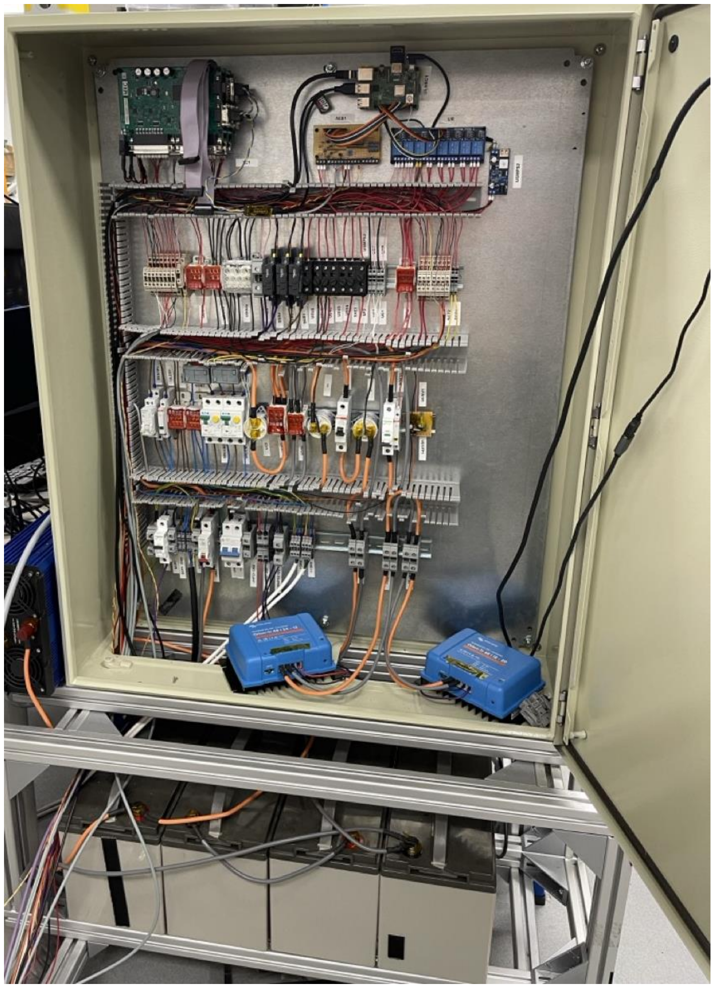


Figure 8. Electrical enclosure of the HyTest rig

This rig was used extensively to test multiple systems and functionalities in the SHyLO system, including but not limited to:

- Interaction with HyAI using the new HyBridge software. This included testing:
    - The acquisition of telemetry data from field sensors and publishing it to H2GO Power's cloud data stores for retrieval by the AI optimiser.
    - Transmission of remote-control signals from HyAI to the hardware, verifying that remote actuation could be achieved in a controlled and safe manner.
    - Failure modes and edge cases in the remote-control process.
- Testing embedded microcontroller code before it was deployed into the SHyLO system. This allowed for a much quicker feedback cycle for testing logic and identifying and rectifying bugs.
- Validating and finding shortcomings in the SHyLO control philosophy, for example, determining that the coolant pump needs to be turned on shortly before solenoids are actuated or that the conditions for initiating charge/discharge need to be refined.

5.0 Demonstration study

For the demonstration study the SHyLO unit has been integrated to Kiwa HHP as shown in the process flow diagram in Figure 9.

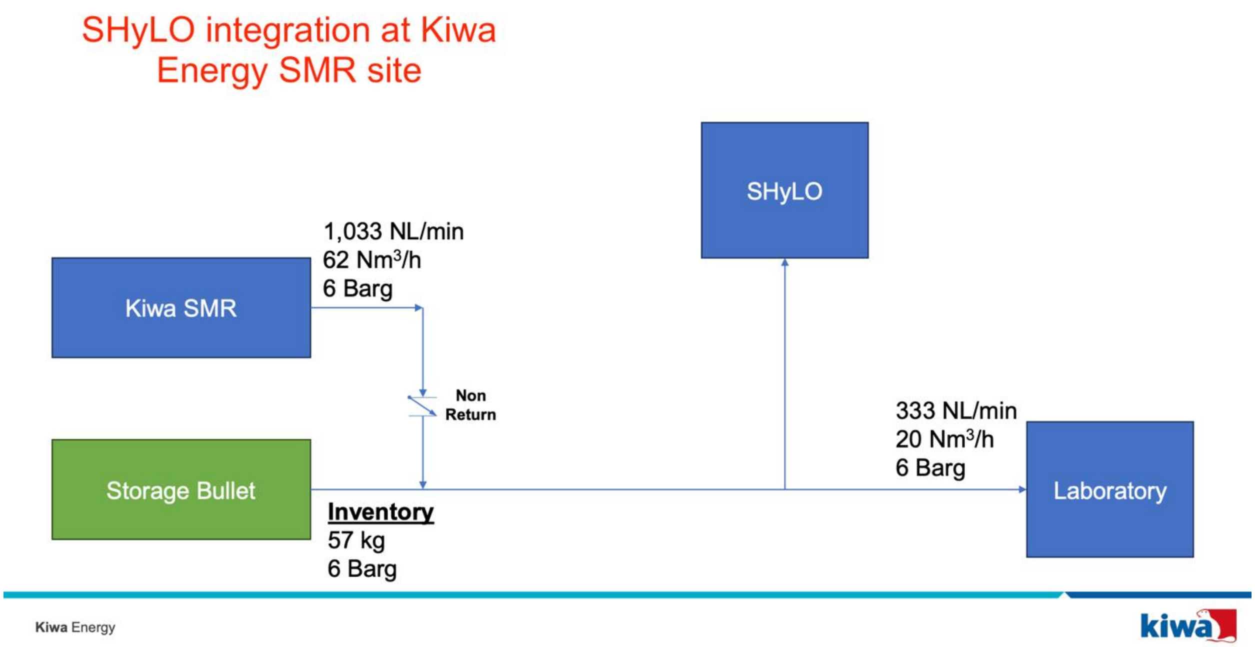


Figure 9: Process flow diagram of SHyLO unit integration at Kiwa SMR site

The Kiwa SMR produces hydrogen from bio-methane at a pressure up to 6 barg, which is directed either into a storage bullet with a volume of 106m^3 equivalent to ~57kg of hydrogen or into Kiwa laboratories where it is employed for testing hydrogen powered boilers.

Figure 10 shows an aerial picture of Kiwa HPP where the SHyLO unit can be seen on the lefthand side and the pressurised storage bullet on the righthand side.

Figure 10: Kiwa HPP site with H2GO Power SHyLO unit (left side).

5.1 Demonstration objective

The overall objective of the demonstration was to validate the system under a range of operational conditions, confirming whether product assumptions held at scale. Key considerations included:

- Hydrogen flow rate from the H2GO reactor was controlled by heat in or out, depending on whether in desorption or absorption mode.
- System control at scale was a crucial validation point of the demonstrator unit.
- The feasibility of the demonstration would be assessed on the ease of the system to tolerate the flow rates and pressure at the demonstration site.

The test programme was divided into hardware and software elements respectively, testing of the SHyLO modular prototype and the HyAI platform.

Hardware: HySTOR, SHyLO storage system:

- Assess H2GO technology as a stack of 21 reactors.
- Vary rates of hydrogen desorption.
- Test as a full stack or as individual banks/columns of 7 reactors.
- Understand product performance at reduced hydrogen flows.
- Assess across full depth of hydrogen discharge.

Software: HyAI platform

- Demonstrate the ability of the HyAI platform to accept and process data from H2GO hardware products.

- Modify & optimise system operating parameters for operation and predictive maintenance.
- Minimise unplanned downtime.;
- Demonstrate interface between the site SCADA and HyAI to control H2GO hardware
- Products.
- Test phases will include periods of remote control and forms of ‘autonomous’ operation.

6.0 Technology scale up

The activities for scale up investigated an effective manufacturing strategy for the H2GO Power hydrogen storage solution that would enable wide roll-out of the technology across the UK. The activities defined a high-volume manufacturing process, key suppliers in the supply chain and opportunities to improve design for manufacture characteristics.
Work was carried out detailing a blueprint for a manufacturing line including a high-volume bill of process, bill of sequence, cycle times, required manufacturing equipment and material handling activities that would be required to enable the high-volume scale-up of H2GO Power hydrogen storage solution.

6.1 Methodology

To develop a manufacturing strategy that allowed for volume production of the H2GO Power hydrogen storage system, a series of steps were undertaken throughout the duration of the SHyLO project as more defined information on the product design and assembly process became available. The ultimate goal was to outline the future manufacturing facility concept along with the definition of the main utilities and labour requirements. These, in turn, were considered to estimate the overall capital investment needed to support the business.

The main steps that will be covered in detail in the next sections are:

- **Product Definition:** the SHyLO unit was built to demonstrate the effectiveness of H2GO Power hydrogen storage technology and as such it is expected that a future commercially available unit would undergo further design modifications. Starting from the current system design and Bill of Material, the target commercial unit was defined, and the expected production volumes were agreed with H2GO Power.
- **Process Development:** once the product was defined, the optimal production process and assembly sequence were identified, including the Design for Manufacture (DfM) suggestions, recommendation for equipment suppliers and minimum quality requirements.
- **Layout Development:** based on the process flow and the footprint of each production area as well as of the storage area, a full manufacturing facility layout was developed.
- **Labour and Utilities Requirement:** the assembly process and the layout developed were used to estimate the labour and utilities required to run the facility.

- **CAPEX and OPEX evaluation:** the overall capital investment needed to support the first years of the business was calculated by evaluating the initial CAPEX to set-up the manufacturing facility as well as the annual OPEX to run it.
- **Supply Chain Analysis:** as part of the manufacturing scale-up strategy, a particular focus was given to the sourcing of the key metal hydride (MHx) material, which was at the core of the solid-state hydrogen technology. This included the identification of the raw material's geographical location as well as the identification and initial engagement with material suppliers to understand the implications of logistics costs as well as to inform a long-term sourcing plan for key materials.

For the purpose of developing a scale-up strategy, HSSMI considered a modified system design consisting of:

- 20ft or 40ft container divided into three zones, the hydrogen room, the electrical room and the balance of plant room. The larger size (40ft) would enable insertion of multiple stacks of reactors at each end of the container, while the standard shipping size (20ft) would reduce complexity in handling, transport, and shipping.
- Hydrogen room containing the reactors stacks. The H2GO Power target stack frame design was a 6(W) x 8(H) reactor configuration for a total of 48 reactors. However, from a manufacturing point of view this configuration presented several challenges, the handling of the stack being one of the most difficult due to the considerable weight (approximately 10 tonnes). Hence, due to current uncertainties around the stack design, HSSMI agreed with H2GO Power to start the manufacturing strategy analysis by considering a 40ft container with 96 reactors arranged in 4 stacks of 24 reactors each, namely with a 3(W) x 8(H) reactor configuration. H2GO Power future commercial product would be a 20ft container with 96 reactors arranged in 2 stacks of 48 reactors each. This would be dependent on future progress being made on the stack frame and system design,
- Electrical room with only 1 electrical cabinet and 1 junction box as a significant reduction in electrical components was expected for future systems.
- Balance of plant room containing the heater and pump for the coolant flow and external chiller, as no major changes were expected for this part of the system.

To summarise, the main changes from the current SHyLO unit and commercial product used to develop the manufacturing strategy were the container size and the number of reactors per container. The process for assembling the containerised unit will be presented in detail in the next section.

6.2 Manufacturing scale up

HSSMI assessed the H2GO process development for the unit build as well as recommendations and changes to achieve the desired production volumes and meet the cycle times. Equipment manufacturers and suppliers were also identified for the critical process of filling the reactors with the MHx material. Finally, as part of the process development for volume production, a build book template was created to capture all the sub-assembly and assembly steps, with the aim of facilitating the creation of a comprehensive record of the unit build and informing future builds.

A summary of activities that were carried out are as follows:

- Bill of Process, looking at
    - Reactor Filling
    - Reactor Activation & Conditioning
    - Reactor Stack Assembly
    - Electrical Cabinets Assembly
    - Container Assembly and FAT
    - Build Sequence
- Design for Manufacture
- Reactor DfM
- Container DfM
- Filling Equipment
- Build Book
- Process Failure Mode Effect Analysis

Based on the results from the manufacturing activities, the overall building and external facilities footprint was calculated, as reported in Table 2. Facility footprint estimation.

Table 2. Facility footprint estimation

Production Area	**SQM Estimation**
Inbound and Warehouse	876
Reactor Filling	56
Reactor Activation and Test	105
Reactor stack Assy	56
Container Assy	128
Balance Of Plant Assy	32
Electrical Assy	80
Customisation	64
Offices and People Support Areas	230
Gang ways and Walk isles	675
Container Testing	238
Utilities (Hydrogen, Compress Air, DI Water, Power, etc.)	264
Waste Areas and Yard	72
TOTAL Building Area	**2,876**
TOTAL External Facilities	**566**
TOTAL Site Area	**3,442**

The overall site size was estimated taking into account additional space around the facility for parking spaces, for trucks to have access to the site for deliveries and for picking up the finished container. The final layout is shown in Figure 11.

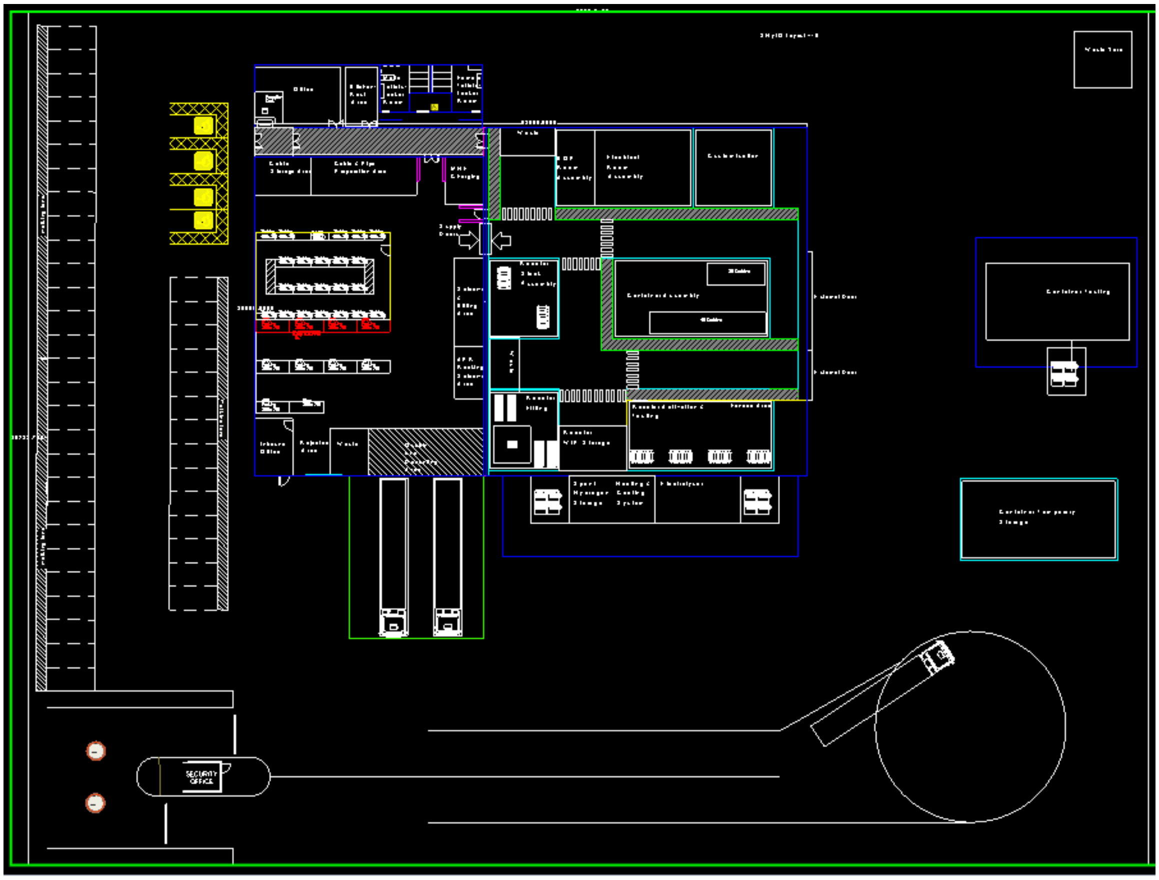


Figure 11. Final facility layout

6.3 Project acceleration support

As part of the funding H2GO utilised acceleration support provided from associated partners. The support researched how the markets were likely to evolve, and future trends associated with 3 sectors:

- Hydrogen Mobility (eg. Hydrogen vehicles)
- Hydrogen Infrastructure (eg. Fueling stations)
- Hydrogen Heavy Industry (eg. hydrogen for power)

The feedback provided was valuable to acquire specific external viewpoints on areas where the H2GO technology could play a role in the future, and feed into future strategies.

7.0 Project impact

7.1 Technology technical progress

At the beginning of the project a prototype of the technology had been tested in a representative environment and therefore in a position to meet TRL 6. The product was used for demonstrations including in an on-site demonstration at the Royal Institution in December 2020 coupled with a fuel cell, see Figure 12, illustrating that the technology can be used as a stand-alone system to provide safe and low-pressure backup power.

Figure 12. H2GO Power hydrogen storage unit demonstration low-pressure hydrogen storage at the Royal Institution

At the end of the project the technology was approaching TRL 8; through the deployment on the SHyLO project TRL 7 was being demonstrated at the Kiwa Energy site (Figure 13), and in parallel on the SHyGaN project as discussed in Appendix 5, the system was in the process of being integrated into a commercial design at the Northern Gas Networks site.

Figure 13. SHyLO unit deployed at Kiwa Energy

7.2 Technology economics

Use of the H2GO technology to store hydrogen was generally suited to typically short-term storage, because of the higher CAPEX costs, which was also true of compressed gas storage, generally seen as a main competitor for solid state storage. The SHyLO project was able to validate the cost of the technology through building of a commercial scale system.

Technology economics were to be defined by the use case and specific requirements of the application. For example, key drivers for cost of storage such as:

- Asset utilisation (cycles per day).
- How the system is integrated into the wider site and ability to utilise waste heat streams.

Furthermore, key drivers for the technology economics independent of the use case were that similar to many new technologies that go through the commercialisation journey. The SHyLO unit was the first system developed by H2GO at the scale for use in commercial applications and provided valuable data that inform the scale up costs. Key drivers that would impact economics is scale up are as follows:

- Design for Manufacture
- Supply chain maturity
- Volumes

When considering the technology economics, a baseline has been drawn from literature for compressed gas, as previously mentioned seen as the closest competitor. When comparing the H2GO storage with compressed gas it is important to also consider the cost of compression including the cost of the compressor itself. Literature costs for the cost of compressed gas storage differ between sources and for example range between £0.61/kgH2 [6] to £1.39/kgH2 [7]. These costs include the cost of the storage vessels themselves, and the costs involved in compression.

The H2GO process required energy to heat and cool the system as detailed in section 7.3. However as also described in the SHyGaN project in Appendix 5, and section 10.3 when recovering heat, efficiencies over 90% are achievable. Figure 14 presents the H2GO LCOS for 2 scenarios; where heat recouperation is not possible and where it is. Figure 14 also presents a range of costs for compressed storage as identified above for the purpose of a comparison.

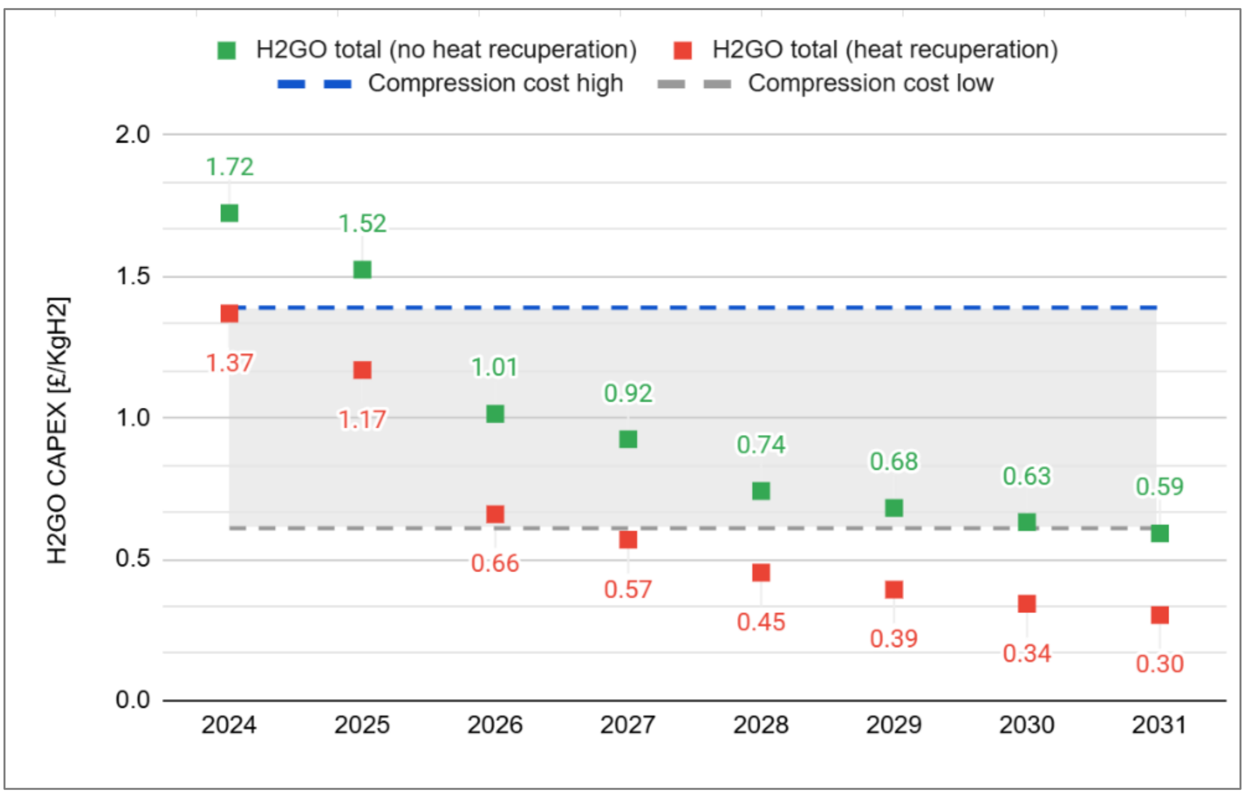


Figure 14. LCOS for the H2GO technology with comparison against compressed storage alternatives

In all scenarios it was predicted that the H2GO LCOS would be lower than compressed in the long run as the technology would be scaled, although the LCOS presented here for compression does not include any foreseen cost down. Reductions would be expected to be seen, however any progress would be viewed as modest, as in comparison to the H2GO technology, compression storage is a mature technology and has been around for a significant amount of time. The cost down of the H2GO storage would be more aggressive as it corresponded to a first of a kind system, at the beginning of the cost down journey, as described in section 7.2.1.

It is important to note here that while it is important in some markets for the business case to undercut existing methods of storage, as discussed elsewhere in this document, the technology has additional significant benefits to offer. While on the journey to meet cost parity there would be applications where solid state would be the only technology that could be deployed due to safety considerations, that would impact the exclusion zones, planning and space requirements. In addition, the costs presented here are for modest hydrogen storage amounts. Discussed later in this document are the potential benefits of the H2GO technology in consideration of the COMAH regulations. Therefore, when hydrogen storage would be required in excess of 5 tonnes there would be cost benefits equal to savings of millions of pounds over the lifetime of a project for the permitting and management costs, further improving the cost benefit of the technology.

7.2.1 Technology cost down

The LCOS has not been presented for the demonstrator system as it corresponded to a first deployment prototype. However this deployment brought the capability to determine accurate costs for a system that could be built following this trial, and subsequent future costs were calculated from the improvements that are detailed in section 6.0 and generally include:

- **Maturing and understanding of the regulatory barriers and requirements**. H2GO expertise sat in understanding the regulatory landscape and developing the system accordingly. In cases where there were no regulations or regulations were still evolving, H2GO Power was influencing these and that could be demonstrated through different engagements. This enabled design choices to be made such as around ATEX requirements (for explosive atmospheres), and being able to demonstrate how leak rates and risks of hydrogen gas escaping would be significantly lowered through the H2GO tech, meaning that the systems would be classed as Zone 2 NE (negligible extent) and expensive ATEX components would not be required. This corresponded to a significant proportion of cost associated with the BoP.
- **Manufacturing improvements.** Many of these improvements were underway and directly associated with volume scaling. As large units were to be built, the capability of optimising design to maintain performance and reduce cost was a focus. Additionally, many processes were currently manual and an investment into upscaling and automation would realise meaningful cost improvements. One

example on this, would be moving away from manual filling of reactors, to applying a bulk powder filling machine using a vacuum for fast filling. This would reduce the process from minutes to seconds.

- **Supply chain diversification**. A supply chain chain consisting of a global map of diverse suppliers was being established through utilising H2GO IP and knowhow around hydrogen storage materials . One example of a recent supplier sourcing exercise demonstrated a 35% reduction in cost to what originally was projected for the materials' component. Another example was looking at the effect of particle size on performance and simplifying the manufacturing process, which had a significant impact on materials cost.
- **Product improvements.** Product KPIs focused on improvements to reduce the overall system costs overall system whilst enhancing performance. These included the following:
  - **Usable hydrogen.** Optimising the amount of hydrogen usable in each reactor. This was already high at 90%.
  - **Packing density (system).** Optimising the amount of reactors that could be installed into a system.
  - **Packing density (reactor).** Optimising the amount of material that could be filled into each reactor.
  - **System efficiency.** Optimising the amount of energy required to power the absorption and release of hydrogen. This was achieved by optimising the balance of plant and through heat recuperation, an optionality that exists in many deployment environments.
  - **Cycles**. Increasing the number of cycles that the system could carry out in its lifetime.

7.3 Technology performance metrics

The following parameters were taken into consideration to establish the performance metrics of H2GO Power technology:

- Purity of hydrogen output
- Operating pressures and temperatures
- Hydrogen release rates
- Storage densities (volumetric and gravimetric)

H2GO Power technology is agnostic to the source of hydrogen. The system's output hydrogen purity is highly dependent on and is always greater/equal than the purity of hydrogen input. Assuming an input purity of 99.9995%, it is to be expected an output purity of ≥ 99.9995%. To validate this, a purity measurement was conducted by a third-party company on a lab scale and the results confirmed an output purity of 99.9995% (Type 1, Grade E and Category 3 specified in BS ISO 14687-3:2014(E)). The results of the gas analysis can be found in Appendix 1Appendix 4.

In the H2GO Power system, hydrogen is chemically bonded to H2GO Power storage material and stored in near-ambient pressure. The operating pressure is highly dependent on temperature and state of charge of the material as indicated by PCT (Pressure-Temperature-Composition) curves.

The absorption and desorption of hydrogen in H2GO Power systems occur through reversible reactions (up to 18,000 cycles). Hydrogen absorption takes place at temperatures ambient temperatures via a thermodynamically favourable reaction (requiring active cooling). Conversely, hydrogen release occurs through a thermodynamically unfavourable reaction that requires active heating at low-grade temperatures.

In the case of SHyLO, storing 38kg of hydrogen, comes with a charge/discharge rate of 90kgH2/day. Based on the above energy requirement the round-trip efficiency (RTE) for SHyLO was calculated to be 73.3%, however, if the system allows for heat recouperation (as described in Section 10.2 for the SHyGaN project), RTE efficiencies can exceed 90%.

One of the main advantages of H2GO Power technology was the high volumetric hydrogen storage density compared to other conventional storage technology. The current volumetric density was 62.7 g/L and is comparable with LH2 (70 g/L) and exceeds by far the density of compressed H2 at 700atm (39.6 g/L). It is expected that work conducted on optimising the compaction of the powders within modular vessels to achieve a random packing density of 64%, could lead to volumetric densities as high as 71.2 g/L. The relatively low gravimetric hydrogen density, made H2GO Power technology suitable for stationary applications where the overall weight of the system did not represent a barrier. Although H2GO Power systems were not suitable for hydrogen transportation and had lower release rates when compared to compressed hydrogen, the high volumetric density and the inherent safety of the technology can allow larger deployments enabling the use of hydrogen in areas where compressed or liquid hydrogen remains prohibitive. Section 7.4.2 in this report highlights the advantages of H2GO Power storage densities in more details. While hydrogen flow rates were lower than what could be achieved with compressed hydrogen, they were still suitable for the majority of use cases. Further details on flow rates can be found in Section 8.2 of this report. Where a very fast flow is required, for example, in refuelling applications, it may be beneficial to co-locate compressed with solid state to create a hybrid system, storing the majority of hydrogen in solid state and gaining the safety and density benefits, with a suitable amount stored as compressed gas depending on demand.

The SHyLO unit was integrated with Kiwa Energy's Steam Methane Reforming (SMR) plant, as outlined in Section 5.0 of this report. The SMR produces hydrogen from biomethane at a maximum pressure of 6 bar.g. The hydrogen would then either be directed to Kiwa Energy laboratories, where it would be used for testing hydrogen-powered boilers, or stored in a bullet tank with a volume of 106 m^3, equivalent to 57 kg of hydrogen at 6 bar.g. The demonstration flow diagram for SHyLO commissioning scenario can be seen in Figure 9: Process flow diagram of SHyLO unit integration at Kiwa SMR site.

During the Site Acceptance Test (SAT), the SHyLO unit was initially assessed using a 95:5 nitrogen-hydrogen mixture. This allowed for a leak check and eliminated any risk of an explosive atmosphere while validating the operational modes. At this stage, the modular reactors were kept isolated to avoid unnecessary consumption of the nitrogen-hydrogen mixture.

Upon completion of the SAT, the entire system, including the modular reactors, was exposed to pure hydrogen from the SMR site to proceed with commissioning. Over two consecutive days, a total of 25.83 kg of hydrogen was absorbed, which equates to 68% of the system's total capacity. The system was fully discharged over the following two days. A first discharge into Kiwa bullet was performed at nominal flow rate and the flow and pressure profiles are shown in Figure 15. A cold start was chosen as a starting condition. While the whole system warms up it can be possible to see a dip in flow (left) which however restores as the system temperature and internal pressure increase. A steady state is reached after about 2.9 hours when the flow rate reaches the nominal value of ~700 L/min.

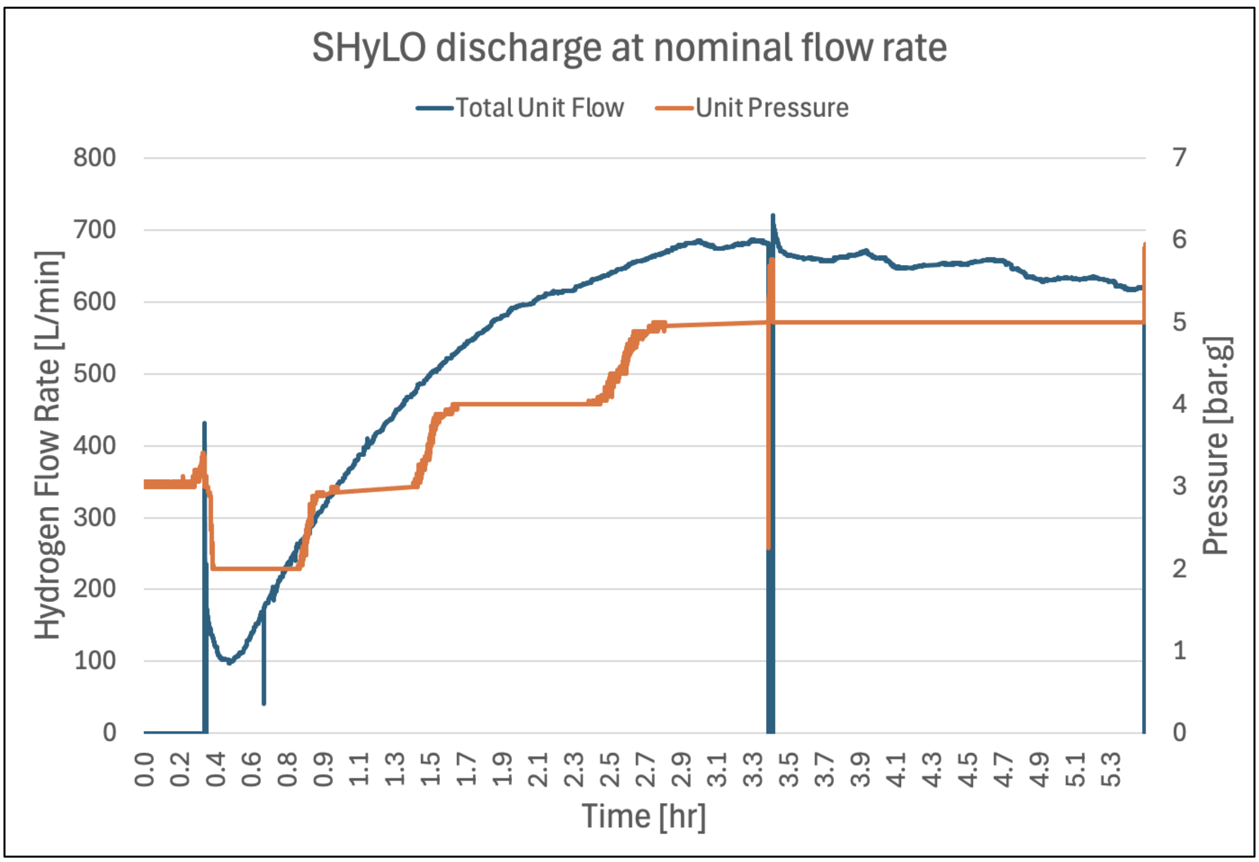


Figure 15: Hydrogen flow (blue line) and pressure (orange line) profiles for SHyLO discharge at nominal flow rate.

Figure 16 illustrates the discharging profile for the final five hours (second day of discharge), where the transition from discharge within the Kiwa bullet (green region) to the venting stage (blue region) is shown.

During the discharge phase within the bullet, the hydrogen flow rate and pressure decreased along two different profiles due to pressure equalisation between the bullet and the SHyLO unit. High flow rates, such as the nominal 700L/min, could only be maintained when the pressure differential between the internal pressure of the SHyLO unit and the downstream pressure exceeded 2.5-3 bar. Once the pressure differential falls below 1 bar, the output flow rate drops to around 20% of the nominal rate. A brief vent to the atmosphere was required to fully empty the system.

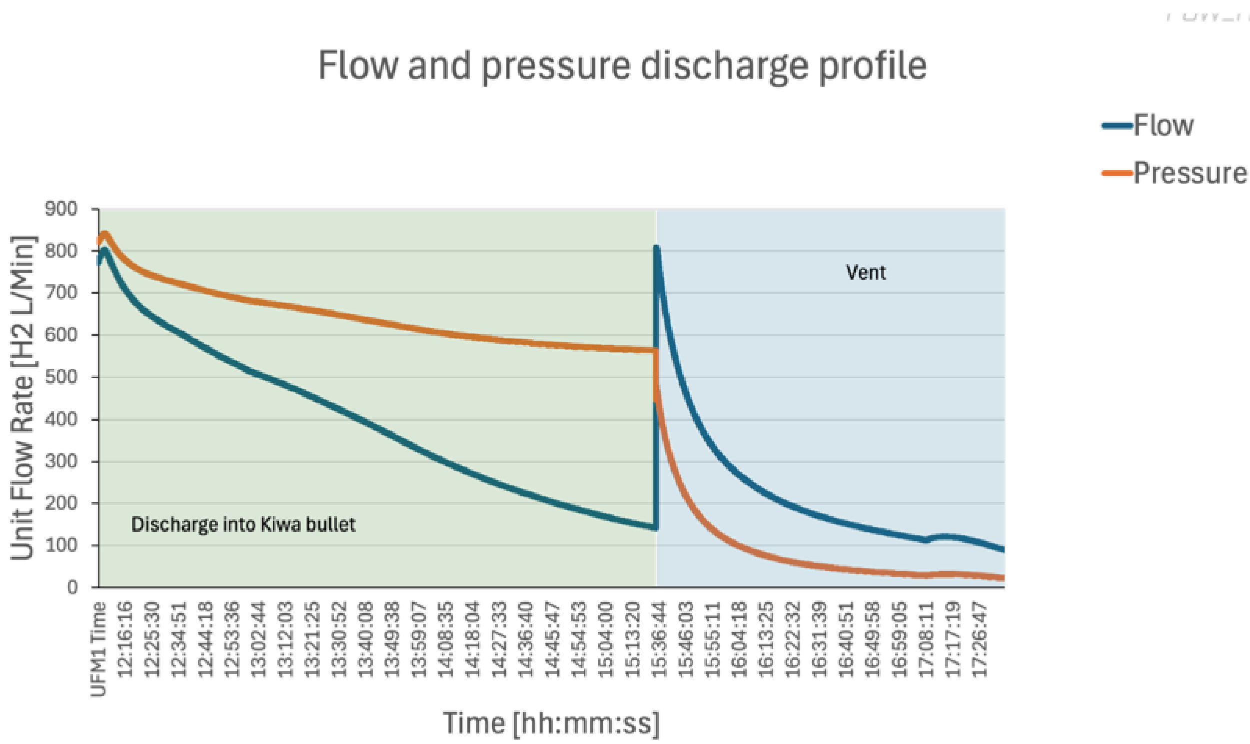


Figure 16: Flow and pressure profile for the last 5 hours of discharge showing the transition between discharge on the bullet (green area) and venting of the remaining hydrogen (blue area).

Apart from 2.25kg of H2, the remaining hydrogen absorbed during commissioning was reintroduced into the Kiwa bullet for use in the Kiwa laboratory. As explained in the previous paragraph, the venting of 2.25kg of hydrogen was necessary to allow decommissioning. In normal operation, by adjusting the downstream pressure, it is possible to use the full amount of hydrogen.

Given the limited time available for the demonstration study, it was not possible to assess the GHGs mitigated in MtCO2/year, however theoretical calculations were performed to define the same parameter based on natural gas displacement over the lifetime (20,000 cycles) based on a 200kgH2 storage commercial system.

Considering a 20% capacity loss over the system lifetime, the total energy throughput of a commercial system based on H2 LHV is 119.9 GWh which equates to a displaced emission of ~24.3 Mt of CO2 based on natural gas displacement. [8]

7.4 Technology safety and risks

The outputs from the safety activities provides significant insights into the safety benefits of the technology and can be broken down into the following areas:

- Safety distances
- Storage volumes
- Product safety and compliance

7.4.1 Safety distances

It can be intuitively concluded that storage as a high-pressure gas comes with some higher risks. The amount of energy that a compressed gas can hold under compression is significant as naturally the gas under storage wants to occupy a much larger volume, and as hydrogen under ambient pressure and temperature conditions has a very low density, storing at high pressures creates a significant amount of stored energy.

A consequence analysis was conducted to assess the qualitative impact of the effect of storing the hydrogen as a chemical bond compared with storing as a compressed gas. The EMEC Eday site was used as a reference site for this work and a compressed gas of 200 bar as that is the pressure of storage on site.

Results from the consequence assessment were provided in both tabulated and graphical formats. Using pre-determined contours obtained through research in the literature, graphical results for jet fire plumes thermal contours, flash fire thermal radiation clouds, and delayed ignition overpressure contours were applied to accurately scaled maps and site plans. Following this, tabulated results provided precise, numerical information that can be easily compared in each scenario. Using a mixture of tabulated and graphical formats allowed for a better understanding of what entities, such as personnel or buildings, could be affected by each scenario. The assessment investigated the impact of the consequence of failure by assessing credible flammable masses that could occur, jet fire modelling, flash fire modelling and blast modelling. Release modelling was carried out using Det Norske Veritas (DNV)'s Phast version 7.11.

The outputs of the study are multiple, assessing each of the different types of failures along with differing scenarios of rupture bore size, and not possible to be presented here in their entirety. However, Figure 17 and Table 3 show an example of one of the assessments for the H2GO storage and the 200-bar compressed storage which is typical of the results shown.

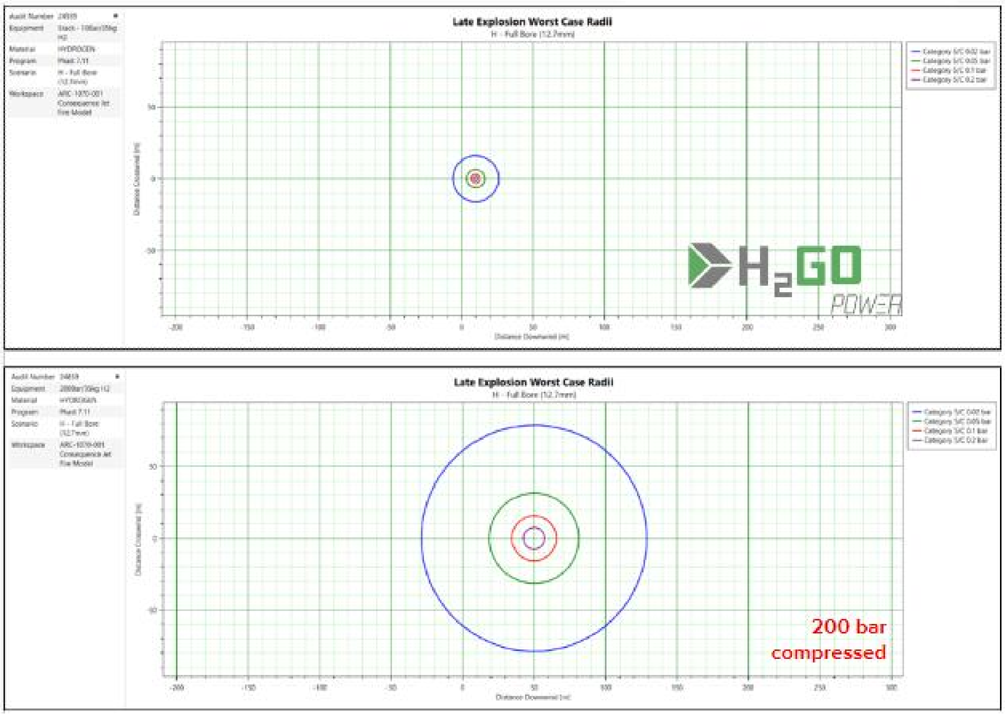


Figure 17. Extract from ARC consequence analysis report comparing H2GO storage (top) and 200 bar compressed storage (bottom)

In Figure 17 the coloured contours correspond to differing overpressure distances with a clear reduction in radii with the H2GO technology.

Table 3. Blast overpressure analysis comparison between H2GO storage and 200 bar compressed storage [5] [9]

	Ref.	**10bar/ 35kg H2**	**200bar/ 35kg H**	**Comparison**
	Weather Condition	5m/s : C	5m/s : C	-
	Flammable Mass	0.02kg	1.95kg	+9,750%
Distance to Overpressure	0.02 bar	25.98m	128.92m	+496%
	0.05 bar	16.35m	81.36m	+498%
	0.1 bar	13.16m	65.60m	+498%
	0.2 bar	11.50m	57.40m	+500%
	0.5 bar	n/a	n/a	-

The distances to overpressure in Table 3 correspond to the effects of overpressure from hydrogen explosions - directly and indirectly on humans, as well as on structures and equipment; 0.2 bar for example is the threshold for survivability (20% probability of fatality indoors, 0% outdoors).

Whilst the analysis needs to be taken into context for the risk profiles attributed to a site, e.g. the likelihood of workers or members of the public being affected by a failure, the consequences have been shown in the analysis to be significantly reduced for the H2GO storage. It's also important to note here that the H2GO storage system densities are equivalent to a volumetric energy density of approximately 1500 bar, so the study is not a comparable like for like volumetric assessment, and the benefits would be more pronounced with a comparison with higher pressures.

The real-life impact of this for a user of the storage is a reduction in the space requirements required for the storage on site, and/or a reduction in building costs where the removal of blast/jet fire walls would not need to be constructed unlike in the case of compressed gas storage. Furthermore, there is a possibility that this benefit could determine the feasibility of deployment of a hydrogen project or not. As the green hydrogen economy grows, and storage will be required in more and more locations, deploying compressed gas may not be possible due to the space constraints or risk profile that needs to be managed on site. This in turn, would result in materials based storage as being an only option for deployment.

7.4.2 Hydrogen storage volume limitations

Hydrogen is a heavily regulated substance, it has a qualifying quantity of 2 tonnes for hazardous substance consent [10] and is classified under entry 15 of Schedule 1, Part 2 of the Control of Major Accident Hazards (COMAH) Regulations 2015. [11] Under the COMAH regulations, deployments involving between 5 and 50 tonnes of hydrogen require lower-tier safety measures, while those exceeding 50 tonnes are subject to upper-tier controls. Under COMAH regulations, large-scale hydrogen deployments may not always be possible in certain areas and locations (e.g. highly populated areas or proximity to sensitive areas) due to inabilities to adequately manage the risks or provide a suitable buffer zone around high risk storage sites. This applies to molecular hydrogen, including both gaseous and liquid forms (CAS number: 1333-74-0).

Given the inherently safer nature of chemically bonded hydrogen compared to free molecular hydrogen, H2GO Power's technology could enable large-scale hydrogen storage and deployments in areas where gaseous hydrogen would fall under COMAH regulations. As outlined in section 7.3, while H2GO Power's technology achieved volumetric densities similar to liquid hydrogen, the hydrogen in the system is chemically bonded to a storage alloy. This bond makes the hydrogen inert, requiring energy input to break the bond and release the hydrogen.

H2GO Power consulted with the Health and Safety Executive (HSE) and had positive conversations on how the H2GO solution would be considered in regard to the COMAH regulations, the details of which cannot be disclosed in the public version of this report.

At a high level the H2GO Power's systems contained small amounts of gaseous hydrogen in the system's headspace (dependent on operating pressure), with the rest being chemically bonded. Therefore the question was posted to the HSE if only the gaseous hydrogen that was stored in the system should be considered, and would the below interpretation in Figure 18: Theoretical comparison between the mass of hydrogen that can be stored with H2GO Power technology (assuming vessel at 10 bar pressure) and compressed gas before triggering COMAH regulations. on the impact of the technology the COMAH regulations be accurate.

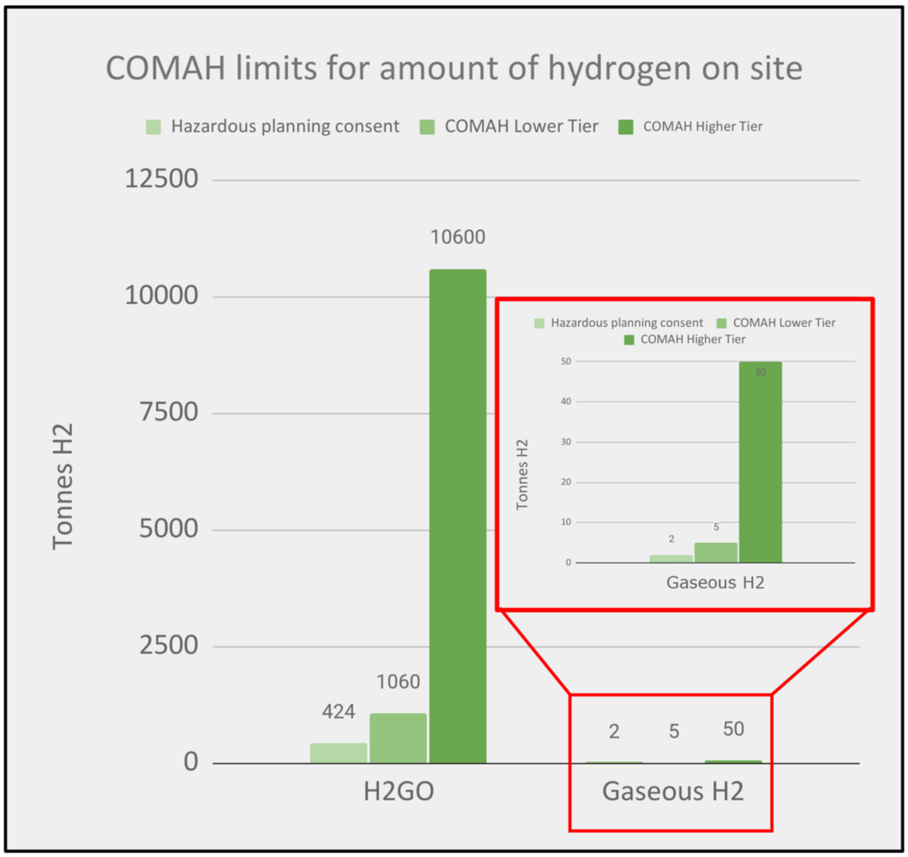


Figure 18: Theoretical comparison between the mass of hydrogen that can be stored with H2GO Power technology (assuming vessel at 10 bar pressure) and compressed gas before triggering COMAH regulations.

The figure shows that, when employing H2GO Power technology, the threshold for the lower COMAH tier (5 tonnes of molecular hydrogen) could only be reached after a total storage capacity of 1,060 tonnes. This could significantly facilitate large-scale deployments that would otherwise be restricted when using compressed or cryogenic hydrogen.

It is important to note that COMAH regulations and Hazardous Substance Consent (HSC) could also still pertain to the storage materials used in solid-state hydrogen storage systems. However, H2GO Power had prioritised and employed storage materials that did not carry any hazard codes that could classify them as regulated substances under COMAH nor HSC.

7.4.3 Product safety and compliance

Product safety and compliance has already been discussed previously in this document and can be seen in section 3.2.

7.5 Technology commercial traction

This report has set out the significant benefits that the technology can bring to hydrogen storage. As such, there have been discussions around deployments and one example refers to a scenario of investigating to use the technology as a solution for gas turbines , that they would be non-compliant by 2030.

These correspond to a large source of emissions of the wider gas sector and hydrogen has been shown to be a viable solution for reducing these emissions from gas turbines, especially when using green hydrogen from renewable electrolysis. Due to the intermittency of renewable electricity generation, hydrogen storage is needed on site to meet demand and due to the power required, significant volumes are required. Existing gas turbines can be converted to hydrogen and in operation can use up to 1 tonne of hydrogen per hour. Typical compression stations have at least three turbines, therefore large amount of hydrogen (tens of tonnes) would be required on site. H2GO Power technology was attractive as if adopted, it could result in not triggering the COMAH restrictions that apply at over 5 tonnes.

However, in the case of this example and in general, there is a slow pace of hydrogen projects that are reaching an investment decision. This combined with a limited appetite from off-takers and higher production costs for newer technologies has resulted in limited commercial traction. This has been cited as a reason to terminate the projects prematurely under discussion in this report, as identified earlier in the document.

8.0 Conclusions

The project set out to validate the list of indicators identified in the table below which have been provided along with their status at the end of the project:

Metric	Status	Commentary
Validate benefit to cost ratio against competitor technologies, i.e. levelised cost of hydrogen (in terms of storage) of <£0.61/kgH2	Achieved	Discussed in section 7.2

Validate >100 cycles of operation with storage material capacity degradation of <0.01% per cycle	Achieved	Discussed in section 8.2
Validate technical performance, measured by flow rates, achieving >33 NL/min per reactor sustained for >5h.	Achieved	Discussed in section 8.2
System efficiency >70% (energy in vs energy out for full cycle)), comparing energy required to heat reactors (H2 desorption), energy required to cool the reactors (H2 absorption) and base operation.	Not Achieved	At the stage of the testing conducted it did not reach assessment at the system level of the energy is vs energy out for a charge and discharge cycle. Efficiency is discussed in section 7.3
Validate peak flow in <30mins for cold start.	Not Achieved	At the stage of the testing conducted it did not reach assessment at the system level of cold start performance characteristics
Transient response 10%-90% and 90%-0% of 15mins	Not Achieved	At the stage of the testing conducted it did not reach assessment at the system level of transient response
Purity of hydrogen output >99.95%	Achieved	SeeAppendix 1Appendix 4
Validate user testing of HyAI dashboard (used to help the site operators understand/visualise the HyAI model's real time decisions)	Achieved	Upon completion of the HyAI dashboard, extensive testing was conducted by internal and external end users, with their feedback actively collected to refine the dashboard implementation and inform subsequent development iterations.
Integrating the SHyLO and HyAI system with assets at EMEC's Eday hydrogen production site	Partly Achieved	HyAI was successfully integrated with the SCADA system at EMEC's Eday hydrogen

		production site. However, not all assets were integrated with HyAI (e.g., the electrolyser) because of commissioning delays at the site.
Live field testing HyAI which involves using the cloud-based model to control the on-site hardware assets in real-time. Assessed across: reliability; decision safety; decision quality	Not Achieved	While HyAI was successfully integrated with the on-site hardware assets and used the retrieved telemetry data to perform offline testing, it did not get to the stage of autonomously controlling the hardware assets via HyAI.
Gross PnL from system operation improved by >10% using HyAI against control baseline	Partly Achieved	HyAI demonstrated it can improve gross PnL by >10% using historical data. The missing step was to achieve the same result during live field testing.

8.1 Technology viability

The project demonstrated the ability to scale the technology to a commercial scale system and through the work conducted there were 2 key areas that provided evidence around the business case for the use of solid-state hydrogen as a storage mechanism, these were:

- Deployment viability, focusing on scaling up costs (LCOS) and safety
- Performance

Upon commencement of the project, it was understood that the benefits of storing as solid state would bring safety benefits. However, as the safety work evolved it became apparent that these benefits were significant, and larger than first anticipated. The results show that solid state hydrogen can be an enabler to the green hydrogen economy by removing the risks that exist with other methods of storing. Specifically, these are:

- A reduction of the exclusion zones around the storage unit and reduction in the amount of space required for deployments

- A potential significant increase in the COMAH thresholds based only on the gas that remains unbonded to the material

In addition, it has been shown that the costs are also predicted to be below that of compressed gas storage equivalents. This is important where the other benefits become less attractive, for example, where space may not be a concern or deployed in remote locations.

8.2 Performance assessment

Although some of the objectives established for the demonstration stage could not be met at scale, the H2GO Power R&D team evaluated the performance of H2GO Power technology at the modular reactor level in the laboratory. A primary goal of the demonstration was to validate the cyclability of the storage material for approximately 100 cycles while retaining over 99% of the original storage capacity. Figure 19 illustrates the relationship between storage capacity and cycle number, with green and red bars representing the absorption and desorption cycles, respectively. Notably, there are no observed capacity losses compared to the full capacity after activation (indicated by the yellow line), which confirms the excellent cyclability of H2GO Power's storage material. It is important to mention that the fluctuations in the graph are attributed to variations in cycling parameters during laboratory testing and do not reflect changes in storage capacity. As the material and reactors tested at lab scale are the same deployed in the SHyLO unit, a similar capacity retention is expected to be observed at scale.

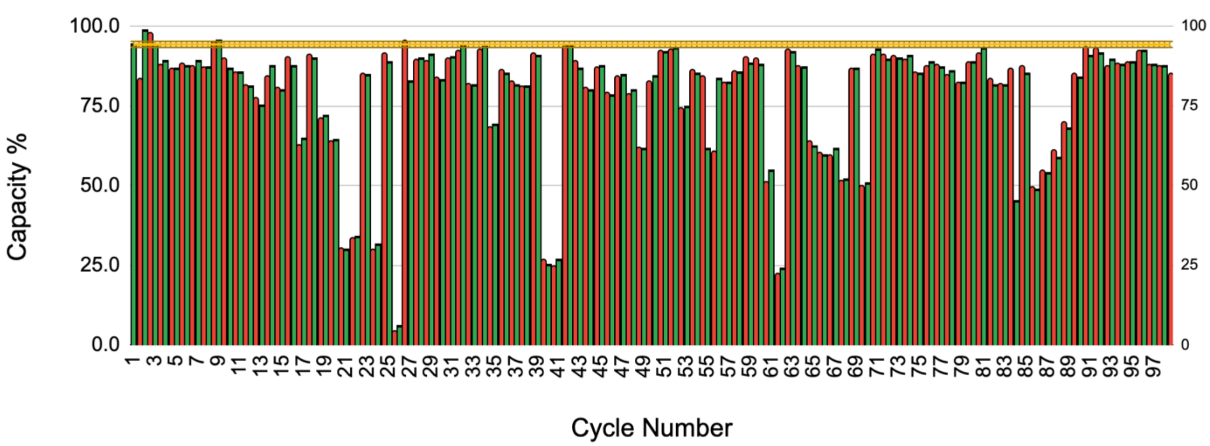


Figure 19: H2 storage capacity vs cycle number for an H2GO Power modular vessel. The yellow line represents the max storage capacity following activation. The storage capacity is fully maintained at cycle 95.

During the demonstration phase it was possible to perform only one cycle as part of the commissioning and decommissioning phases. The profile of a unit desorption at nominal flow rate has been shown in Figure 15. However, in order to demonstrate and validate the ability to achieve nominal (and higher) flow rates for >5 hours, individual reactors were tested at H2GO Power facilities. Figure 20 show desorption profiles for a modular vessel identical to the SHyLO vessel containing the same batch of storage material.

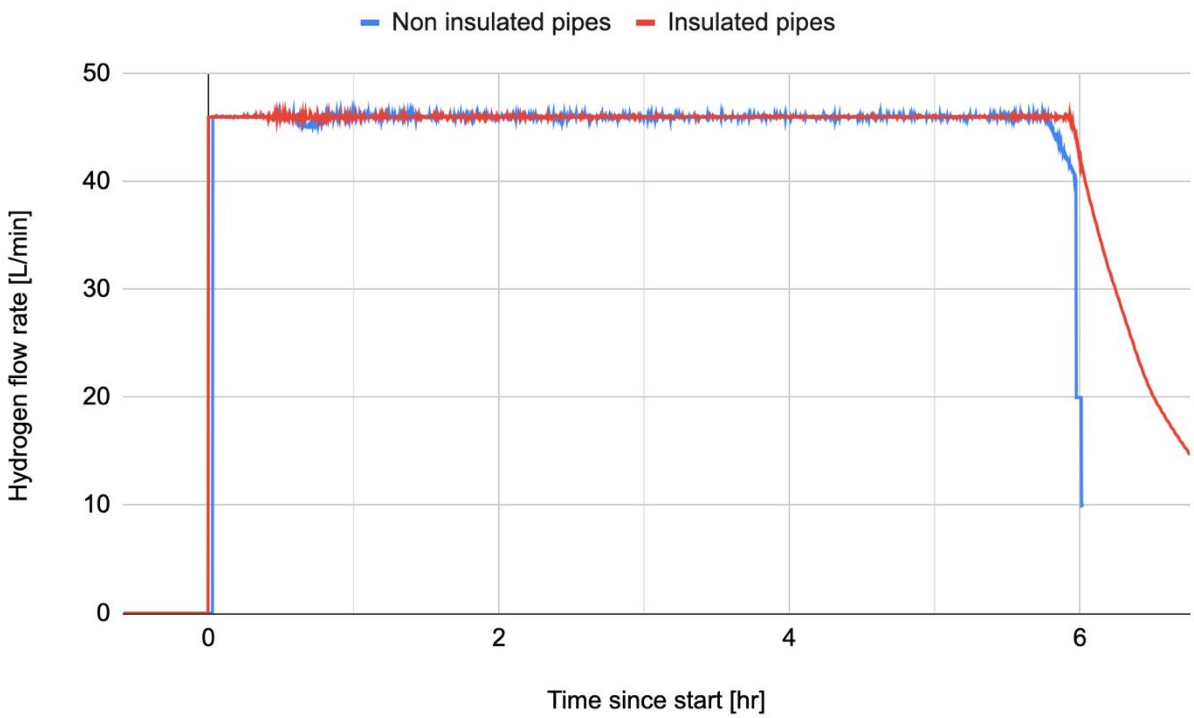


Figure 20: Desorption profiles at peak flow rate (45L/min) for an H2GO Power modular vessel. Insulation of the coolant pipe leads to ~6% more hydrogen released at the desired flow rate.

Individual reactors can achieve release flow rates as high as 45 NL/min with ~45 minutes of warm-up time, translating in 945 NL/min for the SHyLO unit. This is equivalent to just over 5kgH2/hr (5.06 kgH2). The warm-up time and the peak flow rate is highly dependent on the heating power used to drive the hydrogen desorption reaction. Preliminary tests were performed in H2GO Power laboratories to future proof maximum performances for a commercial 200kgH2 storage unit. By using a modular vessel identical to the ones used in SHyLO and increasing the power of the heating element by three times it was possible to achieve flow rates as high as 100NL/min, equivalent to 59KgH2/hr for a 200 kgH2 unit as reported in Figure 21. It is worth noting that the higher the sustained release flow rate the lower is the amount of hydrogen that can be released at the desired rate, however it illustrates a potential capability to accommodate a high degree of fluctuating demand.

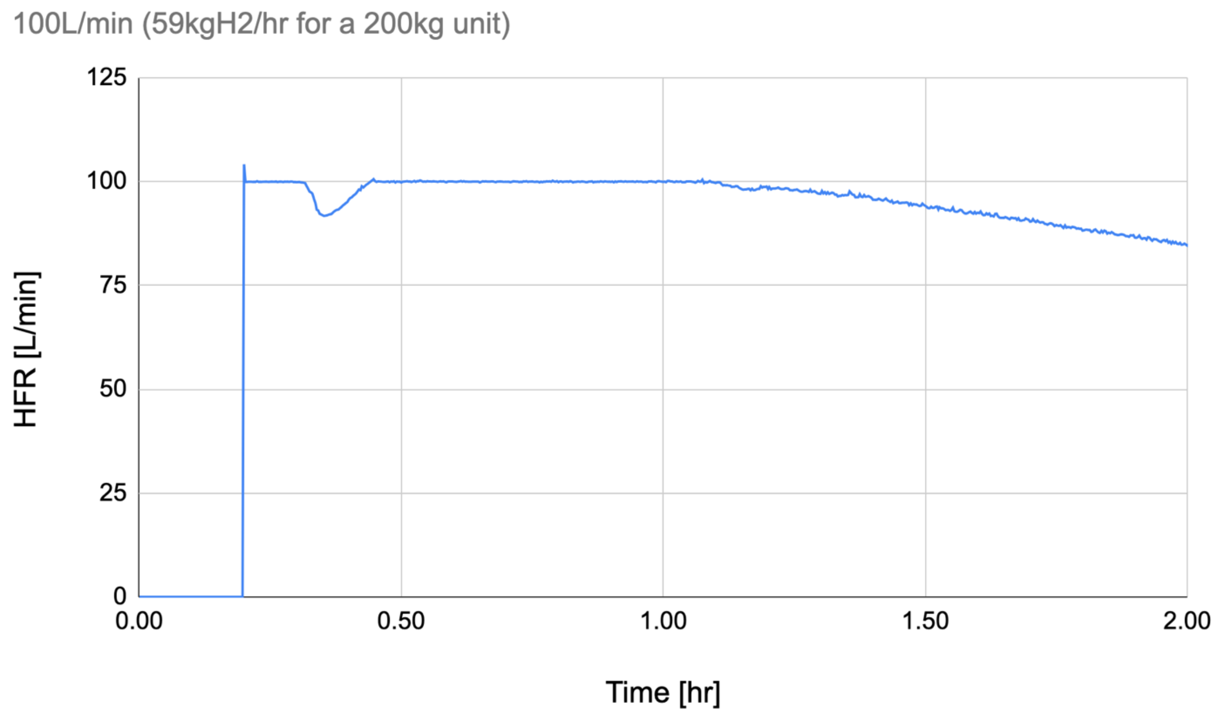


Figure 21: Peak flow rate of 100L/min for an H2GO Power modular vessel.

8.3 Wider impact

Despite that the project was unfortunately terminated prematurely, wider impact was observed during its implementation. Should the project have continued until its scheduled termination, this impact would be much higher and noticeable. This impact could be summarised shortly in the following points:

8.3.1 Job creation

The SHyLO project had been a significant milestone for H2GO Power. This project was anticipated to enable the demonstration of H2GO's proprietary solid-state hydrogen storage technology at a large scale and under fully operational conditions. Therefore, the fulfilment of the project's scope was directly related to the company's scaling up. The H2GO Power's team prior to commencing the SHyLO project was limited and a series of new hires was necessary for implementing the project, but also to prepare the company for scaling up and commercial entry. As a result of the SHyLO project 10 new hires were made covering a broad range of disciplines such as electrical engineering, systems engineering, mechanical engineering, software engineering, business and management. All new hires possessed a high-quality skill-set adequate to support the project's implementation and H2GO Power's expansion.

8.3.2 Improvements to skills and experience in the sector

The green hydrogen sector is still nascent, and as such the required skills and experience for this sector are still evolving at a fast pace. Moreover, from H2GO Power's experience during the hiring of new employees it has been observed that finding applicants with experience directly related to the hydrogen sector was difficult. In addition as the applied technology was novel, even in cases of experience with the hydrogen sector, additional knowledge was needed to be transferred so that new hires could integrate completely with the new roles. This was achieved through active participation and knowledge transfer with new hires, as well as encouraging employees to bring forward their ideas and past knowledge on their everyday activities. Therefore, all of the employees hired by H2GO Power during the SHyLO project, significantly enhanced their knowledge and skills and/or developed new skills.

The project's impact on this however goes beyond H2GO Power, as for fulfilling the project's requirements there was engagement and collaboration with a multitude of organisations directly or indirectly related to the hydrogen sector. In several cases, due to the novelty of H2GO Power's solid-state hydrogen storage technology it had been necessary to directly engage with these organisations, in order to effectively communicate the technology's needs and uniqueness for ensuring that a service or product tailored to H2GO Power's technology would be provided. Such organisations include hydrogen supply chain companies, engineering suppliers, consulting companies, and more. Outside of the project's consortium H2GO Power engaged with tens of such companies within the UK and abroad, where notable and beneficial knowledge exchange for both parties took place. This type of dynamic engagement among others, allowed to overcome technical challenges.

A specific mention should also be made to the project's consortium and the knowledge that they received through their exposure with H2GO Power's technology. As the hydrogen sector is still relatively limited, by working in such a project and a distinctive technology, remarkable skills and experience was acquired through this project which can be transferrable to other hydrogen-related project. All project partners are well-established in their fields and work with companies and technologies of a broad spectrum with ranges from startups to multinationals. Such experience and skills gained can be used for example by EMEC for another hydrogen project demonstration, or by MTC for the manufacturing of another hydrogen-related demonstration unit, while HSSMI and ARC can build a larger knowledge base to provide consulting on the scaling up and risk management of hydrogen technologies respectively.

8.3.3 Partnerships and supply chain development

As the SHyLO project required the demonstration of a commercial scale unit, the activities that were taken for manufacturing and demonstrating were also pivotal for defining the product's supply chain and forming the relevant partnerships. Through the process of designing and manufacturing the demonstration unit, H2GO Power had the opportunity to engage with a multitude of stakeholders from the wider hydrogen sector within the UK and beyond. As a result of this, the most substantial parts of the product's supply chain were defined so that a commercial entry would be facilitated. These mainly included materials and hardware suppliers, but also certification bodies, software providers and more. Since the demonstration was limited and the company's commercial entry was not achieved, few of these partnerships were formalised through contractual relationships. These were mainly for completing the project's scope and H2GO Power was expecting to extend such relationships beyond the project.

8.3.4 Recruitment activities

As mentioned, SHyLO was a milestone for H2GO Power, which required increasing its workforce significantly. Furthermore, due to the high degree of innovation involved in the project, all new hires needed to be highly skilled for their roles. Considering also the dynamic environment and evolving needs that can be observed during scaling up, new hires should also be capable of undertaking several responsibilities when needed and be flexible. For achieving this a robust recruitment process was more than necessary. Towards this end, and for ensuring the best value for money H2GO Power utilised its established network with Imperial College and other institutions (especially for the case of entry-level employees), while also when it was deemed necessary, used the services of several selected recruitment firms known for providing high quality personnel. In addition, most new vacancies were promoted through the company's and employees' social media accounts to leverage on existing contacts and network.

8.4 Lessons learned

8.4.1 Cost overruns

The circumstances under which the project costings were calculated changed significantly between submission of the SHyLO project compared with the project commencement date. The SHyLO project was conceived pre-August 2022 and upon commencement significant world events had increased the costs of many items that were well beyond what could have been considered at the time of application. Throughout the project cost overruns were increasingly being encountered, mainly down to the following reasons:

- Inflationary supply chain pressures
    - This was experienced on many of the materials that needed to be purchased throughout the project. One such example from procurement of the hydrogens storage reactors that increased 242% between budgeting and ordering. These vessels were a significant part of the materials budget of the project and hence had an impact on overall cost.
- Unfavourable foreign exchange rates on imported materials.
- Initial underestimation of system balance of plant requirements.
    - For example, at proposal stage, EMEC budgeted for a two-stage compressor that would be able to compress the hydrogen output from the SHyLO

container from low pressures up to 350 bar to go into the high-pressure storage existing on site, which was budgeted at £440,000 but quoted at £594,000 during the project. This was over the total hydrogen related budget, even without the integration works. Therefore, a one-stage compressor was procured with the capability to compress from near ambient pressures up to 35 bar at £275,970. However, with the addition of the pipework and control design and installation works, there was an overspend on the hydrogen budget of approximately £175k.

- Unforeseen costs, examples include:
    - incorrect budgeting with regards to transportation and logistics of components and the final system, specifically those that contained hazardous materials and required additional measures when shipping and storing.
    - Increasing overheads as project deliverables increased the complexity of H2GO operations as the company expanded to ensure delivery. During the submission overheads were 20%, however overhead costs increased to 37%. The largest component driving this was rental increases. (Note this was in part mitigated by the move to Kiwa).
    - Increasing labour costs due to inflationary impacts.
    - Electricity prices also significantly increased after the proposal stage. For example the electricity price was estimated at 15 p/kWh to operate the system at Eday. However, this increased to 66.1 p/kWh. (Note in this example it was in part mitigated by the move to Kiwa).
    - The requirement to change from CE to UKCA marking, post-Brexit, impacted lead times and cost for the compressor.

8.4.2 Delays

Throughout the project many delays were experienced. Some of these are categorised and identified as follows:

- Developing a first of a kind system:
    - Unknows in the actual work required to develop a system of this complexity without prior work to rely on an inform timelines required.
    - Complexities of testing and validating such a product, for example delays experienced in factory acceptance testing (FAT) due to the volume of tests needed to be conducted for a first system.
    - Difficulties with software integration and clearing out errors at the master controller level (PLC) and the embedded software level which required multiple code amendments and iteration in testing to fault find the causes.
- Supply chain:
    - Increasing supply chain pressures due to world events impacted lead times on certain components and extended critical paths.
- Complexities arising from outsourcing build:

Additional resources were required from H2GO to support the build. This was necessary to ensure suitable progress, meet the required specifications, and address issues encountered, an example as illustrated in Figure 22. The H2GO team provided significant support on top of the MTC resources initially allocated to the project, and provided agility to arising issues. This took a significant amount of H2GO team resource that was not anticipated on top of the MTC resource supplied to the project at the beginning of the project.

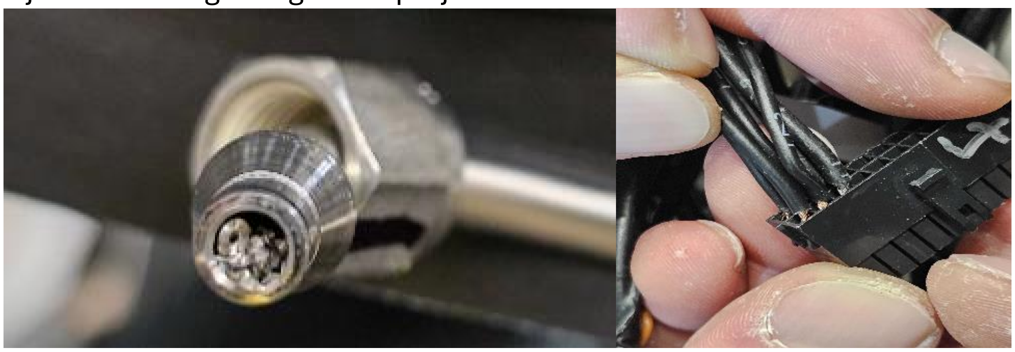


Figure 22. Examples of issues encountered during build: Swarf not cleaned out in hydrogen piping (left), and poor termination of connectors (right)

- Sign off delays from MTC on specific activities were not anticipated. These included the ability to power up the 415V system without a comprehensive review from internal MTC electrical authorised person, who had arisings constraints due to the unplanned nature of the activities.
- Delays in shipping the unit from MTC to Kiwa arising from ambiguity on who should be responsible for lifting the unit on to the transporter, along with delays in documentation and site visits from the logistics company.
- Regulatory uncertainties, inexperience with using hydrogen and the novelty of the technology led to a highly cautious approach to reviewing and mitigating risks and increased review and sign off for activities. In multiple instances risks were deemed too high and alternatives needed to be determined.
- Manufacturing issues with the bespoke ISO container.

▪ Complexities with site integration activities:
  - Water in the hydrogen lines due to not being cleared out of the Kiwa pipework after hydrostatic testing by an external contractor. Upon purging the system water was pushed into the SHyLO unit which resulted in dismantling of hydrogen lines for drying.
  - Incorrectly assembled, faulty and leaking components including:
    - Coolant PRV incurring multiple failures.
    - Airlocks in the coolant system and difficulty in refilling/topping up coolant frequently due to the need to raise the coolant reservoir above the system at a height.
    - Incorrectly fitted plastic coolant tubing in build - rework required with new ferrules and refilling of system.
    - Multiple leak points found throughout FAT/SAT that needed to be addressed.

    - No door arrestors fitted in build which needed mitigation to manage risks when windy conditions were experienced on site.
    - Incorrect adaptors fitted to coolant pressure transducer in build and replacement pressure transducer was required.;
    - Additional work required to determine the lightning protection on site as current arrestor did not provide full protection to the area where the unit was deployed.
- Finally, weather conditions limiting working time on site.

8.4.3 Site integration issues at EMEC

Due to a combination of supplier delays at the EMEC site throughout the project a new demonstration site had to be found to mitigate substantial delays to the project.

8.4.4 Project administration delays

There were initial delays with complexities of agreeing terms between multiple partners and signing of the collaboration agreement that led to a delayed project momentum and all consortium partners getting up to speed.

Appendix 1 – SHyLO system specification

Unit size	2.90 x 2.44 x 3.91 m
Unit weight	10 tonnes
H2 capacity	up to 1066 kWh up to 32 kgH2 (34 kg max capacity) *(dependant on flow rate)*
Nominal flow rate (absorption and desorption)	700 NL/min *(can charge/discharge at different rates depending on supply and offtake specifications)*
Max flow rate (desorption)	Up to 1,050 NL/min 5.6 kg/hr
Max charge/discharge duration	5.7 hours
H2 purity (in)	>99.9995%
H2 purity (out)	>99.9995% *(Type 1, Grade E and Category 3 specified in BS ISO 14687-3:2014(E))*
Hydrogen output pressure	Confidential
Hydrogen input pressure	Confidential
Operating temperature range (ambient)	-10 to 30 °C
Electrical requirements	415V AC (3ph) 50/60 Hz 80A, 3p+E+N
Communication	PROFINET
Connectivity	Ethernet

Appendix 2 – SHyLO schedules

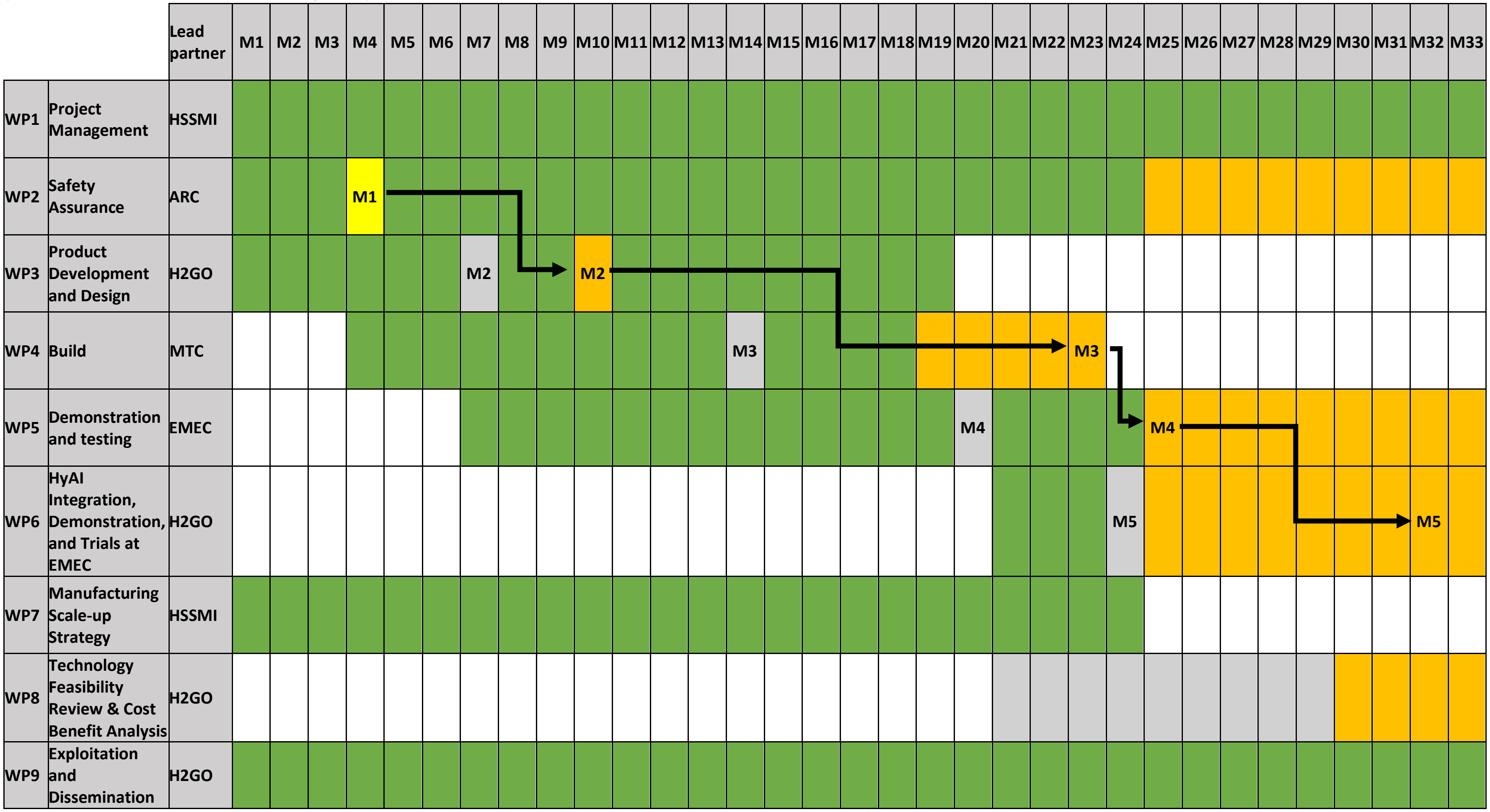
Original schedule as submitted

(Black lines denote critical path)

		Lead partner	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24
WP1	Project Management	HSSMI																								
WP2	Safety Assurance	ARC				M1																				
WP3	Product Development and Design	H2GO							M2																	
WP4	Build	MTC														M3										
WP5	Demonstration and testing	EMEC																				M4				
WP6	HyAI Integration, Demonstration, and Trials at EMEC	H2GO																								M5
WP7	Manufacturing Scale-up Strategy	HSSMI																								
WP8	Technology Feasibility Review & Cost Benefit Analysis	H2GO																								
WP9	Exploitation and Dissemination	H2GO																								

Actual schedule as of end of project

(Black lines denote critical path)



Appendix 3 – Work package breakdown

Workpackage ID	Workpackage Name	Project Partner Lead	Description (inc. Key tasks)
1	Project Management	HSSMI	The project will be managed by a HSSMI and supported by the WP leaders. The objectives of this work package are: • Ensuring the project remains on track in terms of technical delivery, quality, timing, and from a financial perspective. Developing strategies when timing and/or financial creep is identified. • Ensuring effective communication is maintained between partners throughout the project and managing any conflicts that arise. • Risk identification and management and developing effective mitigation strategies with WP leads. • Communication and reporting to the funding body (BEIS). • Ensuring effective IP management throughout the project. Key Tasks: 1.1: General project management activities (M1-M24) – ensuing the scope of the project is maintained, managing deliverables and milestone progress, time management, risk identification, management, and mitigation. This task will be achieved through frequent communication with the WP leads and wider team. 1.2 Communication activities (M1-M24) – arranging frequent and recurring meetings with the full consortium to discuss general project updates, WP progress, and issues. Meetings with specific WP leads will also be organised where necessary. This task also includes communication with the BEIS to provide project progress.

			1.3 Maintaining project documents (M1-M24) – updating and tracking all project documents on a regular basis (monthly). This includes the project Gantt chart, risk register, IP register, milestone and deliverable status. 1.4 Preparation for quarterly review report (M3, M6, M9, M12, M15, M18, M21, M24) – collating all required information from partners to deliver quarterly report on project progress and status to BEIS.
2	Safety Assurance	ARC	The key focus and objective of WP2 is to ensure that the final designed and manufactured solution includes the necessary safety requirements to enable certification of the demonstrator and future products. Other objectives include: • Establishing an initial baseline of information covering legislation, standards and guidance relating to hydrogen storage systems, high power electrical systems, software safety assurance especially for machine learning/Artificial Intelligence (AI) • To take the current Safety Programme of H2GO's solution and update it considering the identified legislation, standards and guidance • Identify the principal hazards associated with the proposed system in both its design, test deployment, and envisaged operational deployment configuration. Ensure these risks are tracked and reviewed as a part of an ongoing project review and also prior to significant project milestones so that all stakeholder agree it is safe to proceed. Key Tasks: 2.1: Safety baselining (M1-M2) – this includes a review of UK legislation to ensure current relevant legislation is known. Reviewing relevant HSE guidance and information to identify relevant standards and guidance. Reviewing relevant professional UK and international bodies. 2.2: Updating safety program (M2-M3) – this includes collating and identifying specific standards to be worked to and confirming relevant project milestones and safety activities to be completed before hand. Developing software

			assurance strategy based on relevant standards for software safety assurance and current best practice for applying this to machine learning/AI. 2.3: Hazard identification, tracking, and analysis (M2-M24) – generation of a preliminary hazard list (PHL) based on an initial review and HAZID of the solution. Hazards will also be identified throughout the entirety of the project with a HAZOP of the initial solution design to feed into the design process. Will also carry out a site HAZOP for final solution to be installed, layers of Protection Analysis (LOPA) for safety instrumented systems, Fault and Event Tree analysis to understand propagation of causes to hazards, release scenario modelling to assess the extent and severity of potential dispersion, jet fires and explosions. Hazards, and the associated Safety Requirements to control those hazards, will be tracked in a Hazard Log that will be regularly reviewed and updated as part of the ongoing project reviews 2.4: Development of the risk management report (M2-M24) – the Risk Management Report will be developed and updated as the project progresses and at key milestones (including: at end of task 2.1, at the end of the design work (WP3), at end of manufacture / prior to trials, and at end of trials.
3	Design and Development	H2GO	The key objective of this WP is to generate a detailed design of the H2GO solid-state hydrogen storage solution that will be demonstrated and trialled at EMECs site. Other objectives include: • Encompassing all design aspects to ensure that the final design and build will meet the required performance, technical and legislative standards, and regulations to facilitate successful demonstration and trials. • Use modelling and simulation work to validate the design of the solution and to identify key risks. • Define required equipment and materials that will need to be purchased to allow for the build phase. Key Tasks:

			3.1: Requirements definition (M1-M2) – this task involves defining the specifications and key performance parameters of the solution in order to successfully build and demonstrate a large-scale hydrogen storage system. As part of this task, long lead time items will also be defined. 3.2: Container conceptualisation (M1-M3) – this task will focus on designing key architectures of the modular hydrogen storage solution with multiple storage vessels. The system architecture (incl. logic, software, control systems, power distribution, etc.) will be designed, as well as a proposed electrical architecture. There will also be an activity around the designed scale up of the balance of plant, allowing for purchasing of key materials. 3.3: Modelling and simulation for design and build (M2-M5) - This will start with model development and validation against known H2GO data for one vessel, moving to a similar activity for multiple vessels within the overall containerised solution. This virtual validation activity is a simulation of the thermal-dynamics of the BoP design and layout. This will identify key areas of risk and help mitigate issue for prototype design, so establishing the test plan. 3.4: Detailed mechanical design (M5-M7) - This task is a detailed mechanical design for a scaled demonstrator, including the electrical design, control systems, and the design of interfaces within the infrastructure, meeting all legislative requirements. This detailed design will also include specifications of instruments not required in a final product – e.g. potential additional isolation valves, pressure monitoring devices etc. 3.5: Hydrogen reactor optimisation (M2-M19) – Autodesk will work with H2GO on an activity focussed on the hydrogen storage reactor design with a view to optimise performance and design to reach commercial cost targets, along with manufacturing and tooling considerations. This will work in parallel to the main aspects of the project. i.e. the large container demonstrator will be designed and built but will simultaneously iterate H2GO's storage solution concept (specifically the hydrogen reactors) for cost and manufacturing improvements that can then be used for future designs at larger scales.

4	Build	MTC	The aim of WP4 is to provide the build of the final physical containerised hydrogen storage system in line with the design work prior. There will also be a series of component testing activities with the objective of identifying any defects within build (e.g. leaks on a weld). Key Tasks: Task 4.1: Build (M4-M14) – the physical integration and packaging of the H2GO hydrogen storage system, involving the modification of the container to facilitate storing H2GO hydrogen storage vessels, following the detailed designs from previous tasks. Task 4.2: Component testing (M15-M18) – test and identify any issues with the build process, not fully testing the overall solution with hydrogen. The test plan will have been agreed as part of the initial specifications within earlier tasks. Initial test will be a pressure test with an option to undertake a whole system pressure test using nitrogen and a debug and calibration of the system control software.
5	Demonstration and Test	EMEC*	This work package will focus on the preparation of the sub-station at EMEC to receive the SHyLO system, and the installation and operational testing of that system. Key Tasks: 5.1: Specification and tendering of site upgrade requirements (M7-M11) - following the finalisation of the SHyLO design, EMEC will specify the infrastructure upgrades required at its Eday Substation to integrate the SHyLO system. To include specification of electrical infrastructure, pipework, skids, buffer storage, compressors, civil construction, and communications infrastructure. EMEC will then supply the required design and infrastructure upgrades through competitive procurement processes to ensure value for money. 5.2: Integration and testing of upgraded site infrastructure (M12-M18) - the integration of all upgrades to the site infrastructure identified. H2Go will develop a commissioning test schedule for operating the system, which will then be

			implemented in stages. This will include taking the system up to 100% hydrogen capacity and releasing it. H2Go will be responsible for controlling the system, and EMEC will provide operational support. 5.3: Installation of SHyLO system (M18-M20) - installation of the SHyLO system into its sub-station on Eday. To include electrical, gas and communications integration. 5.4: Site acceptance testing (SAT) (M20-M21) - provide documentation of the safety systems, and key operating parameters (min/max flow rates, pressure retention, storage volume etc.). EMEC will carry out a leak test following the arrival of the system. Further safety assessments will be conducted by ARC and be used to feed into the SAT and operational procedures for the testing phase. 5.5: Performance Optimisation and Testing (M22-M24) – H2GO will implement a rigorous testing programme with the support of EMEC. This will include trailing different operating modes, and integration with the HyAI system or autonomous operation of the wider EMEC hydrogen production facility and sub-station. 5.6: End-of-Project Strategy for Demonstrator (M18-M24) – As the project progresses, the strategy regarding what will happen to the demonstrated hydrogen storage solution post project will be defined. Three options will be considered dependant on the results of the trial: 1) Leave the unit on site to continue gathering data and use it as a test site to continue the improvement of the technology; 2) Move it to another site to assess different use cases; 3) Investigate unit performance by conducting non-destructive testing to validate parameters such as storage capacity degradation (lifecycle analysis)
6	HyAI Integration, Demonstration and Trials	H2GO	The purpose of this work package is to integrate the HyAI platform with the storage unit and perform field testing, wherein HyAI autonomously controls the hardware. This will be done within the context of the system-wide operation at the Eday hydrogen production site. Key Tasks:

			6.1: Develop AI safety and testing plan (M21) - will begin by developing an AI safety and testing plan, which will rigorously outline the requirements and corresponding traceability of the system. 6.2: Integration of storage unit into EMEC EMS and HyAI platform with relevant data sources (M21-M22) - the HyAI platform will be integrated with the relevant data sources for real-time operation, including a IoT data stream from the storage unit itself 6.3: Manual testing of the platform (human operator sense-checked) (M22-M23) - a human operator will sense-check and manually implement model-driven decisions provided by the platform. 6.4: Autonomous testing of the platform (autonomously implemented model-driven decisions) (M22-M23) - an edge device will autonomously implement model-driven decisions provided by the platform, which is closely monitored by a human operator who can override control if necessary. 6.5: Data analysis and review of decisions made quantifying system performance (M23-M24) - data from live testing phases will be analysed to quantify the value of real-time, AI-powered operation to EMEC, as well as determining improvements to the platform, both in terms of modelling and practical deployment considerations.
7	Manufacturing Scale-up Strategy	HSSMI	The purpose of WP7 is to determine an effective manufacturing strategy for the H2GO hydrogen storage solution that will enable wide roll-out of technology across the UK. WP7 will aim to define a high-volume manufacturing process, key suppliers in the supply chain, and opportunities to improve design for manufacture characteristics. Key Tasks: Task 7.1: Define manufacturing process for H2GO hydrogen storage system (M1-M9) – prepare a bill of process (BOP) for the containerised hydrogen storage solution, to include a detailed sequence for unit build and test.

			Task 7.2: Develop design for manufacture approach (M7-M14) – analysis of the design and manufacturing process of the containerised solution to identify opportunities to implement design for manufacture characteristics. Define changes to process, enhancing scale-up of manufacturing to optimise volume and quality outputs for product. Task 7.3: Define a blueprint for volume manufacturing of H2GO demonstrator storage system (M11-M24) – Identify high volume processes, cycle times, equipment and material handling activities to enable a refined BOP and BOS to be defined.
8	Technology Feasibility Review & Cost Benefit Analysis	H2GO	This work package has the key objective of assessing the performance of the H2GO hydrogen storage demonstrator against a predefined set of criteria. This would then feed into a cost benefit analysis with the aim of building a robust business case for H2GO's large-scale hydrogen storage solution. This will be key to raise further investment, attract more customers, and enable commercialisation of this solution. Key Tasks: 8.1: Technology performance validation against a pre-determined set of requirements (M20-M22) – the performance of the demonstrated solution at EMEC's site will be compared to a set of pre-defined criteria including, but not limited to: • Levelised cost of hydrogen per kg • Levels of degradation over >100 cycles • Flow rates • System efficiency • Transient response • Hydrogen purity 8.2: Cost benefit analysis (M22-M24) – this task will utilise the results of the testing and performance review to assess ROIs, total cost of ownership etc, to feed into

			a cost benefit analysis. Validating each set of technical criteria as a technical milestone.
9	Dissemination and Exploitation	H2GO	Objectives: Embed the outputs and results of the project so that the supply chain developments are applied, developed and enhanced. It will also be used to inform external stakeholders and the public in the roles and actions that undertaking such a key piece of work can have on rolling out high-volume solid-state storage of hydrogen. The consortium will also develop an exploitation pathway for the volume manufacturing processes developed within the project around solid-state hydrogen storage. This will also investigate commercialisation opportunities that will become available for this rapidly developing sector. Key Tasks: 9.1: Management of consortium aims (M1-M24) – determine partner outputs and aims, developing consortium exploitation and dissemination plan 9.2: Demonstration event (M22-M24) – develop plans for an event to showcase the demonstrated solution to relevant stakeholders in the wider industry. 9.3: Public dissemination: conferences, events, white papers, academic papers (M1-M24) – all partners to disseminate project progress at appropriate times throughout the project. A register (live document) will be used to record public dissemination activities with input from consortium partners. 9.4: Exploitation pathway for manufacturing process (M18-M24) – develop exploitation pathway for volume manufacture scale-up of demonstrator developed during the project 9.5: Commercialisation of future opportunities (M18-M24) – develop overarching commercialisation plan for exploiting the outputs from the project partners
*Changed to Kiwa as identified in the report			

Appendix 4 – Hydrogen purity report

Report no: D20230227 H2GO H2 CP RGC7932 A 30th March 2023

GAS

Gas Analysis Services Ltd.
Unit 1C, N11 South point Business Park,
Charvey Lane, Rathnew,
Co. Wicklow,
Ireland.
A67 P275.

Report for testing of Hydrogen at H2GO Power LTD.

Customer: H2GO Power LTD.

Location: London, United Kingdom.

Contact: Caroline Dylag.

Sample Dates: 27th & 28th February 2023.

Gases analysed: Hydrogen.

Report Date: 30th March 2023.

Attachments: Reference standards certificates of conformity.
Oxygen analyser certificate of calibration.
Moisture meter certificate of calibration.
Balance certificate of calibration.

Introduction

The requirement was to test hydrogen at H2GO Power LTD in London. The sample points were selected by the customer. Testing was completed on-site with samples being sent to the SGS GAS Laboratory in Rathnew, Co. Wicklow Ireland for further analysis. Results obtained are outlined below.

Methodology

All instruments used were in calibration at the time of the test.
The tests detailed below were completed as per GAS internal procedures.

Test	Method	Revision	Equipment	Serial / Batch Number	Expiry / Calibration due date
Trace Oxygen	IN-73	1.0	Southland OMD-580	00580361	24MAR23
Moisture	IN-40	8.0	MDM 300	167671	11AUG23
Particulates	By filter paper and calculation				
Total Hydrocarbons	IN-39	6.0	Agilent 7820	CN11482009	Time of Use
			1ppm CH4 Bal N2	S1737441	01SEP2026
	Lab reception date:		09th March 2023		
	Lab analysis date:		15th March 2023		
Trace Nitrogen	IN-58	1.0	Agilent 7890A	CN10938118	T.O.U
			2PPM Gas Mix	040009003964	04JAN25
	Lab reception date:		09th March 2023		
	Lab analysis date:		20th March 2023		

Results

Sample Date	Sample ID	Nitrogen (ppm)	Oxygen (ppm)	H2O (ppm)	Methane (ppm)	Non Methane Hydrocarbons (ppm)	Particulates (mg/kg)
Specification		INFO	INFO	INFO	INFO	INFO	INFO
27FEB23	78700/2	ND ≤0.1	0.55	22.3	0.2	ND ≤0.1	0.1
28FEB23	78686	N/A	N/A	3.6	N/A	N/A	N/A
28FEB23	78700/2	N/A	N/A	6.6	N/A	N/A	N/A

Sample condition is acceptable as per LP-3 Sample Reception.

Conclusion

The results obtained pertain to the items/samples tested.

Analyst: Daniel Valvona/ Cathal Brophy

Report compiled by: Cathal Brophy

Report Date: 30th March 2023

Report No: D20230227 H2GO H2 CP RGC7932 A

DocuSigned by:
Cathal Brophy
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Signed: ______________________ Date: ______________
Cathal Brophy for Gas Analysis Services

DocuSigned by:
Gemma Farrell
17365034EA1748.3

Approved by: ______________________ Date: ______________
Gemma Farrell for Gas Analysis Services

Revision History		
Revision	**Description**	**Date**
A	Initial Release	30MAR23

This report was completed in line with the requirements of MF-032 Rev 7.0

END.

[redacted]

Appendix 5 – Smart Hydrogen Gas Networks (SHyGaN)

Department for Energy Security and Net Zero (DESNZ) Industrial Hydrogen Accelerator Stream 1 – Demonstration

SHyGaN Project Closure Report
(Addendum to the SHyLO project Final Report)

9.0 Introduction and overview

9.1 SHyGaN project background

Natural gas is used for multiple applications, including industrial power supply, and heating. In the UK alone natural gas is a significant GHG producer (around 40% of emissions generated from power supply [12] and the main source of emissions from commercial, residential and public sector buildings [13]). Thus, a high proportion of natural gas should be substituted with renewables. Moreover, the current geopolitical turmoil highlights the UK's high geopolitical dependence on natural gas highlighting the need for an accelerated fuel switching from natural gas. Since natural gas networks power multiple sectors, their decarbonisation could positively affect multiple sectors, and hydrogen could be key towards this shift [14]. However, taking into account that natural gas facilities are heavily regulated and that the highest safety standards need to be adhered to, the usage of any hydrogen at such facilities should be compliant with any relevant standard and regulation. This should also be considered for other hydrogen-powered heating applications, as their applicability would be mostly encountered in industrial use cases (where safety compliance is uttermost important), and domestic heating where the safety case is currently being assessed.

H2GO Power, having already developed a technology for a lower risk method of hydrogen storage in a prior project called SHyLO, and being aware of the above market conditions and challenges identified that this technology would have a very high potential for heating applications. Having already engaged with Baxi, an established heating systems manufacturer that had already developed a tested hydrogen boiler prototype, the idea of co-designing and deploying a hydrogen-powered heating system was conceived. For materialising this idea into a fully functional system, a demonstration would need to take place and demonstrate both seamless performance and acceptable safety standards. Towards this goal, Northern Gas Networks was considered as a highly suitable demonstration site, since natural gas facilities apply heating processes, and are heavily regulated.

9.2 The IHA programme and the SHyGaN project

In 2022, the Department for Energy Security and Net Zero (DESNZ) launched the NZIP Industrial Hydrogen Accelerator (IHA) programme offering a total of £26 million "for innovation projects that can demonstrate end-to-end industrial fuel switching to hydrogen" [15]. H2GO Power utilised the above idea and in partnership with Baxi, Northern Gas Networks, the Manufacturing Technology Centre and HSSMI, submitted the SHyGaN proposal for a demonstration project in Stream 1. In September 2022, DESNZ awarded H2GO the SHyGaN project, the only project to receive funding for undertaking a Stream 1 demonstration project.

9.3 SHyGaN concept and innovation

For the case of SHyGaN, to demonstrate an end-to-end system a configuration of the above idea was to bring a turnkey solution for carbon-free and safe hydrogen-powered heat supply by integrating the novel hydrogen technologies of H2GO Power and Baxi, together with market ready hydrogen assets. The main technical innovations that were introduced to jointly operate through the project, were developed separately and through SHyGaN they were scheduled to work together as a system. These main technologies were:

I) a novel hydrogen storage technology developed by H2GO Power as detailed in section 1.3 H2GO hydrogen technologiesof this report.

II) a prototype hydrogen boiler developed by Baxi which through the modification of the gas-air assembly, combustion chamber and combustion electronics, brings to the boiler a safe and continuous operation using 100% hydrogen fuel. As such, when utilising green hydrogen it can achieves provide decarbonised heating, and a power output equivalent to its natural gas counterparts, in the same design footprint.

The system (heat-in-a-box) that would encompass these technologies was conceived to be composed of two containerised and interconnected plug and play units, where the first unit would host integrated stacks of AEM electrolysers manufactured by Enapter for hydrogen production, and Baxi's hydrogen boiler, and the second a series of stackable hydrogen storage reactors applying H2GO Power's proprietary technology. This approach of splitting the main functions of the system between two containers, would give high flexibility and better control over its operation. Combining this, with modular electrolysers, such as from Enapter, and the H2GO's modular reactor, results in a flexible and adaptable system to many different applications.

In addition to the above innovative elements, both containers were designed to be monitored and controlled by HyAI - an AI-driven software platform developed by H2GO that could be integrated to almost any existing infrastructure, including the system's components, optimising overall performance. The optimisation performed by HyAI, was holistic as it did not account for the system's internal operations solely, but also the broader environment such as grid prices, grid emissions, local weather and temperature, together with the effect of other site operations. This holistic approach on HyAI's optimisation made it a genuinely breakthrough solution for the smart control of hydrogen systems. A schematic overview of the envisaged system is provided below:

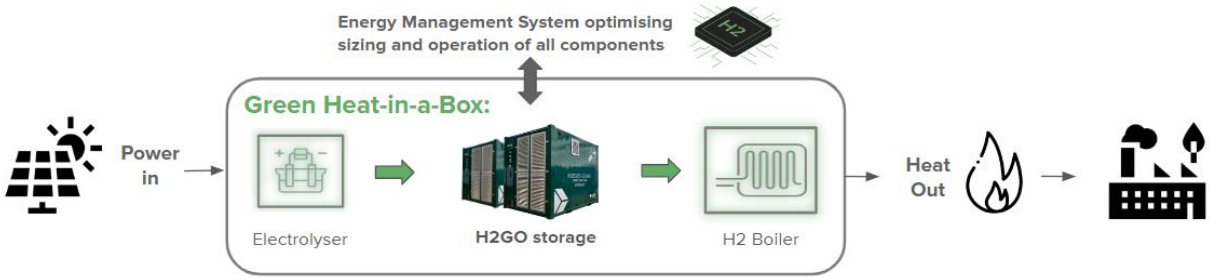

Figure 23: SHyGaN concept

For the demonstration's needs as mentioned, the facilities at Northern Gas Networks' NeRV site was selected, both for their suitability and also for their success as a testing site for novel technologies. The selected process at this facility to be fuel-switched, was that of gas preheating. Gas preheating is a specific operation that natural gas transporters employ while reducing gas pressure for end-user delivery to counteract the Joule-Thompson effect. This process if not conducted properly can result in significant operational issues, and as of now the vast majority of sites applying this process use heat exchangers. The selection of this process for the project's needs can be summarised as follows:

I) a natural gas facility such as the one operated by Northern Gas Networks is a heavily regulated site, where the most stringent safety standards are applied, and this also includes the gas preheating process. As mentioned above, a demonstration on the site, would prove the system's capability to satisfy any safety requirements and demonstrate the technology's potential.

II) The installation of this system at the specific site would also allow the exploration of hydrogen blending, which is considered a viable option in the process of decarbonising the energy sector, at the time that the project was conceived.

III) Northern Gas Networks has a significant track record on hydrogen-related projects which would facilitate the whole integration process, while the experience of their team would add further value to the project.

IV) The selected site contains numerous operational assets, where H2GO's software platform (HyAI) would be integrated, demonstrating the software platform's capabilities as well and its adaptability to a broad range of assets

V) Independent to the project, NGN undertook the installation of a solar panel array at their test site, which provided the opportunity for powering the system directly with renewable energy to produce green hydrogen.

For the demonstration's needs a storage capacity of 30 kg of hydrogen or 1 MWh was considered as suitable. This scale was also appropriate for an initial commercial size, as thanks to the modular and flexible design that was considered for the system, it was also possible to place the system's assets in cascade for serving larger storage and power demands if needed. As such, the following capacities for the system's key components have been estimated for this scale: i) a 100kW electrolyser capacity, and a hydrogen boiler of up to 45kW capacity.

9.4 SHyGaN consortium

The SHyGaN consortium comprised the following organisations and corresponding roles:

H2GO POWER

Main system developer and coordinator
Project coordination leading all system design and dissemination activities.
Involvement in H&S, on-site design, system manufacturing activities, and site installation activities.

BAXI

Provider and developer of the boiler technology
Involvement in H&S, system and on-site design, and system manufacturing activities.

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mtc Manufacturing Technology Centre

System prototype manufacturing
Leading all system manufacturing activities. Involvement in system and on-site design activities.

Northern Gas Networks

Testing facility provider
Leading H&S, on-site design and site installation activities. Involvement in system design and manufacturing activities.

HSSMI

Manufacturing consultancy
Leading the definition of the system's scaling up strategy including aspects such as Design for Manufacture, System end-of-life etc. Involvement in system design and manufacturing activities.

9.5 Objective of this appendix

The objective of this Appendix is to summarise the work completed as part of the envisaged demonstration. This summary document will outline the key findings from the activities undertaken as part of this project, providing conclusions and recommendations for further development in order to support the development of hydrogen-powered heating solutions. This competition has provided the SHyGaN consortium with the opportunity to work on a global-first concept for a hydrogen powered heating that applies solid-state hydrogen storage.

Unfortunately, the SHyGaN project was terminated prematurely as explained in the introduction to this report.

9.6 SHyGaN project objectives

The following is a summary of the main project objectives and a short commentary on the project's performance against these:

1. **Proving through an evidence-based demonstration the feasibility of the proposed system for heating applications in an industrial setting**
   The project was terminated prior to commencing the system's build. Therefore, no demonstration took place. However, the design was mature, and several simulations were conducted, while several independent safety assessments were held (e.g. HAZID, HAZOPs, LOPA etc). Based on the insights acquired from the system's design, the positive results of the demonstration and the findings from the abovementioned safety assessments, the system concept and design indicated high potential, and its demonstration would further justify this potential.
2. **Improving industrial stakeholder understanding on effective delivery of hydrogen solutions through excessive dissemination activities within the project**
   Despite the termination of the project, there were participation in multiple events (national and international), which gave visibility to multiple stakeholders including industry. As stated, through all engagements, the feedback received was highly encouraging and positive. Unfortunately, despite this, the market has been proven to not be ready for the wider adoption of such solutions. Within the coming years should further private and public support be provided for the establishment of hydrogen projects globally, then the market is likely to receive necessary boost to facilitate the adoption of such technologies.
3. **Boost knowledge, confidence and awareness of industrial stakeholders to adopt hydrogen-based systems through a successful demonstration and disseminating project findings**
   As no demonstration was conducted it was not possible to meet the specific objective. However, as mentioned above, the feedback and the dissemination of the results from the work conducted, were met with enthusiasm regarding the system's

performance. Even so, despite the system's capabilities through the feedback received, most stakeholders were sceptical if such solutions can be widely adopted based on the current outlook of green hydrogen deployments, since hydrogen production is not yet cost-effective while several viewed the lack of supporting infrastructure as a barrier.

4. **Facilitate new commercial relationships and market awareness by directly engaging with prospective customers and partners during the project**
   Similarly with objective 2, H2GO Power engaged with multiple stakeholders and participated in many events addressing the wider industry, innovation and energy sectors. Again, as mentioned, despite the high interest received, there was scepticism regarding the maturity of the market that would allow a wider application of such systems.

10.0 System development - process and feasibility

10.1 Core technology operation and challenges

As described elsewhere in this report, the H2GO Power core technology allowed hydrogen gas to be stored in a solid state using relatively low pressure storage vessels known as reactors. To enable the charge and discharge of these reactors, the system accurately controlled the temperature and flow of liquid coolant, while regulating and directing the flow of hydrogen. The challenge for this implementation is to ensure the electrical and mechanical aspects of the system perform reliably and safely at all times.

For the SHyGaN installation, two further significant technology challenges were present. Firstly, the generation of large amounts of hydrogen (>300 NL/min) from the site's solar PV power supply, which was achieved using an assembly of modular electrolysers. Secondly, the integration of a hydrogen boiler to utilise the generated/stored hydrogen for on-site water heating. The integration and control system challenge related to these two aspects was highly demanding due to the large number of interfaces related to the different processes, along with the safety considerations for hydrogen and oxygen flows.

For both installations (SHyLO and SHyGaN), significant effort was made to ensure that the internal system volume could be categorised as Zone 2 NE under the ATEX directive, which allowed significantly reduced costs for electrical components within the system, this has been discussed in further detail in section 3.2.3.To achieve ATEX Zone 2 NE a reliable and effective ventilation system was required, along with a safety system to detect explosive gas and shutdown the system operation.

10.2 System requirements and concept architecture down select

Capturing system requirements on a technology integration project such as this is crucial for successful development and implementation. The process gathered detailed information from all stakeholders for both functional requirements, which specify what the system should do, and non-functional requirements, which describe how the system should perform. This succeeded in establishing different stakeholders' understanding of the project's goals, reduced the risk of scope creep, and provided a benchmark for validating the final product. However, given the first of a kind developmental nature of the SHyGaN installation, refinement of the requirements continued throughout the design phases of the project. A snapshot of part of the customer requirements is provided in Table 4.

Table 4. A snapshot of the first 7 SHyGaN customer requirements

Customer Requirement Number	**Requisite**		**Customer Requirement Description**
CR1	The system…	**SHALL**	demonstrate that hydrogen can be seen as fuel of the future to contribute to global decarbonisation goals
CR2	The system…	**SHALL**	be safe and comply with necessary regulatory requirements approval incl NGN G17, or where due to the innovative nature of the developed product, demonstrate an acceptable level of risk
CR3	The system…	**SHALL**	be capable of providing a continuous 38-45kW peak heat supply when commanded to supplement the current preheating infrastructure at the NGN NeRV site
CR4	The system…	**SHALL**	clearly demonstrate that hydrogen combustion (via a boiler) is an economical way to produce heat
CR5	The system…	**SHALL**	be able to store hydrogen to use as a fuel source for heat generation on demand, when renewable energy is not available
CR6	The system…	**SHALL**	meet any local planning requirements (for instance imposed colour schemes, unit height, etc)
CR7	The system…	**SHALL NOT**	affect any local wildlife through waste product seepage, excessive noise or bright/flashing lights

Although the key system functional blocks for the installation were broadly fixed as part of the project proposal, a traditional design lifecycle was followed, generating, evaluating and down selecting the most suitable architectural concept based on the key performance drivers of both the SHyGaN installation and the product development roadmap of the business, such as performance, cost, scalability, and risk. During this phase, trade-offs were necessary, as no single architecture could perfectly meet all requirements. The down selection process involved detailed analysis and stakeholder input to ensure that the chosen architecture supported the system's long-term goals and was adaptable to future changes. However trade-offs were needed to ensure the scope did not creep and project resources were not impacted. Safety remained the number one priority and where trade-offs could not be accepted unless a satisfactory level of risk could presented that aligned with published general technical guidance. The approach taken to the down select was to build a minimum viable product (MVP) that met the requirements of the project. As with the requirement analysis, the development nature of the project required lessons to be learned during the design phase and architectural modifications to made where necessary.

10.3 Performance feasibility

In parallel with the concept down select, all process flows were simulated to ensure the feasibility and performance of the system. This was based on the initial process flow diagram (PFD).

Six different operational modes were simulated, representing all possible combinations of the system's main components. These modes include Storage Recharge (SC), where hydrogen is stored from the electrolyser; Storage Bypass & Supply (SB-S), where hydrogen bypasses storage and goes directly to the boiler; Storage Discharge (SD), where stored hydrogen is supplied to the boiler; Storage Bypass & Supply, Throttled (SB-ST), similar to SB-S but with throttled supply; Storage Charge & Supply (SC-S), where hydrogen is supplied to both the boiler and storage; and Storage Bypass & Supply & Recuperation (SB-SR), where hydrogen is supplied to the boiler and the storage unit acts as a heating unit. The primary goal was to define the system's predicted efficiency under these modes, assess energy and mass balance, validate pipe sizes, and identify potential system improvements.

To conduct the simulations the following assumptions were made:

- The electrolyser stacks (5 x 8 electrolysers) would be coupled in a parallel flow path configuration; thus, each electrolyser should receive the same pressure and equally distributed flow.
- The maximum system flow rate would be 80 L/min at 25°C (inlet) for the thermal control loop (for the electrolyser only).
- The system was assumed to consume the required power, not the total available power from the renewables plant (96kW).
- Where possible, flow was assumed to be fully turbulent (Reynolds number > 2100) and fully developed within the system.
- 1-D Steady-state isothermal process, the system was at an equilibrium state, and any external venting is to the atmosphere.
- The boiler should operate at maximum capacity (250 NL/min of hydrogen) for all operating scenarios.

- Internal pipes and flow path walls were assumed with a pipe roughness of mild steel pipes.
- Pipes were sufficiently insulated to result in minimal thermal temperature drop during fluid transport.
- The diameter of pipes was similar to those used in deriving K-values (D<4”).
- All calculations considered coolant as water (not water-glycol 30% mix), and volume flow rates of hydrogen are considered at “normal” conditions (NL).

Similarly, the main findings from the simulations are as follows:

- The “Storage Bypass & Supply Throttled” (SB-ST), “Storage Charge & Supply” (SC-S), and “Storage Bypass & Supply Recuperation” (SB-SR), were the best scenarios to operate in terms of system efficiencies, thereby indicating that the effect of HySTOR operation on the overall performance had minimal impact. However, having HySTOR in the system enabled flexibility in the site’s operation when low power was available to produce Hydrogen.
- The “Storage Discharge” (SD) operation mode was recommended to be operated when electrolysers were not used to produce H2 to ensure smooth and continuous running of the plant even during the seizure of H2 production using solar power.
- The “Storage Charge” (SC) operation mode was the worst of the 6 modes in terms of system efficiency (63%) as waste heat produced from the electrolyser could not be recuperated into the heating of the site. This was the only mode where efficiency dropped as the system would not be combusting any hydrogen during this mode. Thus most of the operations performed would be by the electrolysis process with an effective efficiency of approx. 60%, whilst the hydrogen storage reactors store the hydrogen produced. In the future should the capacity of electrolysers increase, a more efficient electrolyser could be considered.
- However, the “Storage Charge” (SC) operation mode would be useful in cases of plant shutdowns or boiler maintenance, where renewable energy would be available to continue H2 production and storage to be utilised later during or after plant startup or high-demand periods.
- For five out of the six operational modes (SD, SB-ST, SC-S, SB-SR, and arguably SB-S), where hydrogen was to be used as a combustion fuel, the system would achieve efficiencies above 86%. This demonstrates that the hydrogen storage unit would have reduced impact on overall system efficiency.
- The Storage Bypass and Supply Mode (SB-S) would not be feasible under this configuration, since the electrolysers were to produce more hydrogen than the boiler’s capacity. Therefore a larger hydrogen boiler could be considered as an alternative configuration, which would have the same efficiency (92%) as the Storage Bypass & Supply, Throttled (SB-ST) mode, provided that the boiler would have 98% efficiency as the boiler originally considered.

For further clarity, the main information for each operational mode together with their associated Process Flow Diagrams (PFD) is provided below.

Storage Charge (SC)

As shown in Figure 24: PFD for Storage Charge Mode in the SC mode, the HySTOR container receives hydrogen from the electrolyser (via the H_2 dryer), while the electrolyser, H_2 dryer, the thermal control loop (TCL) chiller and the thermal control loop (TCL) are active. Moreover, the H_2 boiler, the electrolyser heat recuperation unit and the HySTOR heat recuperation units are all inactive. The model's logic is as follows: i) electrolyser (1) releases H_2 to the dryer (2), which passes it to recharge HySTOR (3), bypasses electrolyser heat recuperation to an air heat exchanger (4), where electrolyser heat is lost to the atmosphere, ii) Hot water from HySTOR is returned to chiller (5), cooled and sent to HySTOR for charging with H_2, and iii) the overall system efficiency depends on electrical power to the electrolyser and both pumps, as well as work done by charging HySTOR (3) with H_2 (potential energy of H_2 stored)**Error! Reference source not found.**. For this mode the assessment of the energy b alance shows that this system would operate with an efficiency of 63.38%. In this mode, heat recovery from the electrolyser is not carried out, while the H_2 boiler is not operational. Thus, heat from the electrolyser is re-directed via a bypass loop to an air heat exchanger – heat is lost to the atmosphere. It was also noted that the electrolyser's heat could be recuperated by using the electrolyser heat recuperation unit and transferring the energy to the natural gas side water which could increase the system's efficiency.

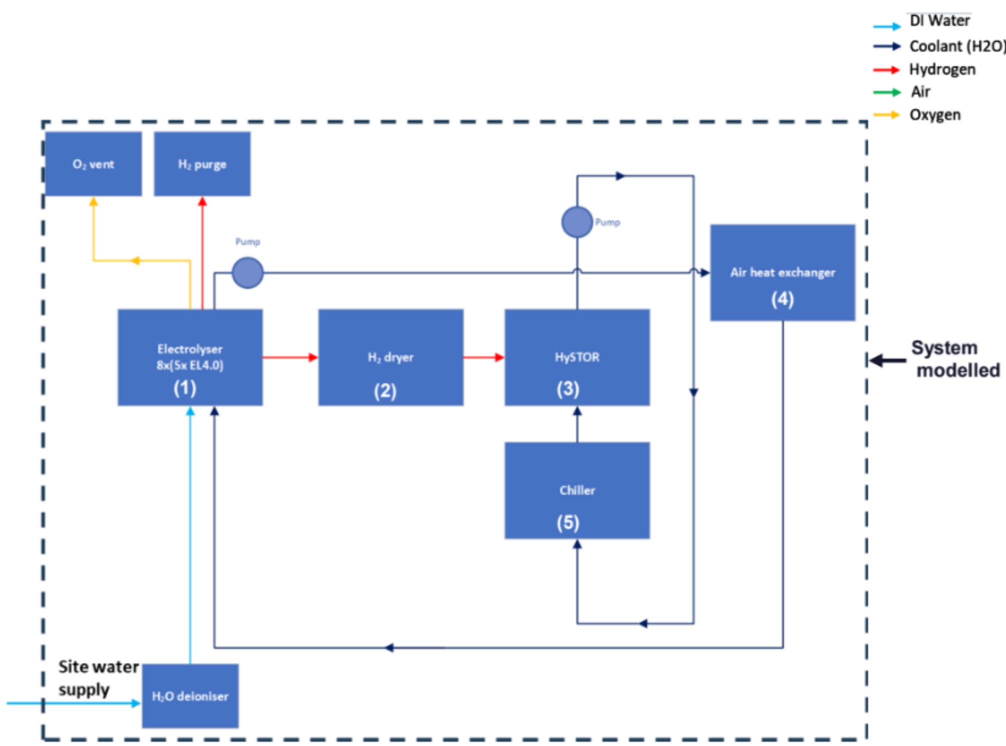


Figure 24: PFD for Storage Charge Mode

Storage Bypass & Supply (SB-S)

As per Figure 25: PFD for Storage Bypass & Supply Mode the SB-S mode, the HySTOR container is being bypassed, and the H_2 from the dryer is directly supplied to the boiler.

During this mode, the HySTOR heat recuperation unit is inactive, and the electrolyser heat recuperation unit is involved in both the thermal control loop (TCL) and hydrogen loop to the boiler. The model's logic is as follows: i) In the SB-S mode, a H_2O deioniser (1), electrolyser (2), and a dryer (3) utilise electrical power from the site grid, ii) Hydrogen (H_2) generated in the electrolyser passes to the dryer and then goes to the boiler (4) for heating the coolant fluid (H_2O) coming in from the natural gas side, iii) The heat recuperation unit (5) uses the heat of the coolant (fluid) to heat the water from the natural gas side before entering the boiler, and iv) Finally, the pumps (6) circulating the coolant loop draw power from the site grid and are considered in the efficiency calculation. In short within this mode the storage bypass and supply process operates the electrolyser (initially assumed at full capacity), producing hydrogen to supply to the boiler. This hydrogen is used as a fuel to heat the water supplied to the natural gas heat exchanger. Also the system recovers heat loss from the electrolysis process using a secondary heat exchanger loop to pre-heat the H_2 boiler supply water from the natural gas plant. However this mode is not feasible to run as the electrolyser's production capacity (333.332 L/min) is larger than the maximum H_2 intake capacity of the boiler (250 L/min). Therefore, the electrolyser should be throttled (as per the current system configuration), producing no more than 250 L/min of H_2, which results in the Storage Bypass Supply & Throttled (SB-ST) operation mode presented as the fourth operational mode below. A larger H_2 boiler with higher hydrogen fuel flow capacity could be considered in the future as an alternative (to replace the current H_2 boiler), which could make this operational mode feasible. With the current configuration, the system efficiency is not expected to differ from that of the Storage Bypass supply & Throttled (SB-ST), mode presented later on this section, provided that the H_2 boiler efficiency remains 98%.

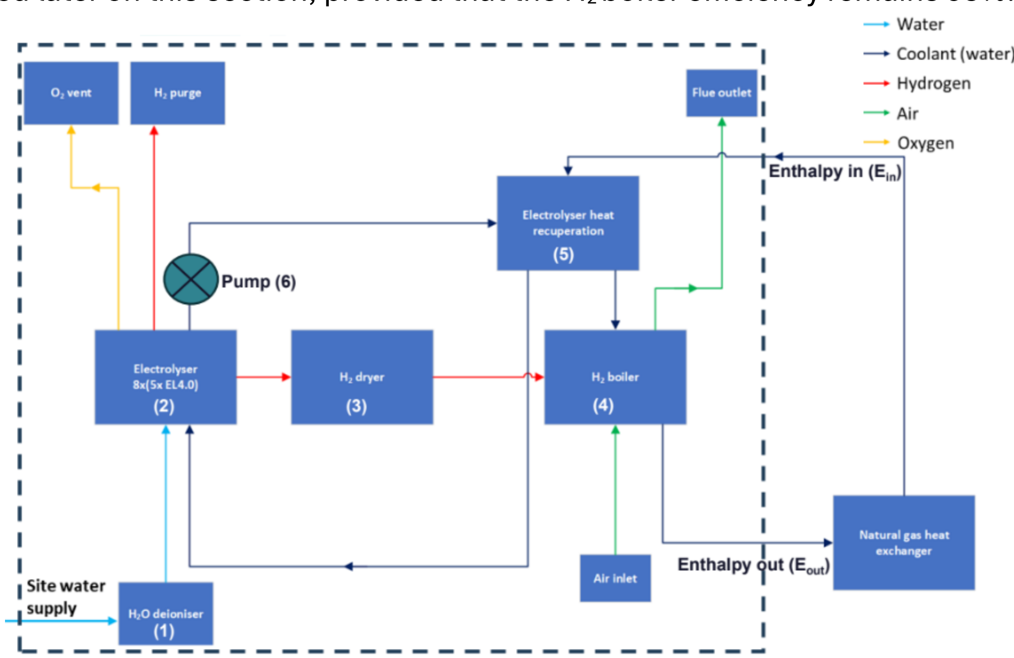


Figure 25: PFD for Storage Bypass & Supply Mode

Storage Discharge (SD)

In this mode (see associated PFD in Figure 26: PFD for Storage Discharge Mode), the HySTOR container (1) directly supplies hydrogen to the boiler, and its thermal control loop is active, whilst the electrolyser heat recuperation and HySTOR heat recuperation units and the electrolysers are inactive. The model's logic is as follows: i) The HySTOR container releases H_2 from metal hydride in the reactors to boiler (2), which returns coolant H_2O to the heater (3) that uses electrical power from the site grid to reheat the coolant, ii) The pump (4) uses power to maintain the coolant flow rate in the thermal control loop, and iii) The overall system can then be incepted as electrical power inputs to components 3 and 4, work done by the HySTOR (1) in releasing H_2 (potential energy stored inside the H_2) and work done by the overall system as energy gained by the natural gas (NG) side coolant H_2O. In this mode, the HySTOR container is used at a reduced capacity sufficient to supply H_2 to the boiler running at full capacity. This is used as a fuel to heat the water on the natural gas heat exchanger water. Heat is provided to the reactors using a heater linked to the water glycol pumped around in a cycle using the thermal control loop. This water-glycol returns to the heater at a lower temperature as heat is expelled to the reactors to release hydrogen. The assessment of energy balance for this operational mode showed an overall system efficiency of 86.6%.

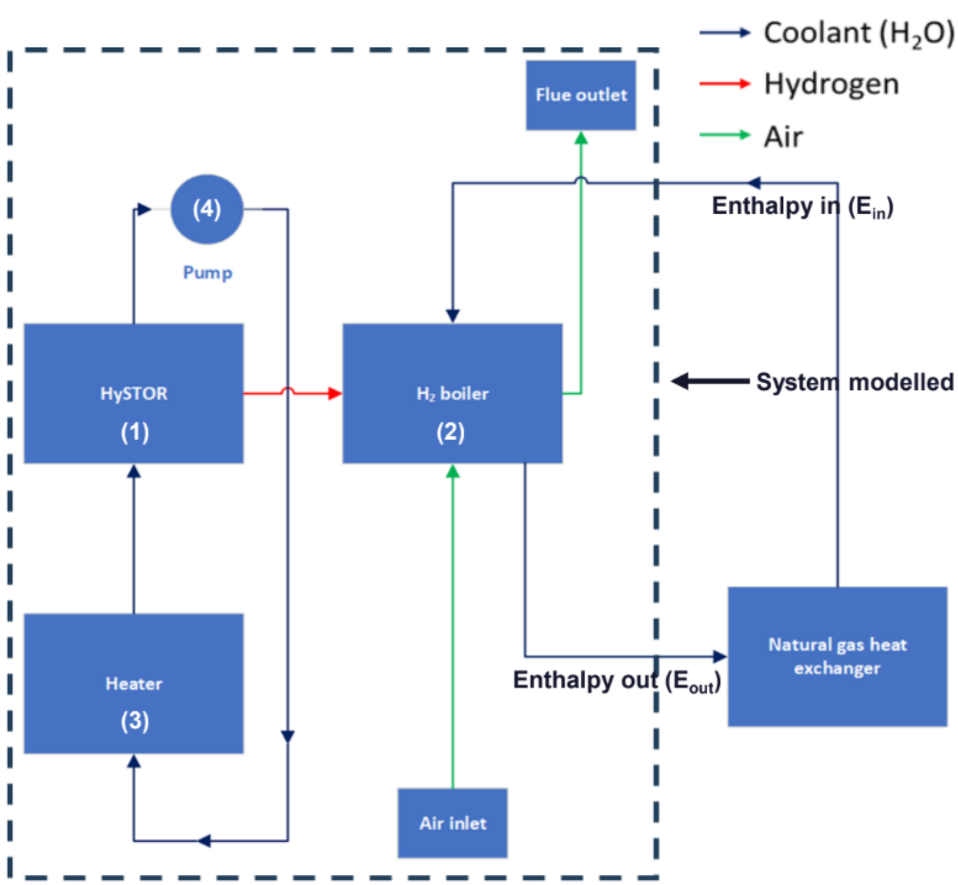


Figure 26: PFD for Storage Discharge Mode

[redacted]

Storage Bypass & Supply, Throttled (SB-ST)

For the specific mode (see associated PFD in Figure 27: PFD for Storage Bypass & Supply, Throttled Mode), the HySTOR container is bypassed, and the hydrogen from the dryer is directly supplied to the boiler, while its heat recuperation unit is inactive, and the electrolyser heat recuperation unit is involved in both the TCL and hydrogen loop to the boiler. In this scenario, the flow of hydrogen production is throttled to match the H_2 boiler capacity. The model logic for this mode is as follows: i) In the specific mode, a deioniser (1), an electrolyser (2) and a dryer (3) utilise electrical power from the site grid, ii) H_2 generated in the electrolyser passes to the dryer and then goes to the boiler (4) for heating the coolant fluid (water) coming in from the natural gas side, iii) The heat recuperation unit (5) uses the heat of the coolant (fluid) to heat the water from the natural gas side before entering the boiler, iv) The pumps (6) circulating the coolant loop draw power from the site grid and are considered in the efficiency calculation, and v) The overall system can be incepted as electrical power inputs to components 2, 3, and 6, thereby outputting enthalpy gained by water (H_2O) back to the natural gas side heat exchanger. The assessment of this mode showed that the storage bypass and supply throttled process operates the electrolyser at 25% reduced capacity, producing hydrogen to supply directly to the H_2 boiler. Furthermore, the system also recovers heat loss from the electrolysis process using a secondary heat exchanger loop to pre-heat the supply water from the natural gas plant feeding into the H_2 boiler. The assessment of the energy balance showed that this mode would operate with a 92.04% efficiency.

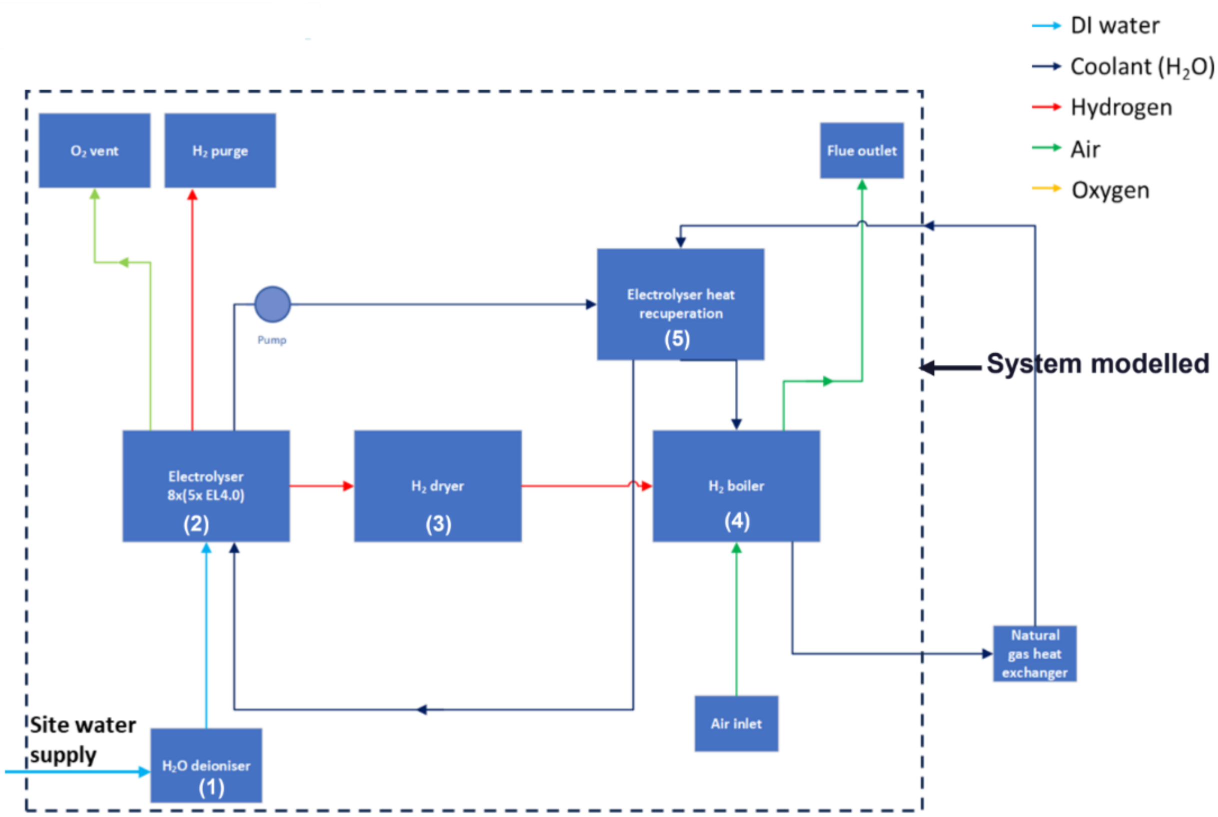


Figure 27: PFD for Storage Bypass & Supply, Throttled Mode

Storage Charge + Supply (SC-S)

For the case of this mode (see PFD in Figure 28: PFD for Storage Charge + Supply Mode), the electrolysers directly supply hydrogen to both the boiler (via the bypass loop) and recharge the HySTOR unit, while all systems except the TCL heater and HySTOR heat recuperation unit are active. Its model logic is as follows: i) electrolyser (1) releases H_2 to the dryer (2), which passes it to the boiler (3) and recharges HySTOR unit (4), ii) Coolant H_2O flows from the (1) to the heat recuperation unit (5) to heat the natural gas (NG) side H_2O, iii) Hot water from (4) is returned to the chiller (6) and further cooled and returned to HySTOR container for charging, and iv) The overall system efficiency depends on electrical power to the electrolyser, the chiller and both pumps, the potential energy of H_2 stored in (4), and heating NG side H_2O. The assessment of this mode showed that the storage charge and supply process operates the electrolyser at full capacity, producing hydrogen to supply to the boiler and the HySTOR container. In addition, the system also recovers heat loss from the electrolysis process using a secondary heat exchanger loop to pre-heat the H_2 boiler supply water from the natural gas plant. The assessment of the energy balance calculations showed that this mode would operate with a 90% system efficiency.

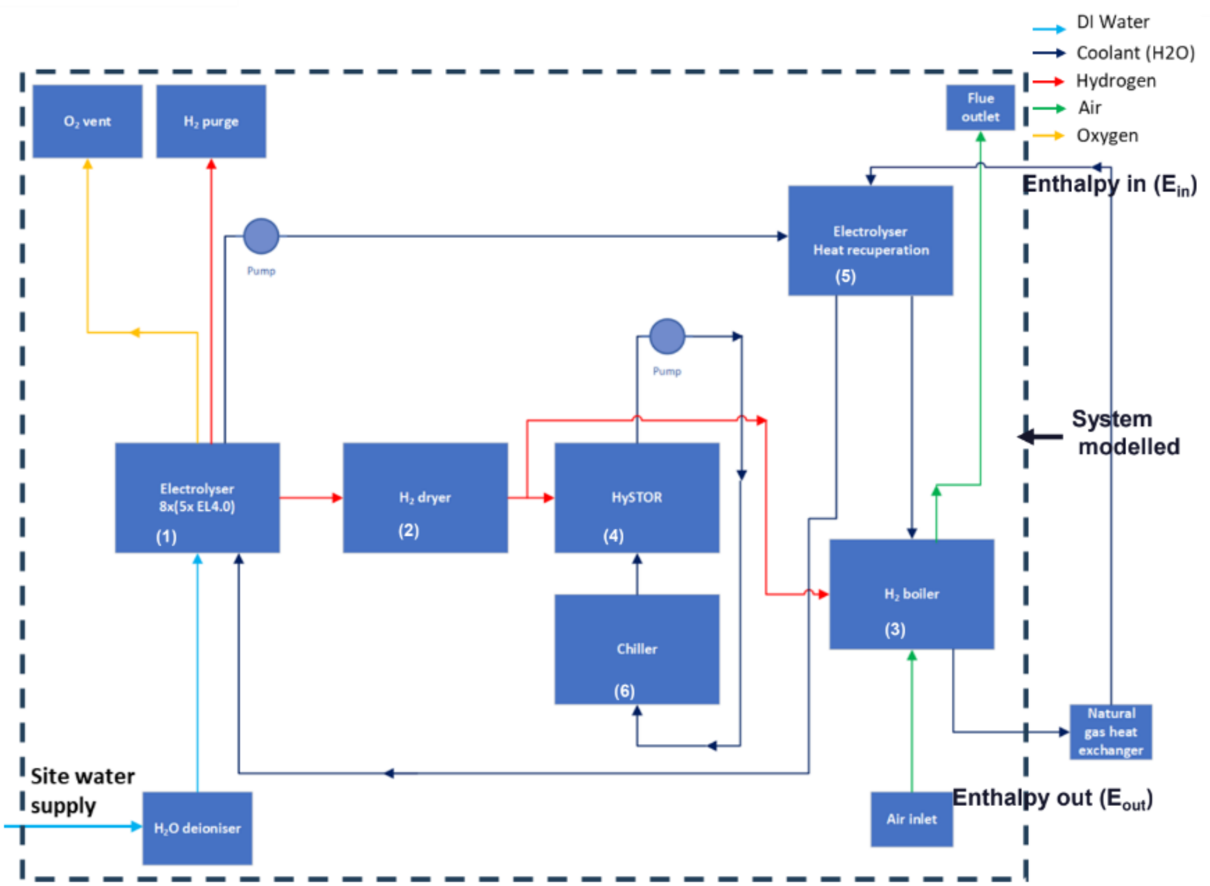


Figure 28: PFD for Storage Charge + Supply Mode

Storage Bypass & Supply + Recuperation (SB-SR)

The final operational mode (see associated PFD in Figure 29: PFD for Storage Bypass & Supply + Recuperation Mode), is applied post-discharge when all the H_2 in the HySTOR unit is depleted. The electrolysers directly supply hydrogen to the boiler, and the HySTOR acts as a heating unit for the HySTOR heat recuperation unit, while all systems are active except for the TLC heater and chiller. For this mode, the associated model logic is as follows: i) In this mode a deioniser (1), an electrolyser (2), and a dryer (3) utilise electrical power from the site grid, ii) The H_2 generated in the electrolyser passes to the dryer and then goes to the boiler (4) for heating the coolant fluid (water) coming in from the natural gas side, iii) The electrolyser heat recuperation unit (5) uses the heat of the coolant (fluid) to heat the water coming in from the natural gas side before entering the boiler, iv) The HySTOR container (6) acts as a heat source to the HySTOR heat recuperation unit (7) to heat the NG side H_2O and outlets to the boiler, and v) The overall system can be incepted as electrical power inputs to both pumps and components 1,2, 3, and 6, in addition to work done by HySTOR as a heating unit, thereby outputting enthalpy gained by water (H_2O) back to the natural gas side heat exchanger. The assessment of this mode showed that the storage bypass and supply process operates the electrolyser (which was assumed at a reduced capacity), producing hydrogen to supply to the boiler, while the system also recovers heat loss from electrolysis using a secondary heat exchanger loop to pre-heat the H_2 boiler supply water from the natural gas plant. Residual heat energy in the HySTOR unit is also recovered as pre-heat energy from the feed water to the H_2 Boiler via the thermal control loop and secondary heat exchanger (this is post-depletion of H_2 from the HySTOR container). The assessment of the energy balance showed that this mode would operate with a 91.2% system efficiency.

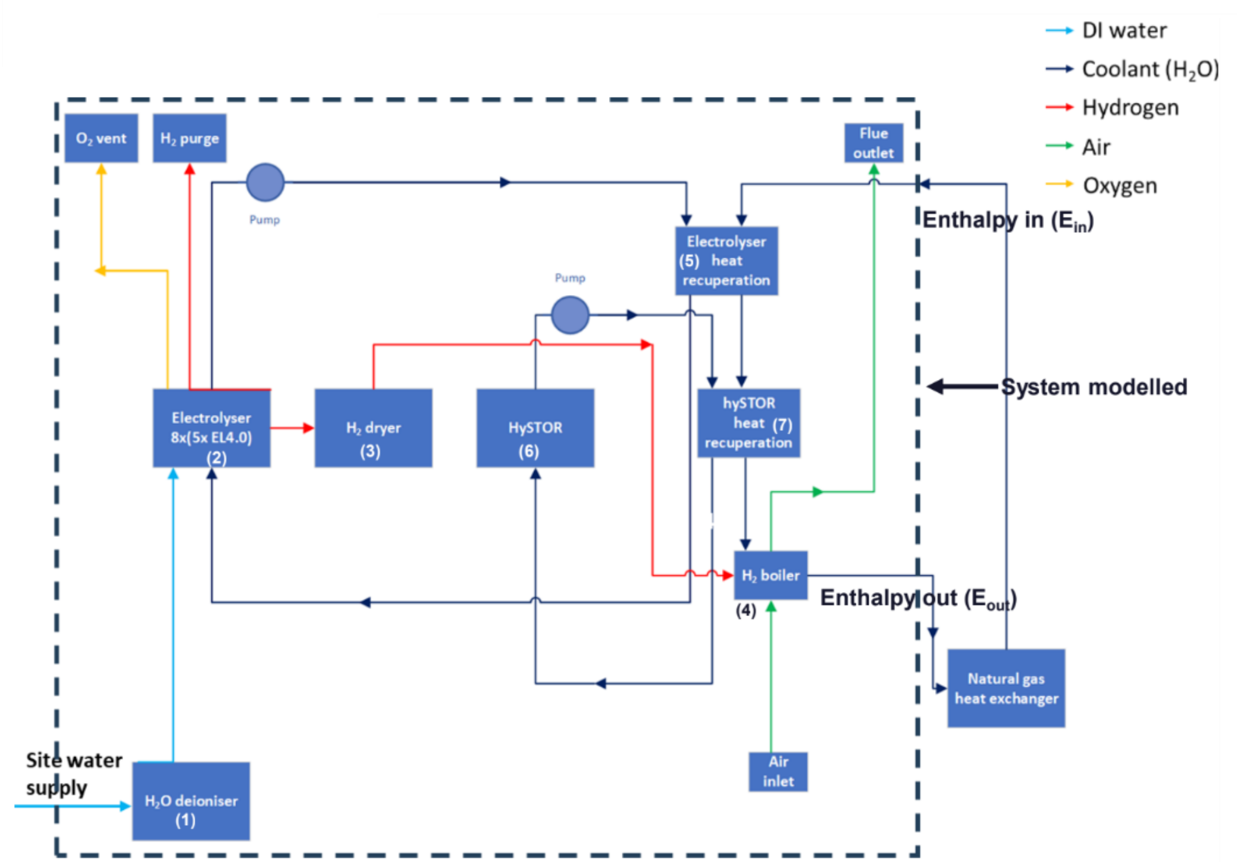


Figure 29: PFD for Storage Bypass & Supply + Recuperation Mode

10.4 System verification and validation (V&V)

A verification and validation plan was used to sequence the build and test activities, phasing the integration of hardware and software to maximise the capture of issues while meeting the timescales, as shown in Figure 30: V&V Plan below. By freezing the design of subsystems and building the system in stages allowed the incremental testing of parts of the design to enable the derisking of design issues being found later in the build. This meant that if issues were encountered with sub systems they could be fixed in advance and not cause delays at later in the project. The V&V plan was derived based on the design and construction of the system and suitable subsystems that could be isolated and meaningful tests carried out that would be representative to that when integrated into the full system.

The more novel and high-risk areas of the development were prioritised for early verification, maximising the opportunity for rework without impact to the project schedule. The activities were grouped and sequenced as follows,

1. Sub-Assembly - Design Verification Activities
    a. High Complexity Component Design Verification
        - Custom designed PCBs
        - Hydrogen Storage Reactor
    b. Purchased Component Calibration and Performance Verification
        - Independent test and adjustment of components (i.e. PRVs) that have uncertain calibration
        - Verification of significant items or items with uncertain performance
    c. High Complexity Component Acceptance
        - PCB acceptance test for each assembly
    d. Component Regulatory Certification
        - Hydrogen Storage Reactor Pressure Certification
        - PCB Pre-compliance EMC Testing
2. Sub-System - HySTOR Beta Balance of Plant Control and Monitoring
    a. Pre-Power Verification
    b. Functional Verification
    c. Performance testing
3. Sub-System - HiAB Balance of Plant Control and Monitoring
    a. Pre-Power Verification
    b. Functional Verification
    c. Performance testing
4. Sub-System - System of Systems Control and Monitoring
    a. Functional Verification
    b. Performance testing
5. System - Factory Acceptance Testing
    a. System Build Acceptance
    b. System Functional and Performance Acceptance
    c. Pre-Installation System Regulatory Certification
6. System - Site Acceptance Testing

a. Site Integration Acceptance
b. System of Systems Functional and Performance Acceptance
c. Post-Installation System Regulatory Certification

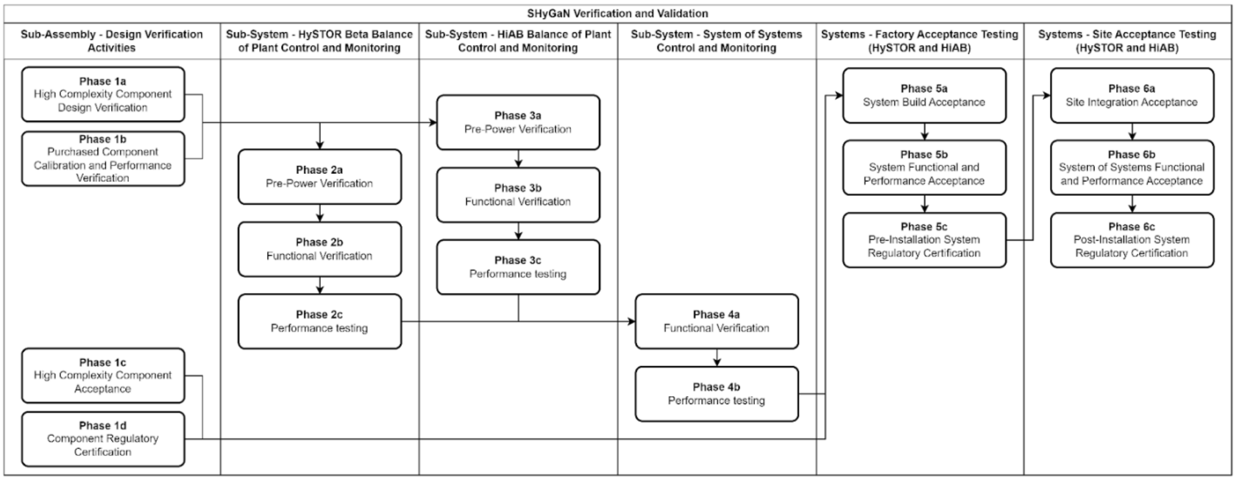


Figure 30: V&V Plan

Due to the large-scale nature of the site integration works, a separate activity was conducted to ensure the modification of the site infrastructure and control system was complete in time for Site Acceptance Testing (SAT). While all stages of the V&V plan up to Factory Acceptance Testing could be carried out in isolation to the deployment, the SAT was required to be carried out in the context of the site to gain value from tests. A site interface control document and general arrangement drawing were iterated to develop and freeze all site interfaces, such as pipework, electrical power, control signal, drainage etc.

Due to the hazards associated with hydrogen systems and the regulations applicable to the intended installation site, all work was conducted in line with the requirements of the Northern Gas Networks' NGN/PM/G/17 standard which controls the processes for appraising and approving modifications to gas systems and includes for risk assessment (such as HAZID, HAZOP, LOPA and QRA activities) and design approval by independent third parties at both system and site installation level.

11.0 Design implementation

11.1 Overview

As described above, the SHyGaN installation would have combined two containerised systems (HySTOR and HiAB) with a number of secondary items to demonstrate the use of industrial hydrogen generation, storage and heating. A hydrogen boiler within the HiAB system would have heated recirculating water and in turn heated natural gas (for entry into the gas distribution network) via an existing heat-exchanger at the NGN site. The hydrogen would have been generated from solar power using electrolysers within the HiAB system and stored in the HySTOR systems solid state storage reactors, when not required for heating. Figure 31 shows block diagram for the NGN installation and interfaces between them.

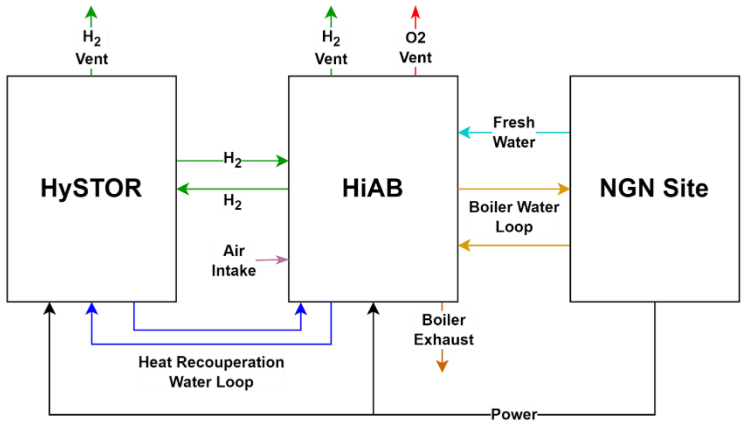
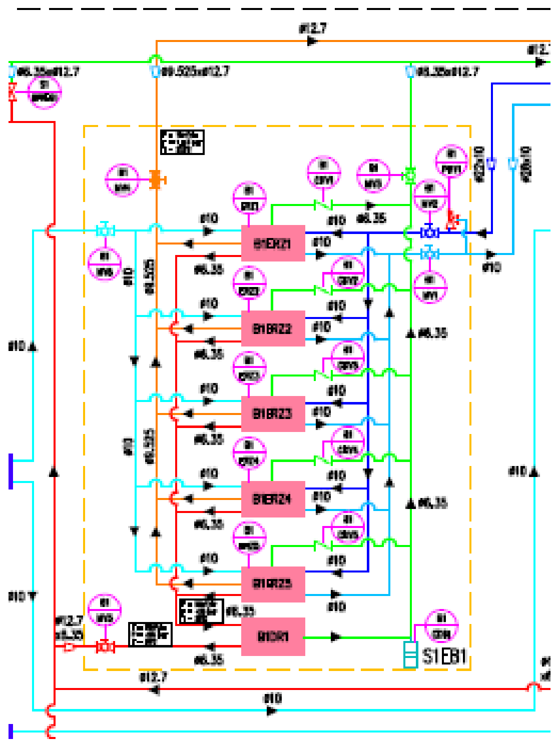


Figure 31. System block diagram for the NGN integration

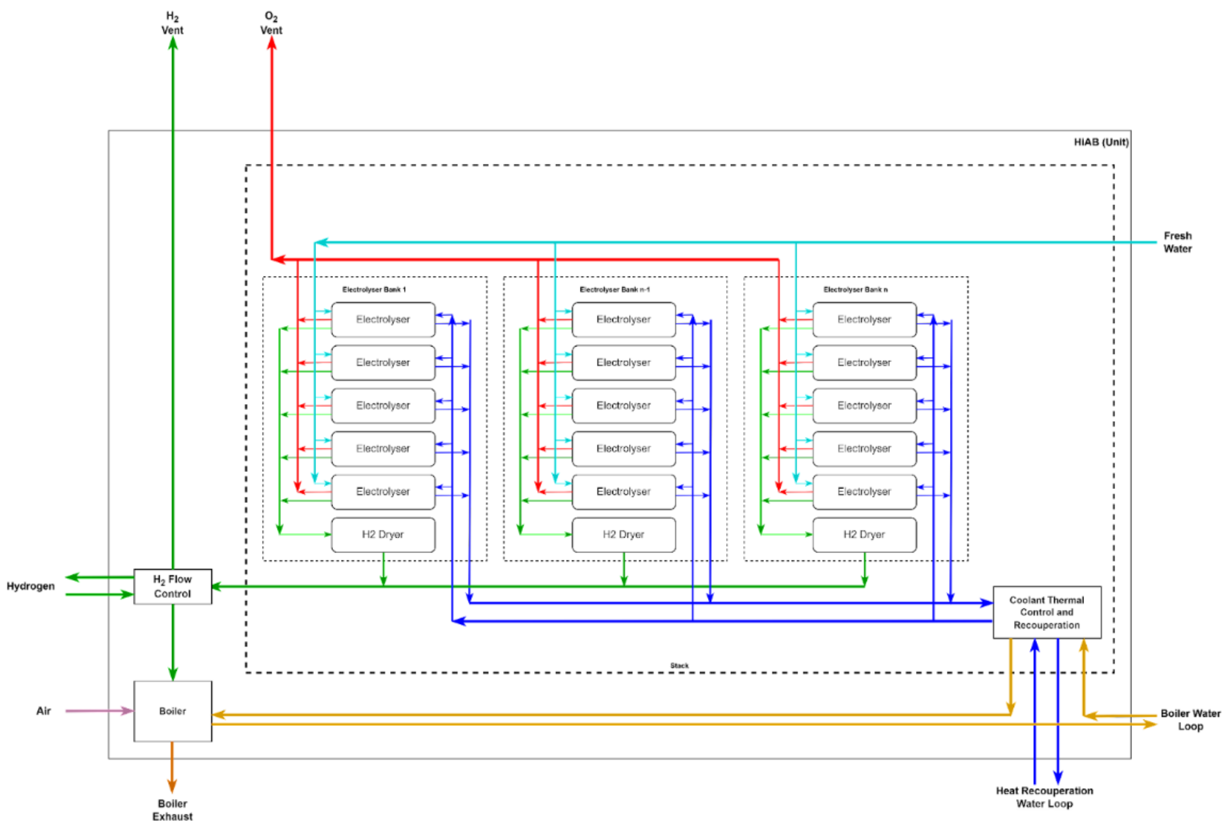
The three system blocks shown above are described in more detail in the following sections. Piping and Instrumentation Diagrams (P&IDs) were developed for each unit and system acting together. A snap shot of each of these is provided as follows with the simplification that abstracts away the complexity of the diagrams which is beyond the scope of what is to be presented here.

The HiAB system combines a number of modular electrolysers and a boiler, as discussed above, which are arranged into control domains similar to those of the HySTOR system as shown in below. The control of the system is segregated into 3 levels, at the top is the System or “Unit” level. The Unit contains one Boiler and one electrolyser “Stack” and is responsible for routing Hydrogen to/from the electrolysers, Boiler and External Storage, depending on the operational mode. Additionally, exhaust flows from the electrolyser and Boiler are managed at Unit level. In some scenarios hydrogen may be vented to purge the system or to prevent overpressure.

Below this is the “Stack”, where thermal and flow control of coolant is managed, cooling the electrolysers and recuperating heat into the incoming Boiler Water Loop. Finally the Stack contains many “Banks”, each containing five electrolysers and one dryer. The Bank allows the modular scaling of the hydrogen generation sub-system, in this implementation there are eight Banks.



(a)



(b)

Figure 32. Snapshot of HIAB P&ID (a) and simplification of this P&ID identifying control domains (b)

As shown in the Figure 33 below, the control of the system is segregated into 4 levels, starting at the top of the system with the “Unit” level, which controls the hydrogen input and output to/from the system; via the System Controller.

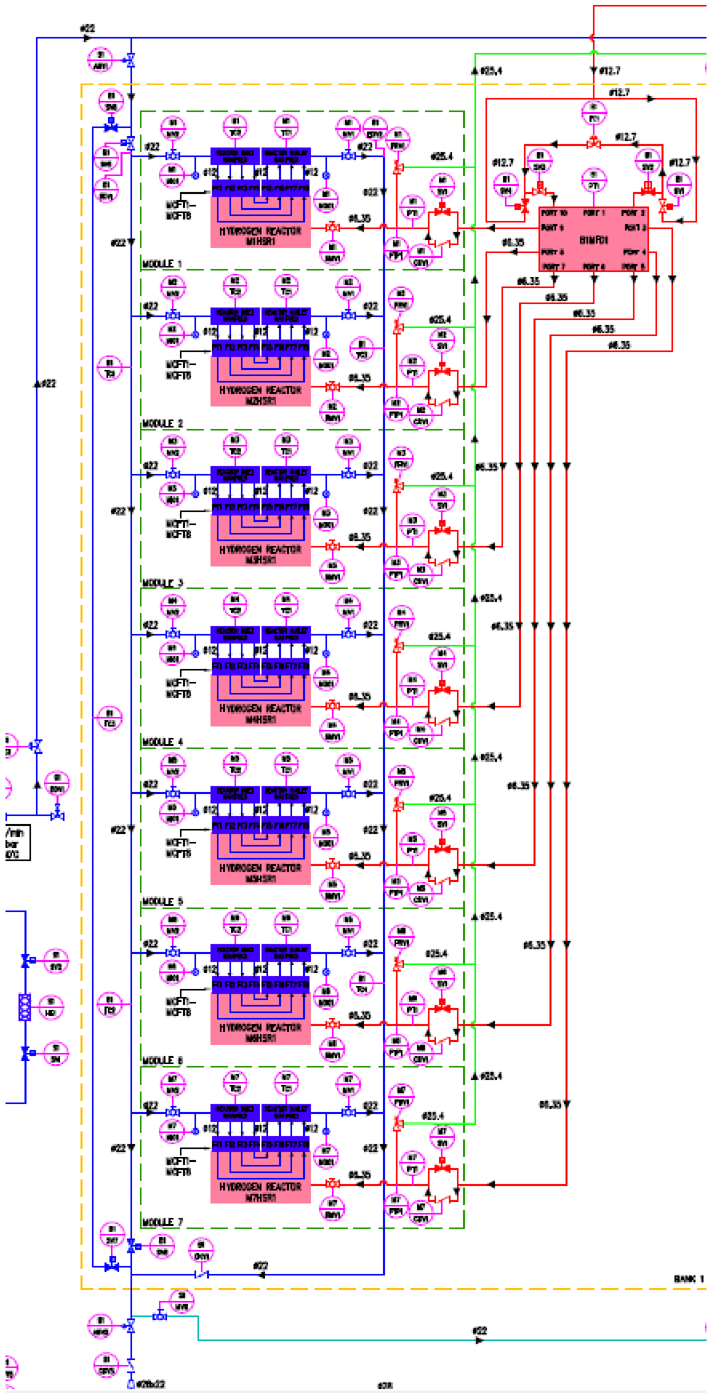
Below this is the “Stack” level, which controls the coolant loop and hydrogen flow for a Stack of Storage Reactors; via a Cross Controller. For future expansion of the control system, there can be multiple Stacks within a Unit, but for the system in question there is only one Stack.

Below the Stack is the “Bank” level, which divides the reactor stack into three subsets of storage reactors. This isolates control of both the hydrogen and the coolant loop of the reactors in each bank; via additional Cross Controllers (1 per Bank).

Finally the bank is subdivided further into modules. A module contains a single storage reactor, along with the hydrogen control elements required to switch the reactor between charge and discharge modes; via the module control items.

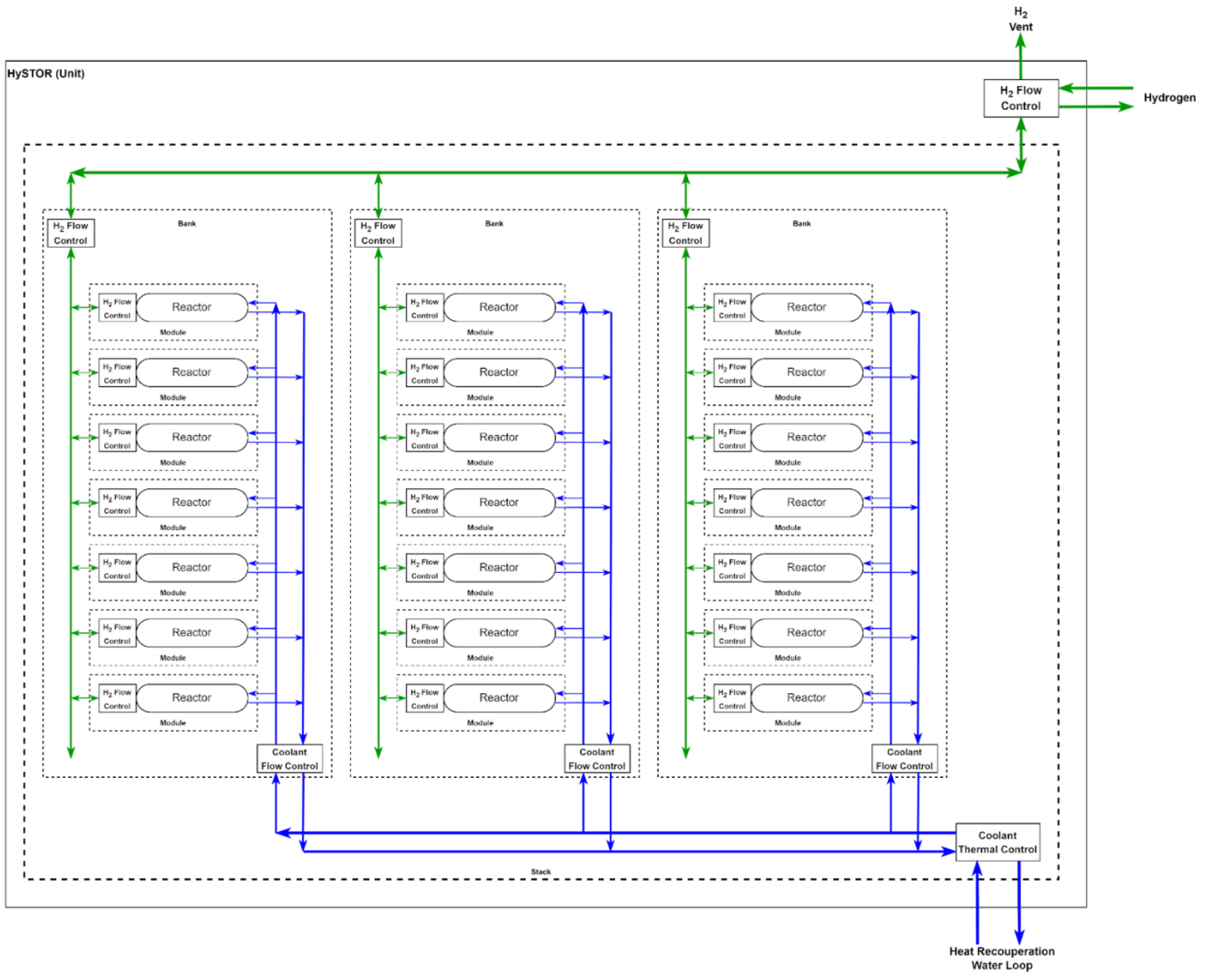
In summary, the Unit contains one Stack, which contains three Banks, which each contains seven Modules. Each Module contains one Hydrogen Storage Reactor, giving a total of 21 Hydrogen Storage Reactors.

Hydrogen flow control (on/off or flow-rate) is distributed between Unit, Banks and Modules, allowing isolation and bi-directional flow of pipework, depending on the operational mode. Thermal and flow control of coolant is distributed between the Stack and Banks, with heating and cooling used in different operational modes. Cooling and warming modes are used to prepare for Charge and Discharge respectively. Additionally, coolant may be allowed to flow externally, for installations with heat recuperation. In some scenarios Hydrogen may be vented to purge the system or to prevent overpressure.



MODULE 1
MODULE 2
MODULE 3
MODULE 4
MODULE 5
MODULE 6
MODULE 7
HYDROGEN REACTOR
BANK 1

(a)



(b)

Figure 33. Snapshot of HySTOR P&ID (a) and simplification of this P&ID identifying control domains (b)

11.1.1 NGN site

The existing NGN site equipment was to be modified to recirculate hot water to/from the existing natural gas heat exchanger with control valves to direct flow to the HiAB system as required. The site electrical system, supporting solar panels, was also to be modified to synchronise the power with the local grid connection.

11.1.2 HiAB system

The HiAB System was designed to generate hydrogen from the site solar supply using a modular assembly of 19” rack mounted electrolysers, controlled to deliver hydrogen from the electrical supply on demand, with water cooling to allow heat recovery. The system managed hydrogen flows between the generation, storage and boiler via a hydrogen pipework assembly with the pressure management components to maintain safety and electro-mechanical solenoid valves to allow flow path control. Finally, the system heated recirculating water to/from the NGN site heat-exchanger using a hydrogen boiler, controlled to deliver heat to the recirculating site coolant loop on demand, recuperation from other system waste heat.

11.1.3 HySTOR system

The HySTOR System was designed to store the generated hydrogen from HiAB, using a modular assembly of solid-state hydrogen storage reactors, controlled to allow charging and discharging of hydrogen, with water cooling/heating to control the reaction and allow heat recovery. The system managed hydrogen flows between the generation, storage and boiler using a hydrogen pipework assembly with the pressure management components to maintain safety and electro-mechanical solenoid valves to allow flow path control.

11.1.4 Control architecture

In addition to these primary system functions, all systems had features to allow monitoring and control, electrical interfacing and containment of the critical components. For the installation level control, an operational mode select philosophy was used. The customer interacts with a SCADA interface in the control room, which allows a number of installation level modes to be requested. The request cascades down to the Upper Level Controller, checks are made to ensure it is safe to enter the operational mode, a response is given to the SCADA and the request is interpreted and cascaded to the next level as shown in Figure 34: Control Architecture below.

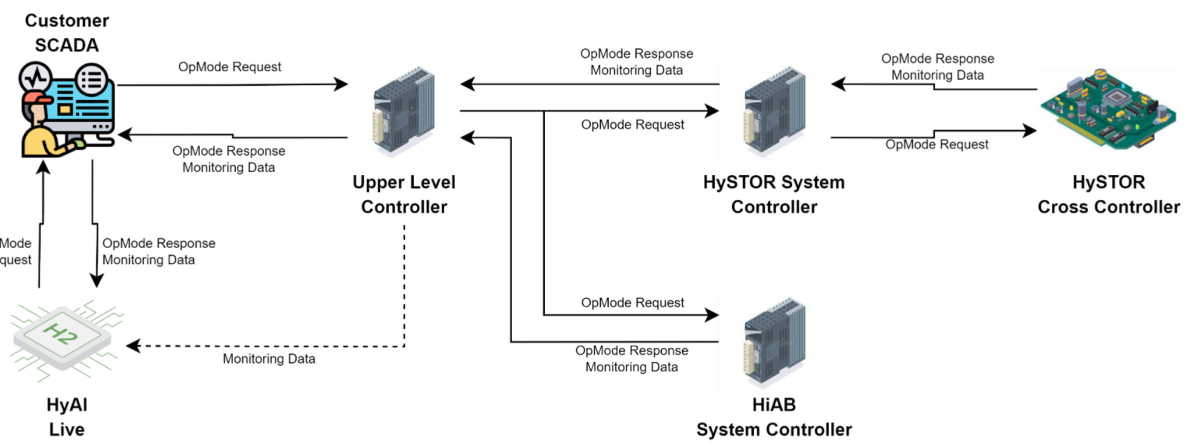


Figure 34: Control Architecture

Finally, the system was also managed via a HyAI Live cloud platform, to optimise the scheduling based on all available data. This used the same operational mode request methodology to control via the upper controller.

12.0 NGN site design implementation

NGN being the project's pilot site was tasked mainly with the execution of the on-site design which is presented within this chapter. Additional to this, NGN worked on the activities related to on-site regulatory compliance and risk management, the outputs of which are provided in section 18.0. Lastly for the preparation of the system's set up, on-site work was focused on creating a health and safety plan where by the time of the project's termination two versions were drafted – a preliminary and an interim which considered safety in design and safety in construction, respectively.

12.1.1 Site parameters and assumptions

The pressure reduction station at the NGN site, incorporates two inlets and four outlets. There are 3 main pressure cuts on site (38 to 19 barg, 38 to 17.2 barg and a 17.2 to 2 barg). One packaged boiler unit supplies heat to four heat exchangers, three of which are located on the High Pressure – High Pressure section and one on the High Pressure - Medium Pressure section. The highlighted section of pipework in Figure 35: NGN Site Pressure Reduction Station Gas Pipework with High Pressure – Medium Pressure system highlighted details the High Pressure - High Pressure High Pressure - Medium Pressure system, cuts and associated heat exchangers which were relevant to the project's scope.

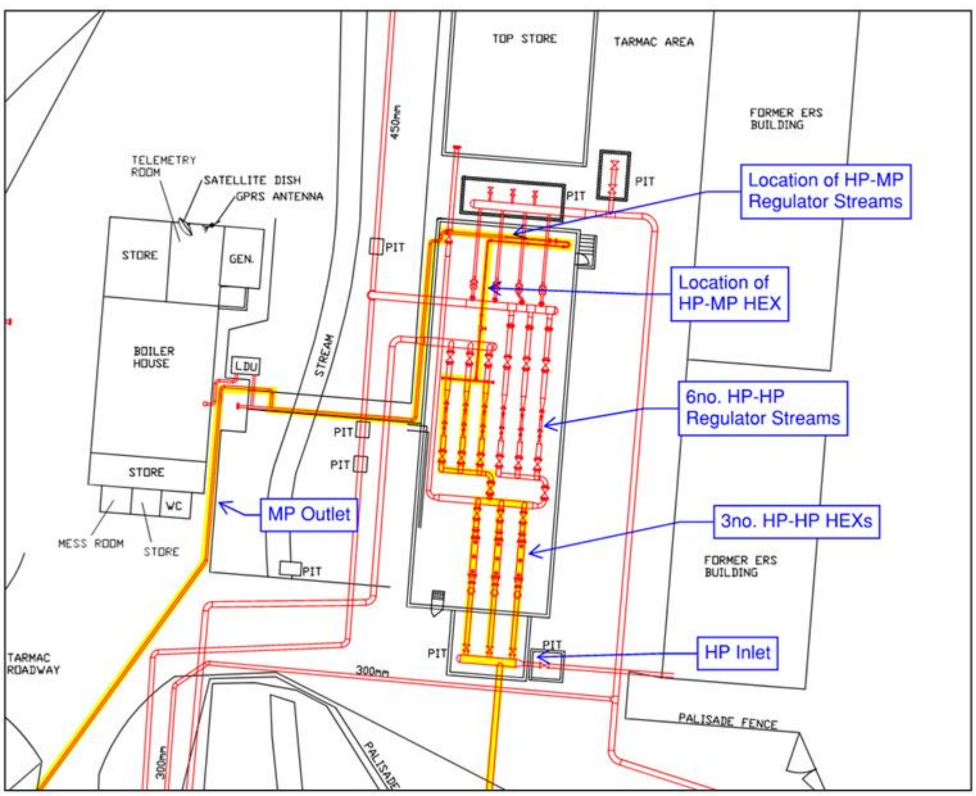


Figure 35: NGN Site Pressure Reduction Station Gas Pipework with High Pressure – Medium Pressure system highlighted

In Table 5: NGN Site Pressure Reduction Station Operating Parameters below the main operation parameters of the NGN Site Pressure Reduction Station are presented.

Table 5: NGN Site Pressure Reduction Station Operating Parameters

Parameter	Value
High Pressure – High Pressure Inlet Maximum Operating Pressure	34 barg
High Pressure – High Pressure Inlet Maximum Internal Pressure	41.8 barg
High Pressure – Medium Pressure Inlet Maximum Operating Pressure	17.2 barg
High Pressure – Medium Pressure Inlet Maximum Internal Pressure	18.92 barg
High Pressure – Medium Pressure Outlet Maximum Operating Pressure	2 barg
Site Maximum Flow Rate	327000 SCMH
High Pressure – Medium Pressure Maximum Flow Rate	11700 SCMH
High Pressure – Medium Pressure Minimum0 SCMH Flow Rate	0 SCMH
Water Pipework Size	50 NB

Similarly, the main parameters of the SHyGaN system that were necessary for the site design implementation are presented in Table 6: SHyGaN system design parameters applied for on-site designbelow. The SHyGaN system equipment layout is also presented in Figure 36: SHyGaN system equipment layout.

Table 6: SHyGaN system design parameters applied for on-site design

Parameter	Value
Dimensions	13m X 12m
Weight	<10 tonnes (each container)
Water Supply Connection	Was TBC until the project’s termination
LTHW Water Connections	28mm Compression fitting
Electrical Power Supply Connection	250A, 415V (HiAB container) 63A, 415V, 5 pin connector (HySTOR container) 25A, 415V (HiAB heaters)
Water Flow Rate	0.49 L/s
Max Heat Power Output	50 kW
Min Heat Power Output	0 kW
Water Flow Temperature	55 °C
Water Return Temperature	35 °C

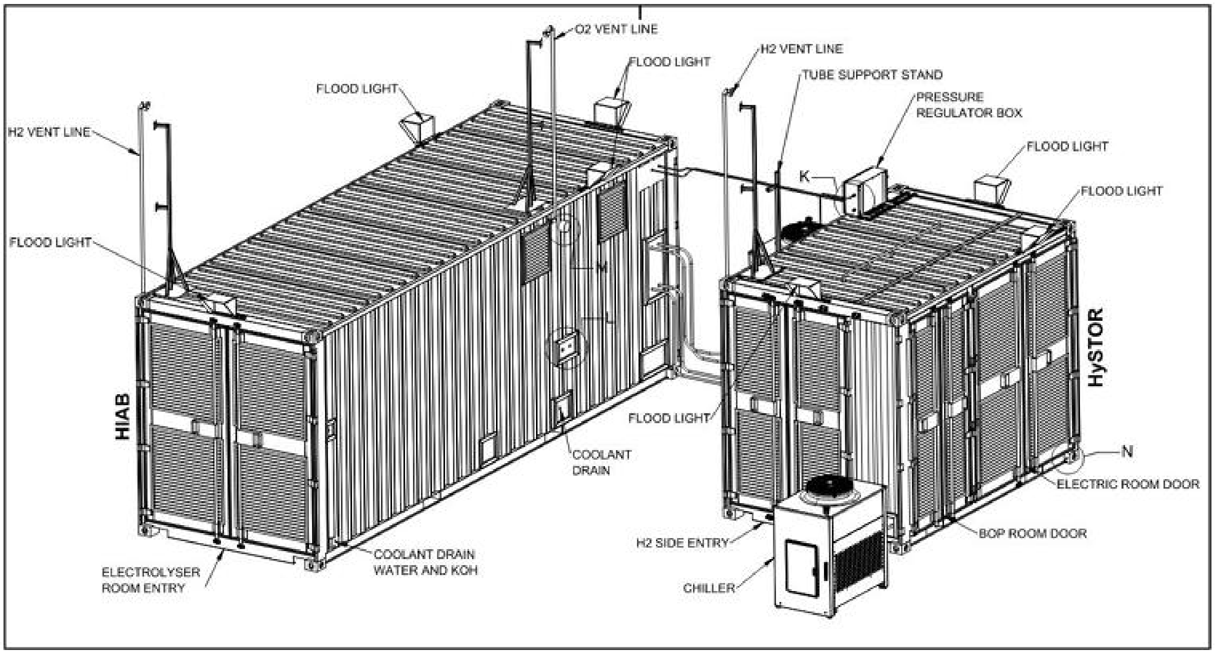


Figure 36: SHyGaN system equipment layout (GA)

For the site design work the following assumptions were made:

1. It was assumed that the HiAB unit would not heat the cold water return over 55 °C.
2. It was assumed that the HiAB unit would not indirectly heat gas over 40 °C and that it would have sufficient ability to monitor and control the outlet gas temperature.
3. It was assumed that all equipment on site downstream of the High Pressure – Medium Pressure heat exchanger could operate normally at gas temperatures up to 40 °C.
4. While the HIAB unit would be connected to the return water of the packaged boiler unit or the High Pressure – Medium Pressure heat exchanger water would be diverted into the HIAB unit, it was assumed that the packaged boiler unit's control could still correctly control the relevant gas temperatures from the signals that it is already receiving without being detrimentally affected by the connection of the HIAB unit.
5. It was assumed that the HIAB unit can operate correctly at the same water pressures and flow rate of the existing packaged boiler unit.
6. It was assumed that there would be periods of no flow through the High Pressure – Medium Pressure heat exchanger during the HIAB operation (i.e. min flow is 0).
7. It was assumed that the existing packaged boiler unit would heat the gas in the 42 barg heat exchangers to reach a minimum temperature of 0 °C at the High Pressure – High Pressure regulator stream outlet header.
8. It was assumed that no hot works would be allowed in the pressure reduction/preheating building and that there would be no gas outage to install equipment.
9. It was assumed that there would be a period of no heating for the 50kW heat exchanger during the year where water pipework could be swapped out.
10. It was assumed that control of valves and pumps would be under H2GO Power's control, via the NGN site's remote terminal unit.

11. It was assumed that there would be no cathodic protection on the existing above ground water pipework or the High Pressure – Medium Pressure heat exchanger and no new equipment would need to be isolated.

12.1.2 Site design layout

On commencement of the site design work five options were identified for tying the HiAB unit into the existing preheat system at the NGN site. All options aimed to reduce heat generation by the existing natural gas boilers, and for all options a pumping system was required to be installed on the return water pipe to the HiAB unit. The five options are presented below:

12.1.2.1 Option A

Option A would divert the cold water return from the High Pressure – Medium Pressure heat exchanger to the HiAB unit. The existing packaged boiler unit would vary its heat output to keep the flow water at required temperature. Option A is presented in Figure 37: Site Design Option A below. That option would require minimal works on the existing water pipework, which in turn would reduce any risks associated with works in hazardous areas. Time and material costs would also be reduced as no new heat exchanger would be required. A key design issue however, would be that the pressure and flow rate of the water would need to match that of the existing packaged boiler unit. The requirement for installing control would also need to be determined to ensure that the return water would not overheat and in turn heat the high pressure gas beyond specified limits, or prevent the existing packaged boiler unit from operating effectively. Moreover, reducing the generated heat from the HiAB unit would be required to mitigate this risk.

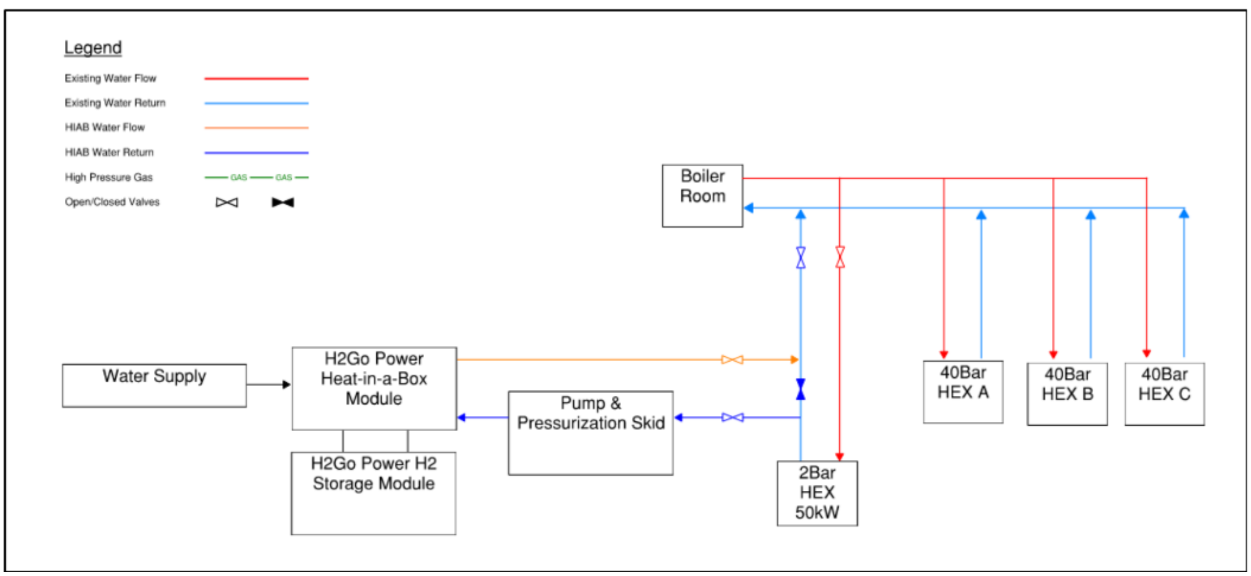


Figure 37: Site Design Option A

12.1.2.2 Option B

Option B would isolate the existing water pipes associated with the High Pressure – Medium Pressure heat exchanger into a separate flow and return circuit which would be connected to the HiAB unit. The HiAB unit would allow for controlling the amount of heat transferred to the gas at the outlet of the heat exchanger. Option B is presented in Figure 38: Site Design Option B below. This option has the advantage that it would allow the HiAB unit to demonstrate its ability to independently control the temperature levels of the gas, and would not have to rely on any existing control system from the packaged boiler unit. An additional advantage would be that the HiAB unit would have more control over the temperature range of the 17-2 barg heat exchanger water circuit than it would have for Option A, due to being isolated from the existing system. A key design issue although for this option, would be that the HiAB unit would potentially need to reduce its output during periods of low demand. An additional design issue would be that the water's pressure and velocity would have to match that was set by the packaged boiler unit. This would be in the case of the HiAB unit going offline, and the existing packaged boiler unit taking over, which in turn would need to have compatible pressure and flow rates.

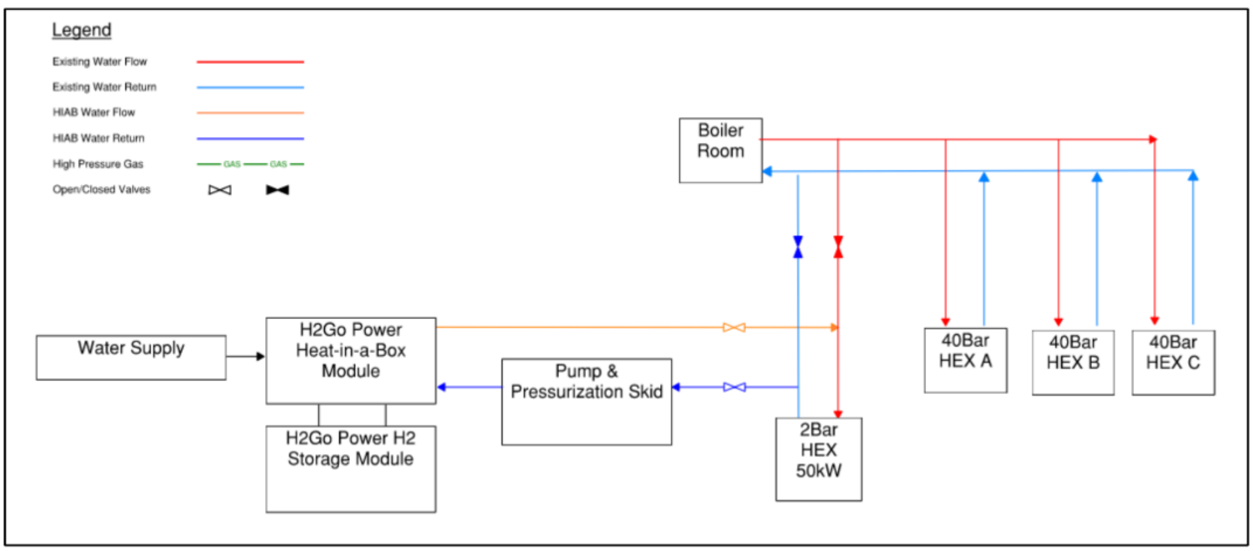


Figure 38: Site Design Option B

12.1.2.3 Option C

Option C was conceived as a combination of Options A and B. Additional valves would be installed within the configuration to allow switching between the systems whenever necessary. Option C is presented in Figure 39: Site Design Option C below. The main advantage of this option is that it would allow the HiAB unit to switch from one mode to the other depending on its operating capabilities. This option would also not add any significant construction risk or cost as only a short additional section of pipe and an additional valve would be required. Concerning potential design issues, these would be similar to the ones described for options A and B: i) the water circuits would need to have matching flow rates and pressures, ii) the water return temperature would need to be limited, iii) the gas temperature would need to be monitored to prevent any overheating, and iv) the HiAB unit would potentially need to reduce its heat output.

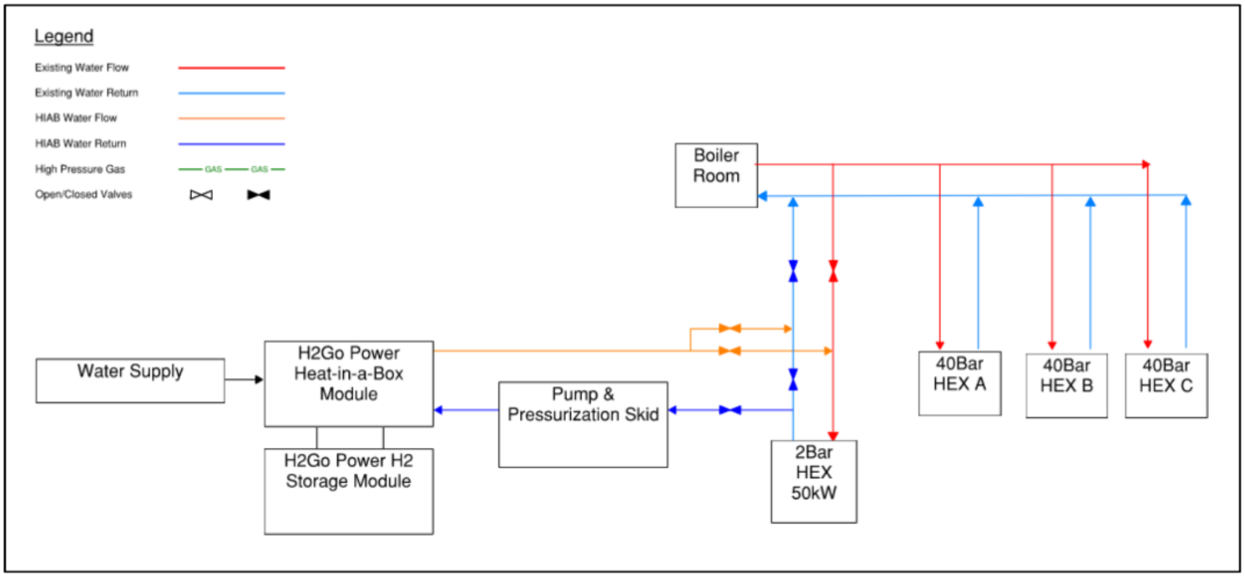


Figure 39: Site Design Option C

12.1.2.4 Option D

Option D would incorporate a new water/water heat exchanger to the existing return water pipe of the High Pressure – Medium Pressure heat exchanger. This option was similar to Option A but in this case the HiAB unit would support a water circuit independent to that of the existing packaged boiler unit. Option D is presented in Figure 40: Site Design Option D below. The advantage of this option over Option A, would be that the HiAB unit would now be able to control its own water pressure, flow rate, and water temperature (as long as the heat transfer would be controlled). Moreover, in the case of any fault in the HiAB system, or in the case of having to shut down the HiAB unit, it would not affect the existing packaged boiler unit setup. Similar to Option A, this option could utilise any excess heat to other heat exchangers during periods of low demand on the High Pressure – Medium Pressure system. However similar to option A, the HiAB unit would require a control system to prevent overheating the cold water return of the exiting circuit, that could cause the existing packaged boiler unit to run inefficiently, or to overheat the gas.

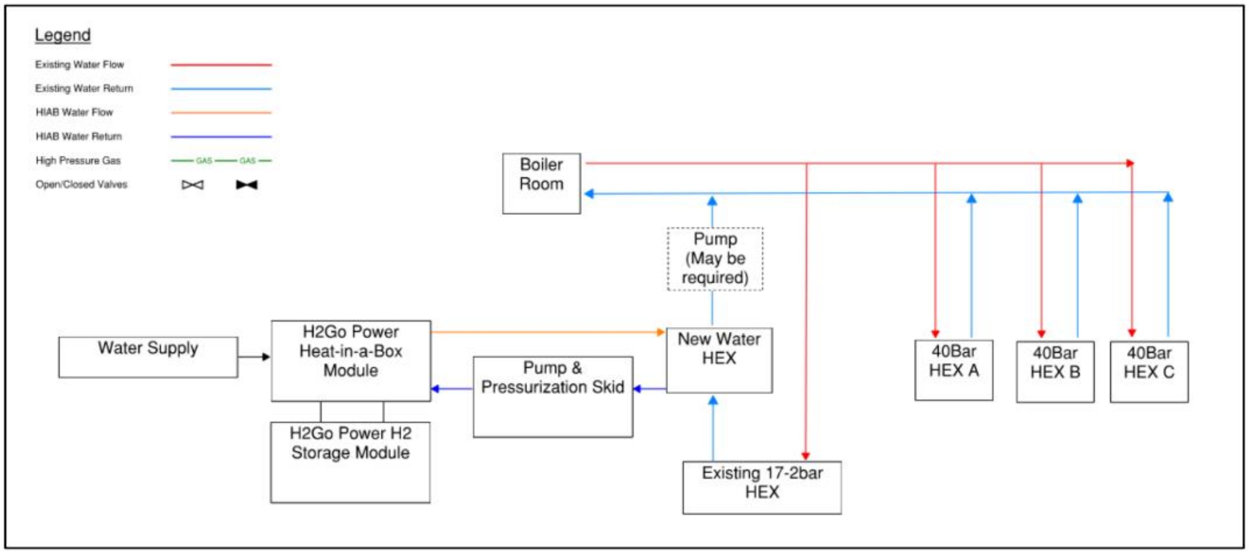


Figure 40: Site Design Option D

12.1.2.5 Option E

Option E would incorporate a new High Pressure – Medium Pressure heat exchanger which would be installed upstream to the existing High Pressure – Medium Pressure heat exchanger. This would enable the HiAB unit to preheat the gas before passing the existing heat exchanger. Option E is presented in Figure 41: Site Design Option E below. For this option the main advantage would be that the HiAB circuit would be independent of the existing packaged boiler unit and a new heat exchanger could be designed to match the heating requirements. This HiAB circuit would have complete control of its own water pressures, flow rates and temperatures, and would not have to consider the existing packaged boiler unit. The HiAB unit could also demonstrate its capability to fully control the gas temperature. The existing heat exchanger could also be turned on or off as required. Despite these advantages, this option would bring significantly higher costs, programme implications, and operational issues arising from the installation of the new heat exchanger and the modification of the existing live gas pipework. The HiAB unit would also have to reduce its heat output if required, to prevent the gas from becoming overheated during periods of low demand. Depending also on the setup, controls and operational set-points may need to be altered to allow the existing packaged boiler unit to operate correctly.

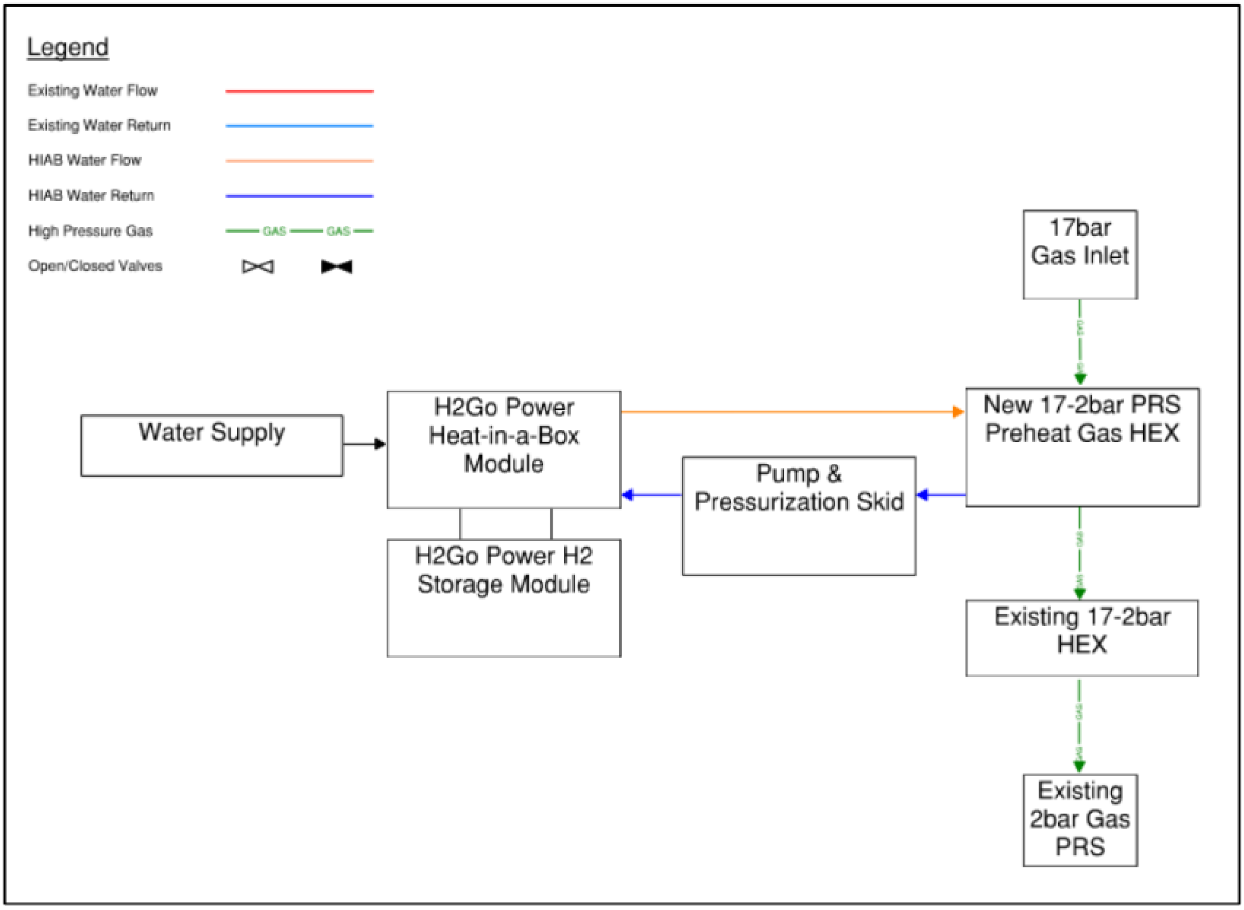


Figure 41: Site Design Option E

12.1.2.6 Selected option

Following the assessment of the options presented above it was decided to proceed with Option C. This option allowed for the SHyGaN system to demonstrate all its capabilities and applicability in a gas preheating setting, while not requiring high-risk and high-cost interventions to existing NGN assets. This option would also allow for higher flexibility by having two different configurations on which the system could be trialled. As SHyGaN was a demonstration project, proceeding with high-risk and high-cost interventions at the NGN site would not be efficient for the project's needs, while the flexibility achieved through Option C allowed for testing and examining better the system's operation. This design option chosen so that the new water circuit could either heat the return water of the existing boiler system or by isolating the High Pressure – Medium Pressure heat exchanger from the existing boiler for the HIAB unit to be solely responsible for the heat exchangers' heating.

Additional features of the associated pipework system included:

- A pressurisation line to be added to the flow of the existing and the return of the new pipes to allow the existing pumps to fill and pressurise the new system.
- A relief valve between the flow and return lines to allow the pressure of both lines to be equalised should existing valves shut while the pumps were still running.

- Two air vents located at a high level on the outdoor pipework were considered to allow air to bleed off .
- Two thermowells at the outlet and inlet of the HIAB unit would allow the return and flow line temperatures to be monitored at the NGN site's remote terminal unit.
- A pumping skid would need to be placed on the return water route to the HiAB unit. This would control any expansion/contraction of the water and set a circulation velocity for the water.

12.1.3 Pipework/equipment location

The onsite layout for the location of the SHyGaN system and NGN's existing preheating infrastructure can be seen in Figure 42: Site Layout. The SHyGaN system was considered to be installed on the southeast side of NGN's site outside the above ground installation. The pipework, and associated pump skid, would be routed along the fence line and across the access road towards the preheating and pressure reduction building. Approximately 220m of above ground pipework would be needed, between the SHyGaN system and the pressure reduction building. Above ground supports, wall brackets and hangars would also be used to support any pipework above the ground level. A suitably rated pipe protection ramp would be required to allow traffic to pass over the pipework.

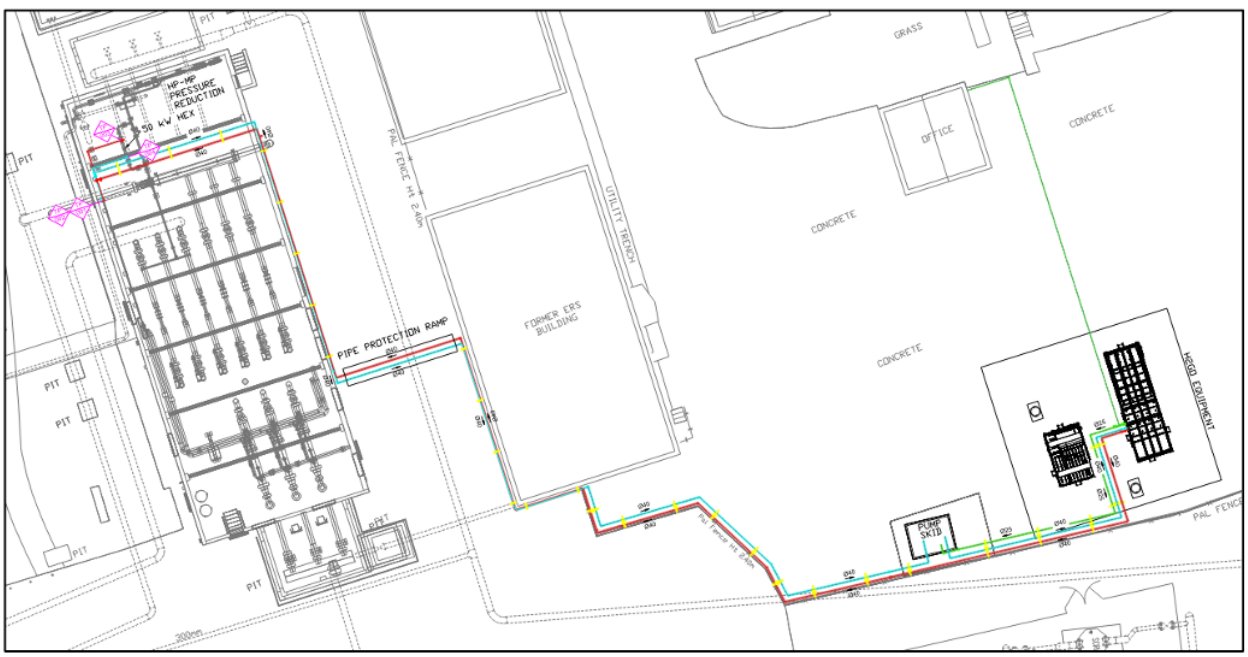


Figure 42: Site Layout

The pipework would be routed alongside the outside edge of the pressure reduction installation building and would penetrate through the wall near its northern side. It would then be routed along the ceiling of the building before connecting into the heat exchanger flow and return routes. The existing water pipework leading to the heat exchanger could be isolated with the valves near their tapping point from the main water pipes and could be disconnected from the flanges located near the wall further downstream. This whole section then would be isolated and replaced with a similar section which would then include tees to connect into the HIAB unit's water pipework and valves as required. Please refer to Figure 43: 3D view of connection to existing High Pressure - Medium Pressure Heat Exchanger (North view). and Figure 44: 3D view of connection to existing High Pressure - Medium Pressure Heat Exchanger (South view). for the 3D view of the associated pipework. Due to hazardous areas restrictions, no hot works would be permitted inside the building and for applying the connections as described, a temporary outage for the water pipework connections would be necessary.

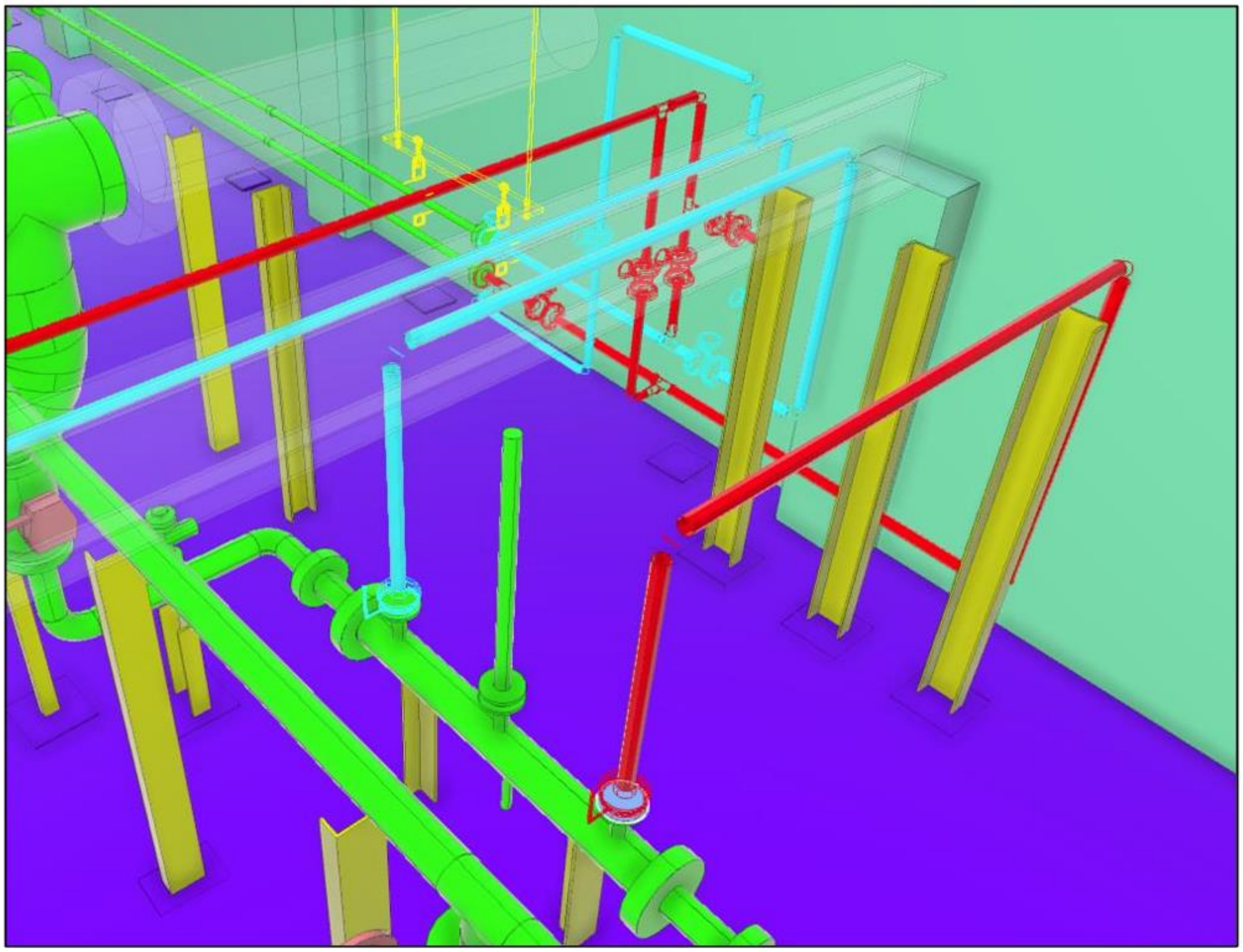


Figure 43: 3D view of connection to existing High Pressure - Medium Pressure Heat Exchanger (North view).

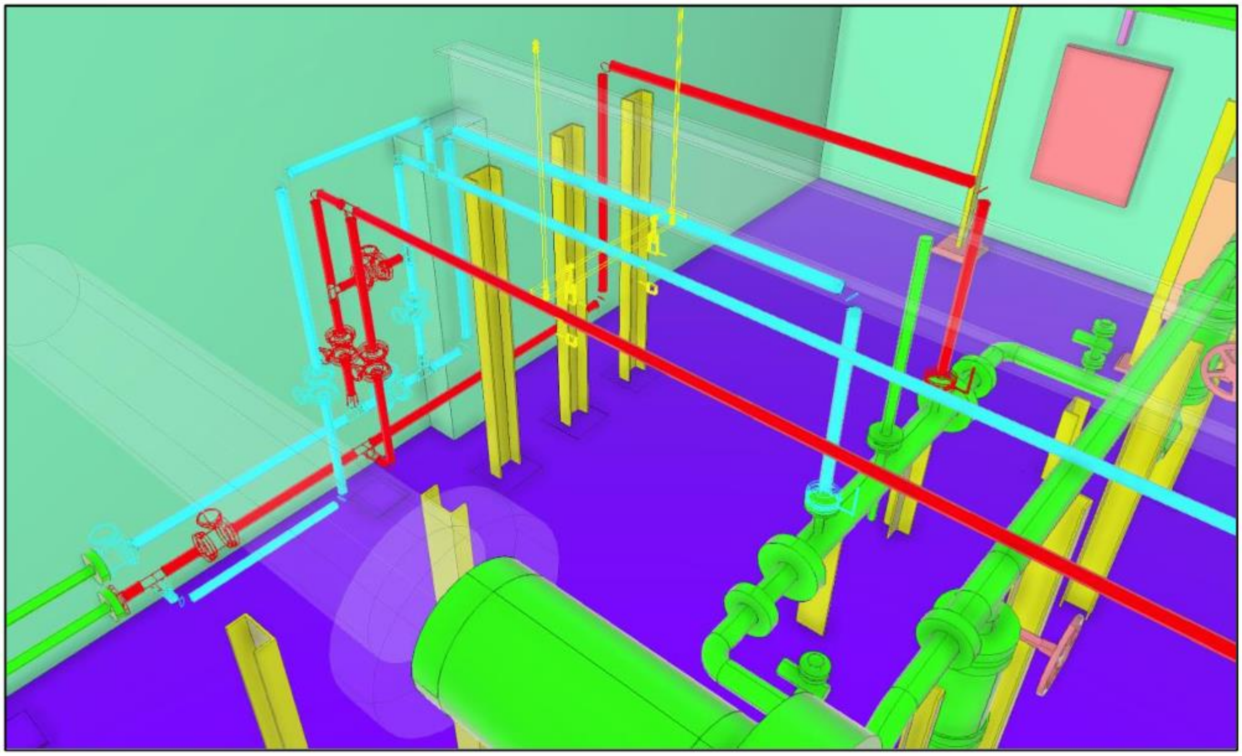


Figure 44: 3D view of connection to existing High Pressure - Medium Pressure Heat Exchanger (South view).

The transport fluid used for the pipes had to match the existing fluid used in the boiler system (70% water and 30% antifreeze) and would need be filled/pressurised using the existing system. As the majority of the pipework's route was to be aboveground and outside, and therefore medium series steel pipes as per the BS EN 10255 standard for tubes and pipes were proposed. The selected pipe diameters would be of 40 and 50 NB, and their wall thickness of 3.2. and 3.6 mm respectively. These pipes had been selected to ensure adequate flow velocities for the low temperature hot water as it was expected to flow from the SHyGaN system to the heat exchanger and to reduce pressure losses. In this sense, the water velocity was estimated at 0.4 m/s, equating to 0.53 kg/s, while the pressure loss was estimated at roughly 1 bar. Similarly, low temperature hot water pipework has been specified to have a max operating temperature of 60 °C and at a minimum of 0 °C. During operation, it was expected to have a flow and return temperature of 55 °C and 35 °C respectively, while it was assumed that the new boiler would not heat the gas to above 40 °C .

12.1.4 Hazardous area classification

SR/25 hazardous area zones exist on site and as the SHyGaN system was to store hydrogen, additional hydrogen hazardous area zones would also apply. A hazardous area plan drawing was created by the on-site designer, to show these new and existing hazardous area zones. These are presented in Figure 45: Hazardous Area Zones at NGN site for the SHyGaN project below.

Figure 45: Hazardous Area Zones at NGN site for the SHyGaN project

Similar with the approach taken in the SHyLO project, the internals of the SHyGaN system were zoned and calculated to define with confidence the hazardous areas around the system as shown in the figures below with the hatched areas indicating where a hazardous area is likely to occur.

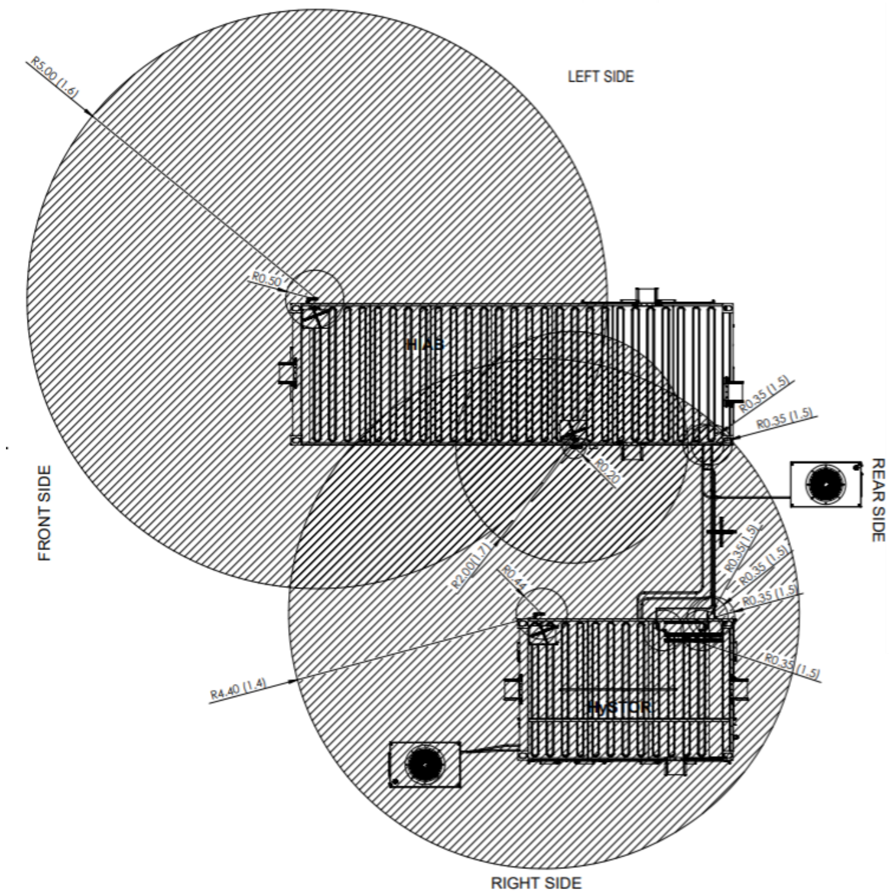


Figure 46: Hazardous area drawing extract for the SHyGaN system (top view)

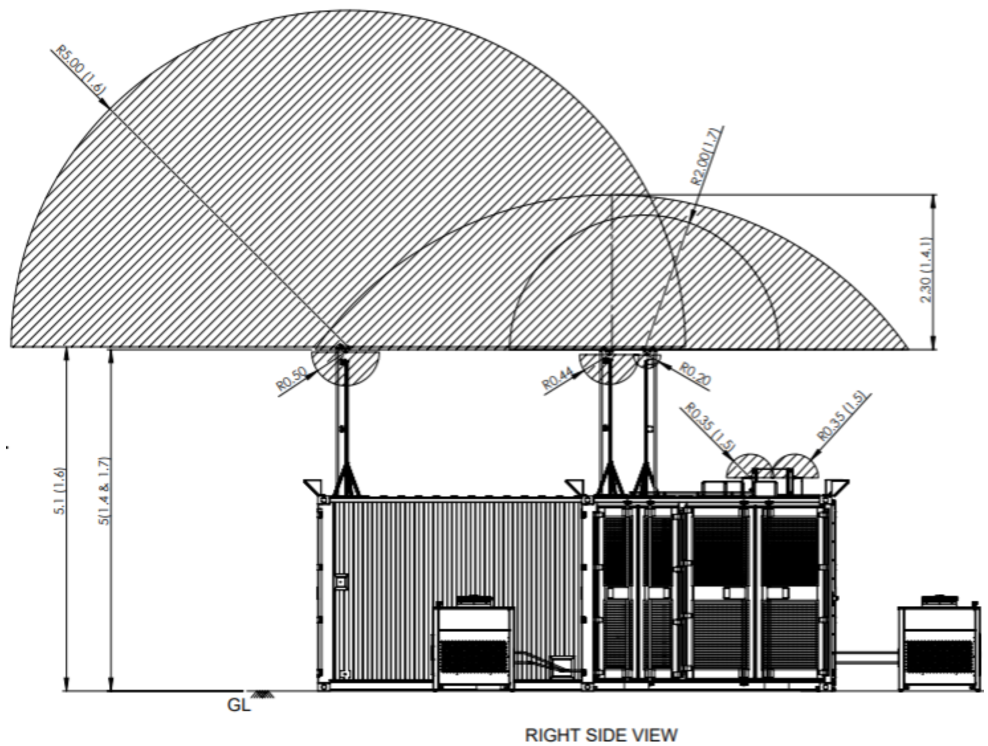


Figure 47: Hazardous area drawing extract for the SHyGaN system (right side view)

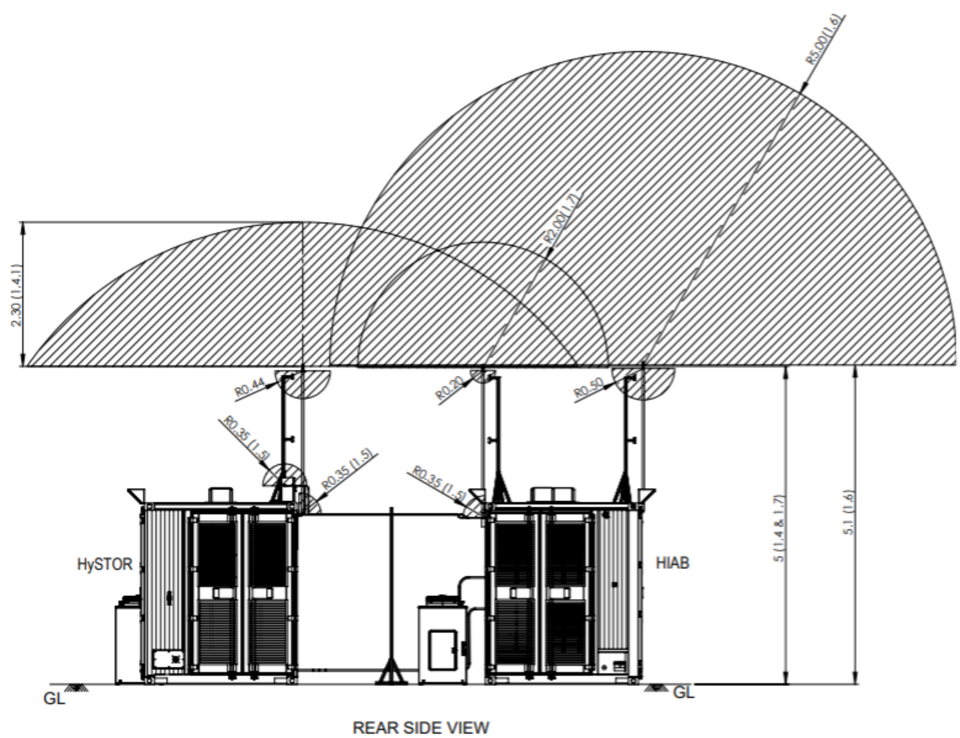


Figure 48: Hazardous area drawing extract for the SHyGaN system (rear side view)

12.1.5 Civils and structural design

The following civil elements were identified as part of the on-site design:

1. The design of a road crossing.
2. The design/specification of low-level pipe supports and racking and hangars.
3. The design of ground protection for the system's containers.

12.1.5.1 Road crossing

For the proposed route the pipe should have crossed an access road inside the installation. As the installation of the SHyGaN system was to be temporary at the NGN site, and not a permanent infrastructure work, the associated pipework should easily be removed. For the case of permanent infrastructure work, a buried road crossing would be much more suitable. Thus, for the case of SHyGaN a temporary ground level pipe ramp was proposed, so that no ground works and minimal design would be needed for the crossing.

12.1.5.2 Pipe supports, racking and hangars

Three types of supports were identified as needed for the installation of the SHyGaN system at the NGN site:

- A steel rack support with U-bolts to keep the pipework off the ground.
- A steel wall bracket support, to support the pipes as they run along the walls.
- A steel ceiling hangar to support the pipework at a high level inside the PRS building.

All the above supports were to be manufactured and installed on site. These supports would have a minimum 3.6m centre to centre separation.

12.1.5.3 Ground protection

The SHyGaN containers were to be placed on the existing concrete foundation at the NGN facilities. The thickness and type of concrete was assumed as being 200 mm thick and type 25 N/mm^2 (cylinder). The soil underneath, per omission, was assumed to have allowable bearing pressure of 75 kN/m^2. With an estimated weight of 10 metric tonnes for each container, the weight was divided into 4 support points measuring 100 x 100 mm and bearing a weight of 2.5 metric tonnes each. Each base plate was calculated to have dimensions of 500mm x 500mm x 20mm, and would be constructed of steel grade S275.

12.1.6 E&I design

E&I Elements which were defined as required within the scope of on-site design were:

- Electrical supplies to HiAB and HySTOR containers.
- Cabling from the electrical switchroom to the containers' location.
- Communications interface link between HiAB / HySTOR containers to the NGN boilerhouse control panel / remote terminal unit and communication link between electronically actuated isolation valves and remote terminal unit.

12.1.6.1 Electrical supply requirements

H2GO Power requested a load capacity of 180kW for the HiAB container, and 46kW for the HySTOR container, summing up to a combined load of 226kW. The isolating transformer for the above ground installation was rated at 60kVA so an alternative supply was required for the new equipment. A 350kVA MV/LV ground-mounted transformer was already supplying the whole NGN site, while there was approximately a 100kVA spare capacity remaining on this transformer. Separate from the SHyGaN project, there was an uprating of the incoming supply to a 2MVA transformer, to be located south of the battery storage unit. This increase in the capacity installation would be available prior to the unit's expected integration on site. The supply to both HiAB and HySTOR containers was to be provided from a new switchgear assembly that was located within the battery house. The installation of this switchgear was not complete the time that on-site design was taking place, and the relevant design information was to be confirmed. Lastly, the HiAB unit's heating supply was required to be backed up by standby power in the event of a mains fault. It was agreed with NGN to supply this circuit via the NGN Essential Services board.

12.1.6.2 Electrical supply cabling

The proposed route would require the cable ducting to run directly from the new battery building to the SHyGaN system. The proposed cable routing is shown in Figure 49: Proposed Electrical Supply Location and Routing.

Figure 49: Proposed Electrical Supply Location and Routing

Furthermore, three power supplies were requested by H2GO Power to be connected to the SHyGaN system:

- HiAB container Primary Enclosure.
- HiAB container Secondary Enclosure EEC3.
- HySTOR container.

The cable entries were to be located externally to the HiAB and HySTOR containers, while their enclosures were top cable entry only. The top entry requirement would require the cables to be installed on a cable tray and bridge system in order to enter the containers from above when leaving the ducting. The HiAB container would also require an external isolator to be installed at ground level on a stand. This would be installed adjacent to the cable tray bridge system, and the estimated height of the cable bridge system was estimated at 2.8 meters.

Calculations for the electrical supply through the use of Amtech software highlighted that a minimum of 2 ducts would be required for the installation. This is because the HiAB container's power cable was not scheduled to pass the tabulated current check when the power cables were grouped in a single duct. The HiAB container's main load was required to run in separate ducting. Both supplies for the HiAB container's heater supply and HySTOR container could be grouped together in one duct. The two proposed ducts could run in parallel with a minimum separation of 250 mm between the ducts. Lastly, the cables were sized as 240mm^2 for the HiAB container, 10mm^2 for the HiAB container's heater supply and 35 mm^2 for the HySTOR container. All cables were proposed as multicore, insulated, and steel armoured.

The electrical requirements for the system were as follows:

- HiAB - 250A, 415V AC (3ph) 50/60 Hz, 3p+PE+N.
- HySTOR - 63A, 415V AC (3ph) 50/60 Hz, 3p+PE+N.
- HiAB Heaters - 25A, 415V AC (3ph) 50/60 Hz, 3p+PE+N.

Circulating pumps were also to be installed external to the HiAB and HySTOR containers for hot water circulation. The supply location and cabling was to be determined subject to pump specifications. Each of the electronically actuated isolation valves would require a level of current ranging between 0.2A and 1.7A. Within the detailed design, a load estimate would be created to capture the load requirements of all equipment that was to be installed on site. Calculations highlighted that the UPS MCB had to be rated to a minimum of 15kA CPD for ultimate breaking capacity.

12.1.6.3 Communications interface link

The interface links between the HiAB boiler and the existing NGN boiler control panel, were to be linked within the existing NGN remote terminal unit on site via Modbus TCP. This link would be used for monitoring by NGN. Control for the HiAB container was expected to be implemented via SCADA. The boiler operation feedback signals could be relayed to NGN for indication, while additional signals were to be transmitted from site to the remote terminal unit to allow for a control flow and monitoring.

Regarding the electronically actuated isolation valves, these would be in operation on site due to the site being unmanned. A remote connection to the remote terminal unit would be required to allow access to the relevant controls. The remote terminal unit would be modified to fit the new control requirements as needed. These electronically actuated valves would have a monitoring system installed to allow H2GO Power and NGN to monitor which valves are open or closed. This monitoring would be used to ensure that the valves are in the correct position during operation.

Two pressure sensors would be installed on either side of the water flow for the pressurisation skid that was to be supplied for the water flow. These sensors would be used to communicate with the SHyGaN system and pumps to inform if the water passing through the system is adequate for the equipment to run. In addition, two temperature transmitters at the outlet and inlet of the HIAB container were identified as needed, to allow for the return and flow line temperatures to be monitored at the remote terminal unit. These would be used to communicate with the SHyGaN system to inform if the temperature of the water level is adequate to heat the system without the boiler.

12.1.7 Corrosion protection design

For mitigating corrosion effects, coating and insulation were considered. Thus, the above ground water pipework was to be internally coated and externally painted to the relevant NGN standards (NGN/SP/CM/1 and NGN/SP/PA/10 respectively). A thermal insulation to the water pipework in accordance with the NGN standard NGN/SP/PWC/2 was defined as needed for preventing heat loss to the environment over the 220m pipe run. This insulation would be 40mm thick preformed mineral wool/rock wool pipe insulation, foil faced and held in place by self-adhesive aluminium tape. All joints between sections would need also to be taped. These would be fitted with weatherproof cladding - polyisobutyl sheeting (PIB), solvent welded with 80mm overlaps between ends of adjacent sheets and 50mm longitudinal overlap on each sheet, arranged at the bottom of the pipe. For additional mechanical protection, in areas where site personnel were likely to come into contact with the insulation, Aluzinc sheeting would be needed with mandrel formed joints between adjacent sections.

12.1.8 Health and safety risk

Some of the main health and safety risks that were identified during the on-site design are presented in Table 7: Health and Safety Risks below

Table 7: Health and Safety Risks

Risk	Description
Valve Operation	If gas works are required leaking valves could cause a gas leak and explosion.
Overheating of Gas	If the new HiAB unit causes the gas to overheat it could cause damage to existing equipment on site resulting in a leak or a shut down.
Damage to existing packaged boiler unit	If the new HiAB unit operates incorrectly with the existing packaged boiler unit it could cause damage to the existing heating system or prevent it from operating which could cause gas on site to be too cold and possibly cause damage to equipment or require the gas supply to be shut off.
Pipework Corrosion	If new temporary pipework is incorrectly isolated from the existing, it could drain the existing cathodic protection and possible cause corrosion on the existing pipework. This could cause a reduced life or leak on the existing site.
Unforeseen utilities	An impact to a live unforeseen underground utility which could result in a gas leak.
HiAB Unit water pressure and temperature	If the HiAB unit operates at a different water pressure and flow rate and the responsibility of the gas heating is suddenly

	switched back to the existing packaged boiler unit there could be a sudden drop in water pressure creating an unacceptable load on the existing packaged boiler unit's pumps.

13.0 HySTOR system design implementation

13.1.1 Functional architecture

The HySTOR System integrated a number of hydrogen storage "Reactors", which are the core solid state storage technology developed by H2GO Power. The system controlled the hydrogen flow to (during charging) and from (during discharging) the reactors via temperature control of a coolant loop. The coolant was heated to discharge hydrogen from the storage and cooled to allow charging of the reactors with hydrogen. The sub-systems, described below, allowed the reaction to be controlled and ensure safe operation for the different operating modes. The sub-systems were implemented in the design as shown in Figure 50: HySTOR Container Subsystem Architecture.

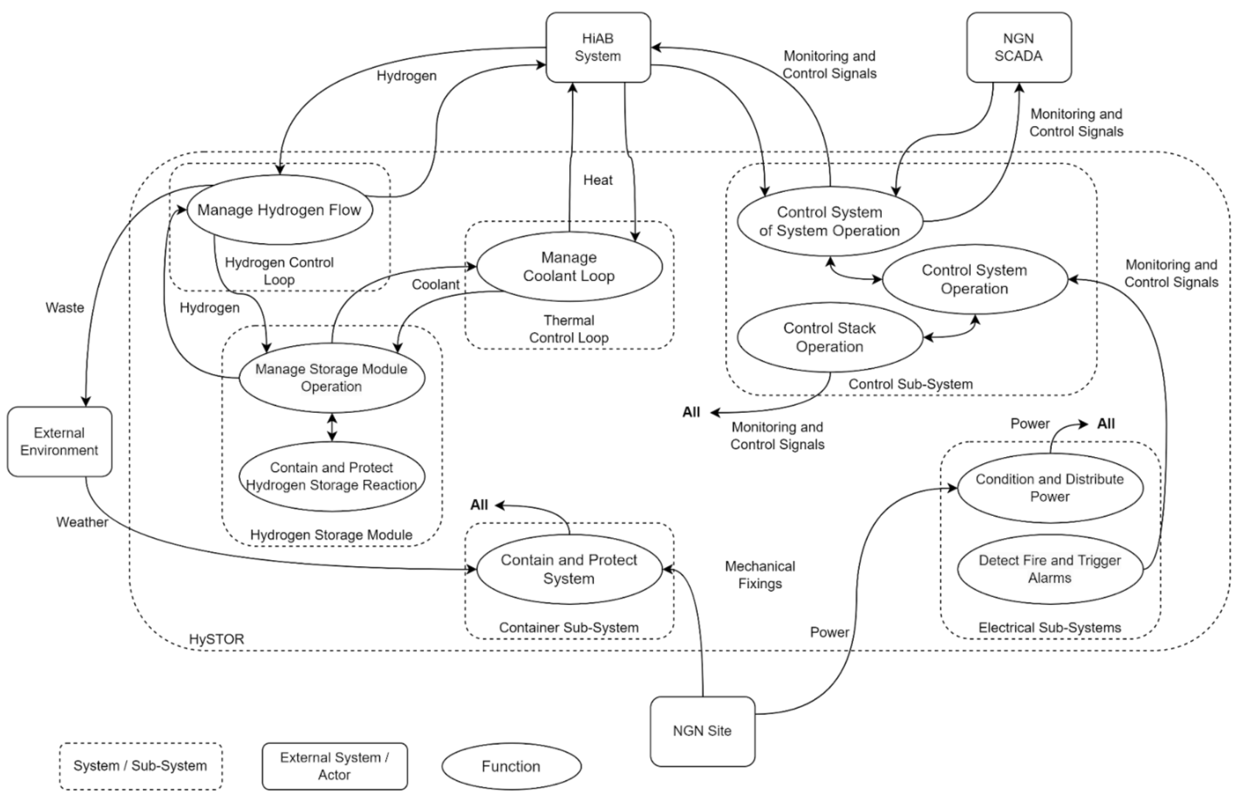


Figure 50: HySTOR Container Subsystem Architecture

13.1.2 Physical layout

As discussed previously, the system was containerised into a single transportable assembly. When deployed on site, the container was to be supplemented with an external liquid coolant chiller.. In addition previous Figure 36: SHyGaN system equipment layout (GA) identifies the GA for the HySTOR and HIAB systems.

The three partitions or "rooms" within the container, as shown, were the Electrical Room, Balance of Plant Room and Hydrogen Room. The HySTOR sub-systems discussed in this document were distributed across the three rooms as detailed in Table 8. Breakdown of HySTOR subsystems and locations. As detailed in the main body of this report the layout of the system is similar to that on the SHyLO development. However work on the SHyGaN project allowed product improvements to be made and optimisation of layouts to be developed.

Table 8. Breakdown of HySTOR subsystems and locations

Sub-System	Physical Component Location(s)
Hydrogen Storage Modules	Hydrogen Room
Thermal Control Loop	Hydrogen Room and Balance of Plant Room
Hydrogen Control Loop	Hydrogen Room
Electrical Sub-Systems (Power Management, Fire Detection)	Electrical Room with cabling to the Hydrogen Room and Balance of Plant Room
Control Sub-System	Electrical Room and Balance of Plant Room with cabling to the Boiler Room

13.1.3 HySTOR thermal control loop

As the HySTOR container for the SHyGaN project applied lessons learnt from the design of the hydrogen storage container from the SHyLO container, effort was put on improving further the design of the hydrogen storage container in terms of cost reduction, ease of assembly, and safety. This rationale was followed as well during the design of the HySTOR container's thermal control loop (TCL), by improving the design of the TCL from the SHyLO project. This task was undertaken by the MTC.

Key features of the redesigned TCL included an improved ease of access with a simplified pipe network design, the use of alternative standard parts that were widely available off-the-shelf, and the substitution of materials such as copper instead of stainless steel in order to reduce costs, improve supply chain reliance, and reduce manufacturing complexity. Additionally, a bracket redesign was undertaken to further enhance the system. A more panelised approach was implemented throughout, allowing for easier assembly and integration of system components, including eliminating manufacturing tolerance issues and re-work. A worker platform was also designed to protect pipework and facilitate ease of access.

13.1.4 HySTOR manifold design

Complementary to the work performed for the HySTOR container's TCL, MTC undertook work on the reactor manifold in order to further the MTC design concepts that were generated from the SHyLO project, to a detailed design that could be taken to manufacture. In the work performed within SHyGaN, the objective was to perform a down-selection of concepts that could fulfil the SHyGaN system's requirements, and carry through these new concepts to a detail design stage. Towards this end, several concepts were taken forward and refined to come up with a solution to progress into a detailed design. A flexible and compliant material was chosen after measurements showed that the pipe stub positions were varying considerably, implying a requirement for the manifold to accommodate this variation from reactor to reactor. The chosen solution was reviewed and considered to meet all the original requirements, with additional considerations to improve how air would be purged from the system.

Following the selection of the concept, simulations were undertaken to model the effect of mass flow balance to the feed manifold and the drain manifold. Furthermore, the pressure distribution to respective outlets and inlet ports has been reviewed as part of these simulations. The simulations showed that pressure drops for the outlet ports of the feed manifold were minimal (0.03% with respect to feed pressure of ~6 bar) and the same applied to the inlets of the drain manifold. Moreover, no design modifications were required at this and the existing design was deemed as sufficient for all of the system's operation modes (see Section 10.3). It was found that the new manifold designs would generate less than 1.5% mass flow deviation (nominally) respectively for their outlet and inlet ports: for both 20°C and 45°C temperatures. However diametric tolerances could influence this. The level of tolerance impact to the flow rate was assessed, has been evaluated for a single branch of the feed manifold and results showed flow would remain within the +/- 5% tolerance, that was set as the maximum accepted deviation. For further validation, a supplier was contacted to confirm that the resulting geometry of the manifold could be manufactured, on which a positive response was given.

13.1.5 HySTOR stack frame

As the original stack frame that was developed within the SHyLO project presented some challenges and potential failure points which resulted in additional work to reinforce the overall structure, for the SHyGaN project it was decided to review the stack frame's design and improve it further. The aim was to make the system easier to install, envisioning either a modular system or a system that can be inserted fully loaded with reactors. This piece of work was undertaken by the MTC supporting H2GO Power to conclude with the most suitable stack frame for the system and was composed of the following activities: i) Review of applicable standards in order to address any non-conformance where possible and the creation of a DFMEA, ii) Assessing if changing the stack frame's material from stainless steel (in SHyLO project) to mild steel with a coating for achieving reduced costs, iii) Reviewing issues experienced in the SHyLO project and by consulting the MTC welding team to minimise distortion/residual stress and reduce cost if possible, iv) Review suppliers and select the best cost/quality, v) Improve the interface with container, and in particular the floor.

The conducted work resulted in four concepts (three new concepts, and the concept applied in the SHyLO project for benchmarking) which were further assessed against: health and safety implications, scalability, capability of removing reactors, reactor storage density, cost, and mass. The three new concepts corresponded to i) an improved design of the SHyLO stack frame, ii) a modular approach for packing three reactors at once, and iii) a concept where reactors could be removed from the stack through a carriage. An overview of the four concepts is presented in Figure 51: Developed concepts for HySTOR container stack frame. The conducted assessment taking into account that the project's intention was to build a prototype resulted in concept B as it was assessed as the most effective choice. Specifically, concept B had minimal health and safety considerations, increased ease in removing reactors, and lower mass against the other two, while the associated costs were also lower for concept B. However, concept B was less favourable against the other two in terms of scalability and reactor storage density which clearly showed that this stack frame concept was suitable for a prototype but certainly not for a commercial version of the product.

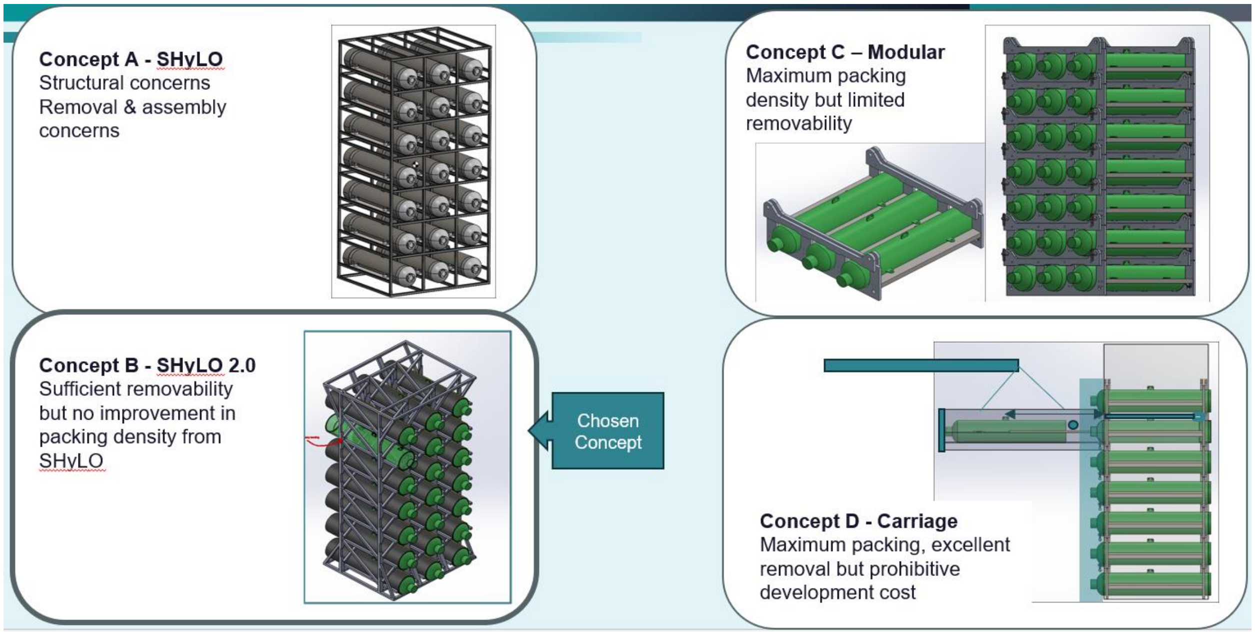


Figure 51: Developed concepts for HySTOR container stack frame

14.0 HiAB system design implementation

The HiAB System integrated a number of modular electrolysers, to generate hydrogen from the electrical supply, and a hydrogen boiler to generate heat from hydrogen. The system controlled the hydrogen flow between the system components and external storage, depending on the user demand. The sub-systems, described below, allowed the hydrogen generation and heating to be controlled and ensured safe operation for the different operating modes.

14.1.1 Functional architecture

The three primary functions of the HiAB System described in a previous section ("Generate Hydrogen from Site Solar Supply", "Heat Water using Hydrogen and Supply to Site Heat-Exchanger" and "Manage Hydrogen Flows Between Generation, Storage and Boiler"), were delivered by eight HiAB sub-systems. The sub-systems are implemented in the design as shown in Figure 52: HiAB Container Subsystem Architecture.

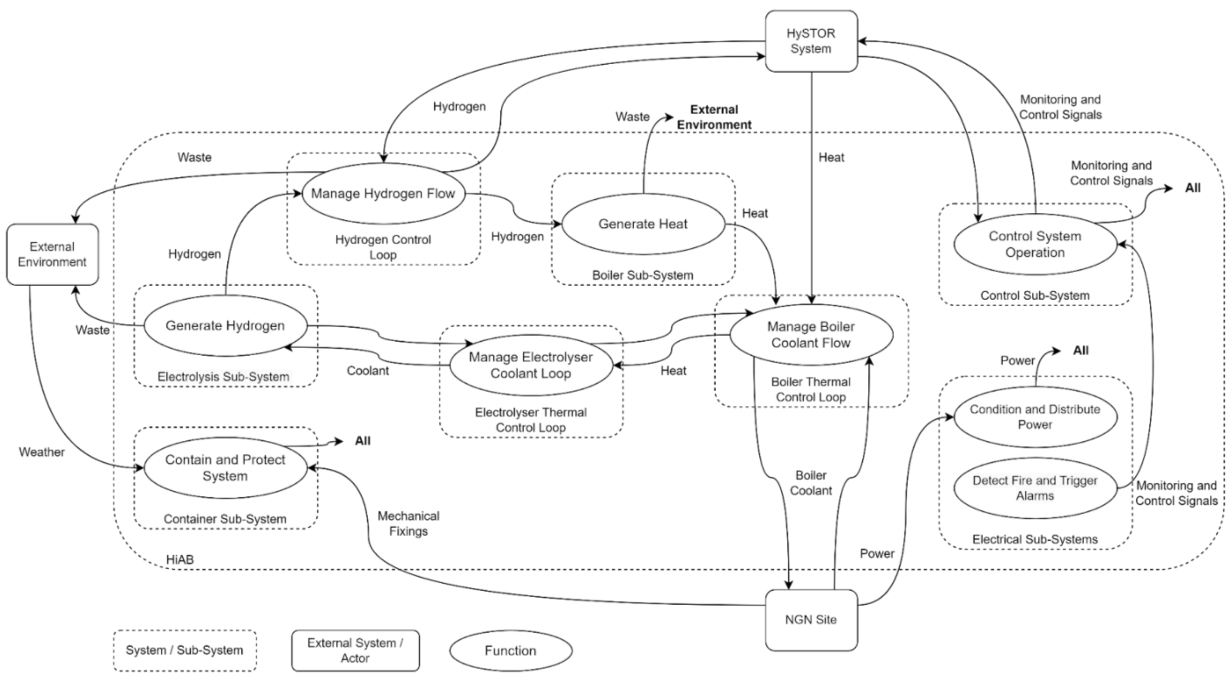


Figure 52: HiAB Container Subsystem Architecture

A summary of the general operating principles of the HiAB container are provided below:

Potable water (tap water) was to be supplied at domestic pressure to the HiAB container from the NGN site. This water was required to be purified to the grade required for electrolysis in the balance of plant room before being distributed to dedicated electrolyser water tanks in the electrolysis room. These tanks would pump the purified water to the connected AEM electrolysers, which would create oxygen gas and "wet" hydrogen at ~99% purity. As the electrical supply to the container would be either from on-site renewable solar or mains supply, this hydrogen could be classed as "green" depending on the electrical supply source. The unwanted oxygen produced by the electrolysis process would be removed from the container via a vent system, and vented to the atmosphere. The wet hydrogen was to be sent to hydrogen driers, which were to reduce the water content further, before discharging it at ~99.99% purity (high purity hydrogen would be necessary for avoiding any downstream damage to the hydrogen storage reactors). Thereafter the "dry" hydrogen would be either:

1. Sent to the HySTOR unit for storage.
2. Sent directly to the hydrogen boiler in the balance of plant room, and combusted.
3. Received from the HySTOR unit, sent to the boiler in the balance of plant room, and combusted.

The boiler was to be supplied with coolant in the form of a water and an ethylene glycol mixture, as part of the HiAB TCL. In order to increase the efficiency of the boiler heating process, the HiAB TCL would pre-heat the coolant entering the boiler by:

1. Recovering heat rejected from the HySTOR TCL, via a heat exchanger.
2. Recovering heat rejected by the liquid-cooled electrolysers, via a heat exchanger.

The hot coolant from the boiler would manifold into an on-site distribution network which would deliver it to the NGN natural gas heat exchanger. This network was designed as a closed loop, so that the cooled fluid from the NGN heat exchanger would be returned to HiAB unit to then be re-heated. Several waste streams were expected to be created during this process, including:

1. Water rejected by the water purification system.
2. Water removed from the oxygen and hydrogen systems (containing trace amounts of KOH electrolyte).
3. Oxygen – vented to atmosphere.
4. Hydrogen – vented to atmosphere when directed to by H2GO Power's safety control systems.
5. Boiler flue gases – vented to atmosphere.

The water / water + KOH wastes were designed to be routed out of the container via drainage points and would subsequently be managed by NGN. Under normal operating conditions, both HiAB and HySTOR units would be controlled remotely by H2GO Power's control software systems, with no personnel permitted inside either container.

14.1.2 Physical layout

As discussed previously, the system was containerised into a single transportable assembly. When deployed on site, the container would have been supplemented with an external liquid coolant chiller. Figure 53: HiAB Container Plan View shows a plan view of the container, highlighting the partitioning of the container and the external interfaces. In addition, previous Figure 36: SHyGaN system equipment layout (GA) identifies the GA for the HySTOR and HiAB systems.

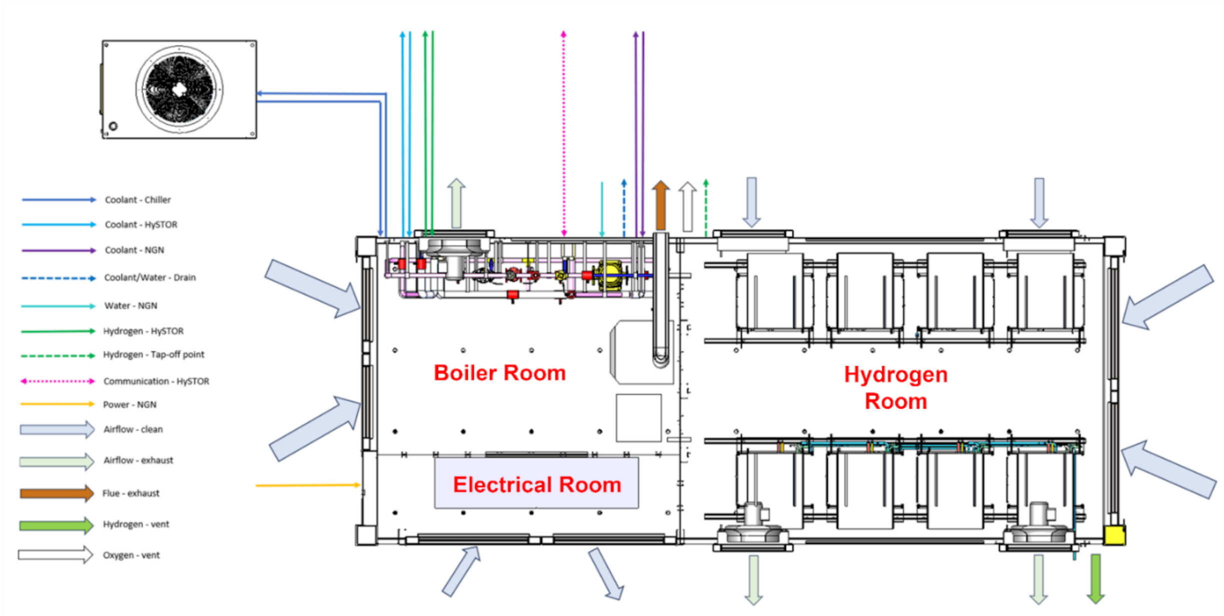


Figure 53: HiAB Container Plan View

The three partitions or "rooms" within the container, as shown, were the Electrical Room, Boiler Room and Hydrogen Room. The HiAB sub-systems discussed in this document are distributed across the three rooms as shown in Table 9.

Table 9. Breakdown of HiAB subsystems and locations

Sub-System	Physical Component Location(s)
Electrolysis Sub-System	Hydrogen Room
Boiler Sub-System	Boiler Room
Electrolyser Thermal Control Loop	Hydrogen Room and Boiler Room
Boiler Thermal Control Loop	Boiler Room
Hydrogen Control Loop	Hydrogen Room and Boiler Room
Electrical Sub-Systems (Power Management, Fire Detection)	Electrical Room with cabling to the Hydrogen Room and Boiler Room
Control Sub-System	Electrical Room with cabling to the Hydrogen Room and Boiler Room

The hydrogen room was designed to be ATEX Zone 2NE compliant and contained all Enapter electrolysis systems and the high pressure (35 bar) hydrogen pipework. This area had a dedicated ventilation philosophy. In support of this, the area contained a single wall-mounted air extraction fan, and double-banked louvre entry doors. Compliance with a firm requirement to protect the electrolysis systems from ambient air temperatures below 5°C necessitated the inclusion of 2x 6kW fan heaters to maintain the acceptable minimum temperature. Later in the project, a requirement to fully insulate the internal walls and ceiling throughout the container to reduce heat loss was also added. This led to a readjustment of the position of all wall-mounted equipment in order to account for the internal cladding sheet outboard of the insulation layout. As the electrolysis systems would produce high-purity hydrogen and oxygen which necessitated regular venting as part of the safety and operational requirements for the system, two external roof-mounted ventilation stacks were also specified. Enapter systems were installed into Hoffman off-the-shelf heavy duty server racks which were hard mounted to the container floor and walls. Baxi also specified a minimum ambient temperature requirement of 0°C to protect the prototype boiler, necessitating an additional 6kW fan heater in the area.

The boiler room contained the hydrogen boiler/flue, water purification systems, thermal control loop, and lower pressure hydrogen pipework (~25 mbar). This room also had a dedicated ventilation philosophy and similarly contained a single wall-mounted air extraction fan, and double-banked louvre entry doors. The size and position of the flue system was developed with Baxi engineering teams to ensure acceptable flow rate and condensate management would be achieved in operation. The addition of heating systems to the container led to a requirement to locate an additional electrical cabinet in this area to house the control equipment for these.

Lastly, the electrical room housed the cabinet containing the primary electrical and networking control equipment. The design of these systems was the responsibility of H2GO Power. Entry to this area was via double-banked louvre doors.

The design of the HiAB container was undertaken jointly by H2GO Power and the MTC. The MTC was responsible for the layout and interconnection of the componentry within the following top-level areas: i) Electrolysis systems, ii) Water purification and distribution, iii) Heating systems, iv) Ventilation systems (for general air exchange as well as H2/O2 venting), v) Hydrogen boiler and flue, vi) Thermal control loop (TCL), vii) ISO High-cube shipping container.

The specification of the componentry within these areas was the responsibility of H2GO Power and was communicated via a Bill of Materials document, which was kept “live” for the duration of the project, with a number of key components “frozen”. For example, H2GO Power determined the specification and quantity of the electrolyser units, and MTC ensured that they were positioned and connected to adjacent systems in a manner which was compliant with both H2GO Power’s P&ID and the safety and functional requirements set by the electrolyser manufacturer. This was one area of considerable iterative design work as electrolyser manufacturer engagement necessitated numerous changes to the P&ID to account for requirements that were not previously considered, with MTC subsequently needing to react to these. On the HiAB design, H2GO Power was responsible for the layout of networking/data, electrical and safety equipment (hydrogen detection, lighting etc.) In Figure 54: HiAB container internal layout (Top - side view, Bottom - top view), the HiAB container’s internal layout is being presented.

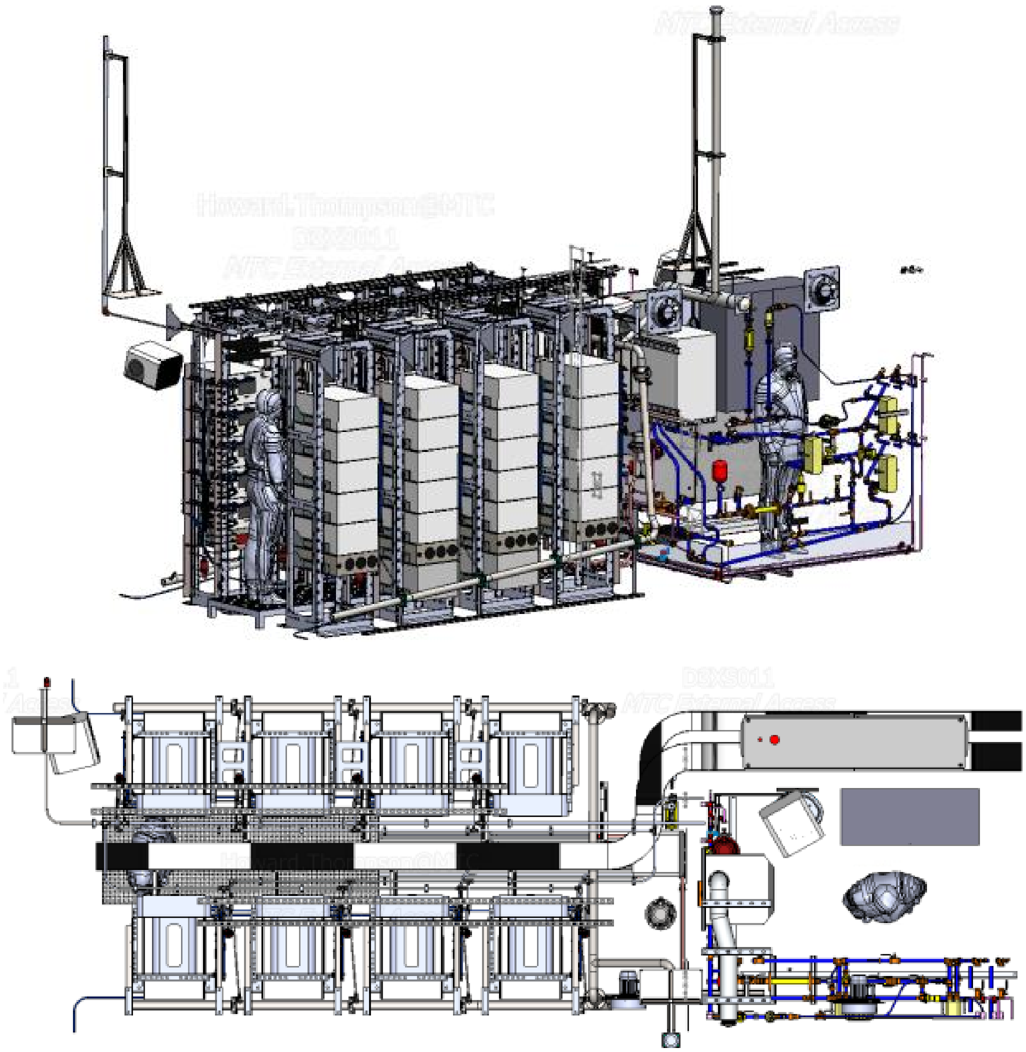


Figure 54: HiAB container internal layout (Top - side view, Bottom - top view)

14.1.3 HiAB thermal control loop

Since the HiAB container was to encompass both hydrogen production and combustion, it was also a novel element introduced into the SHyGaN project. HySTOR, also being a novel element but benefited from the former experience from the SHyLO project which was integral for its design improvements assessing cost reductions, achieving ease of assembly, and ensuring operational safety, while also applying a mounting methodology. As with the HySTOR container's TCL, the design of the HiAB container's TCL was undertaken by the MTC. The layout of the resulting TCL for the HiAB container is being presented in Figure 55: HiAB Container TCL layout.

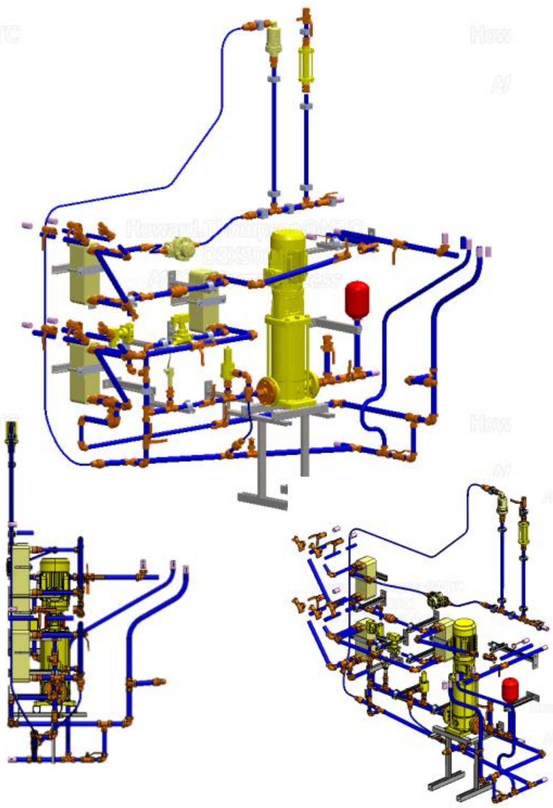


Figure 55: HiAB Container TCL layout

14.1.4 Electrolysis system integration

A significant piece of work delivered by MTC for the HiAB unit design, was the integration of the electrolysis systems in accordance with the system's P&ID and the requirements set by the electrolyser manufacturer. Hydrogen and oxygen gas piping was specified as 316 seamless stainless steel, of varying diameters according to the system's P&ID. Gas fittings were specified as Schwer Stainless Steel Twin-Ferrule "U2" compression type, rated for hydrogen usage at the system pressures expected. Water and coolant piping was specified as POM tubing, of varying diameters according to the system's P&ID. Water/coolant fittings used in the MTC CAD model were Parker Legris LIQUI-fit, however the electrolyser manufacturer confirmed that more readily-available John Guest fittings would be an acceptable alternative for the system's build. The large number of electrolysers required in the HiAB resulted in a highly complex network of gas and coolant pipework to be developed which balanced functional requirements (such as inclined piping to manage water condensate), ease of assembly, reduction of part count, and ease of disconnection for maintenance of the electrolysers - as their maintenance would require convenient access to the various frontal fluid fill / drain ports. Extensive reviews were held between MTC, H2GO and the electrolyser manufacturer to ensure that the designed layout met or exceeded the manufacturer's requirements and guidelines. The connections that were designed for the system's electrolysers are being shown in Figure 56: Electrolyser connections.

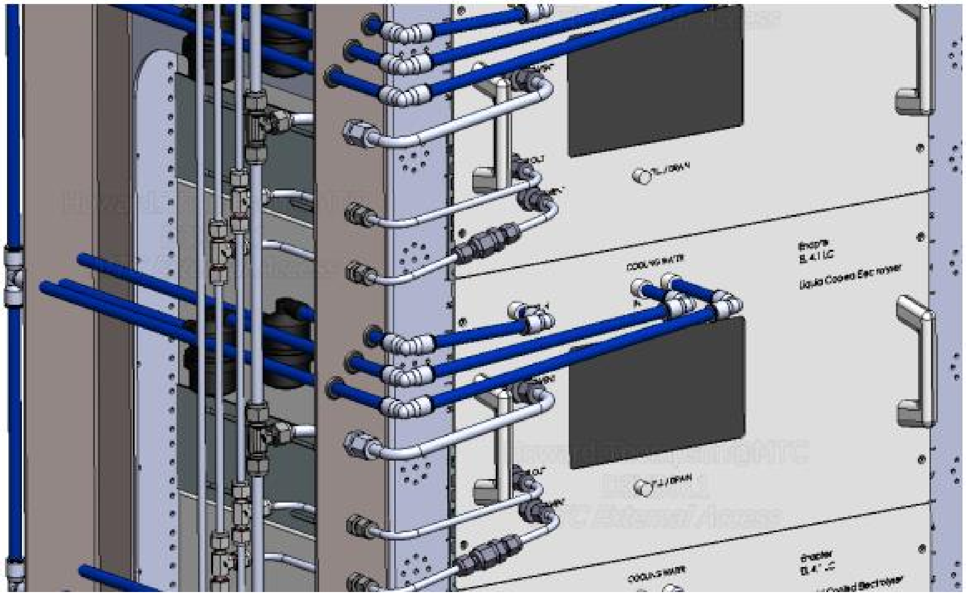


Figure 56: Electrolyser connections

A number of hydrogen line water traps were also required – however at the time that the project was terminated, these had not been specified in detail, and as such, were provisionally packaged as representative envelopes. In order to support the gas and liquid pipework on the Hoffman racks, custom L-brackets formed of laser cut steel were specified in the design, with push-fit rubber grommets to suit plastic piping, and apertures for Schwer bulkhead connectors for steel piping. Depending on the bracket supplier chosen, these could either be a single bracket the full length of the M9616B51 rack, or 2 half-length brackets. The total number of parts needed would either be 8 or 16, accordingly. An example of such a bracket in the design is shown in Figure 57: Custom bracket for COTS racking.

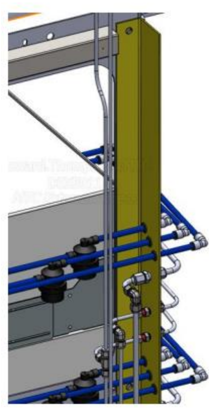


Figure 57: Custom bracket for COTS racking

The system's electrolysers were arranged on design into 8 banks – 4 banks containing 5 electrolysers and 1 dryer each, and 4 banks containing 5 electrolysers, 1 dryer and 1 water tank each. These banks were arranged in 2 opposed rows, as shown in Figure 58: Electrolyser racking integration. The racks were designed to be directly bolted to the 6mm

Durbar steel container floor via RivNuts, and then secured to wall-mounted Unistrut via P1000 Unistrut connecting into the COTS wing bracket P2348-S1.

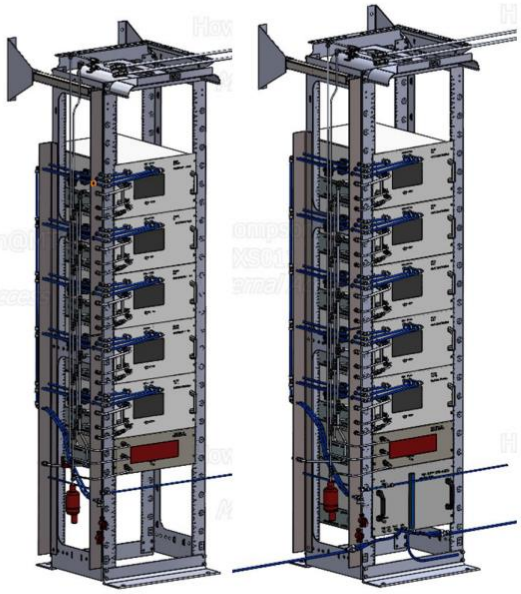


Figure 58: Electrolyser racking integration

14.1.5 Pipework

Hydrogen and oxygen outlet/vent pipework was integrated at ceiling level using Unistrut bracketry and permitting appropriate access to maintenance valves (nominally locked open outside of maintenance periods). An image from the ceiling level gas pipework is shown in Figure 59: HiAB container ceiling level gas pipework. On the other hand, electrolyser coolant and water supply pipework was integrated at floor level, specification of COTS low level grating was in progress at the close of the project to form a suitable access walkway above these. An image from the low level pipework is shown in Figure 60: HiAB container low level pipework.

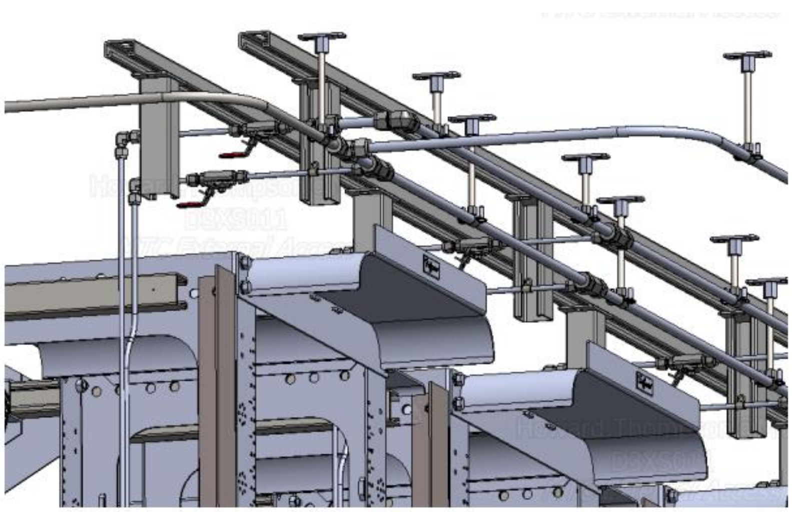


Figure 59: HiAB container ceiling level gas pipework

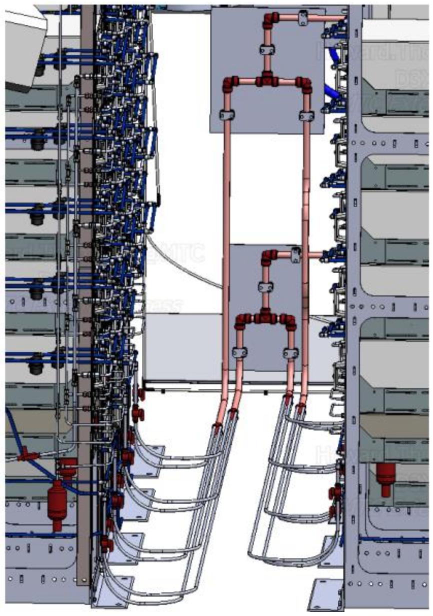


Figure 60: HiAB container low level pipework

14.1.6 Boiler system integration

H2GO and MTC worked with Baxi to ensure an appropriate flue system was specified, routed and supported. An appropriate boiler mounting approach for the container walls was also developed and approved with Baxi. The approach taken for the boiler mounting is reflected in Figure 61: HiAB container boiler mounting. In addition, a large expansion system for safe ventilation of oxygen gas was designed by MTC in order to ensure that entrained moisture in the gas stream could be removed and drained. Back pressure calculations were performed to ensure the pipe diameters were suitable. The considered venting system for the HiAB container's design is shown in Figure 62: HiAB container venting system.

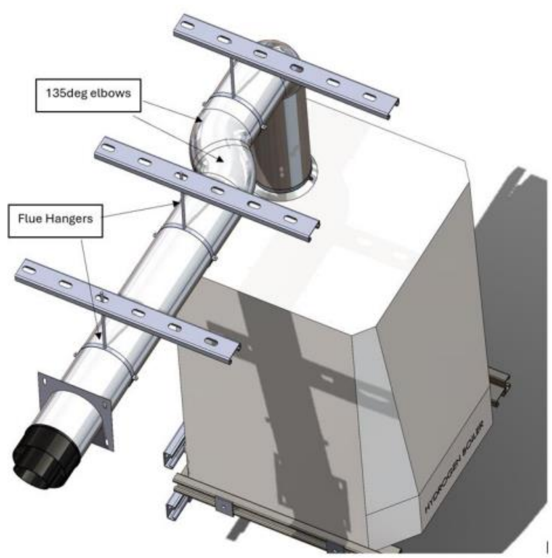


Figure 61: HiAB container boiler mounting

Figure 62: HiAB container venting system

15.0 Electrical and electronic sub-assemblies

As discussed in the control architecture section above, each system is primarily controlled via a commercial PLC. However, for lower-level control and monitoring, three PCBs were designed to cascade the control and monitoring through the modular sections of the system. A “cross-controller” embedded controller board (Figure 63: Embedded Control Board was developed and manufactured to allow ProfiNet interface to the PLC, direct monitoring and control of intermediate levels of the system and single wire interfaces down to the “module” level monitoring and control PCBs.

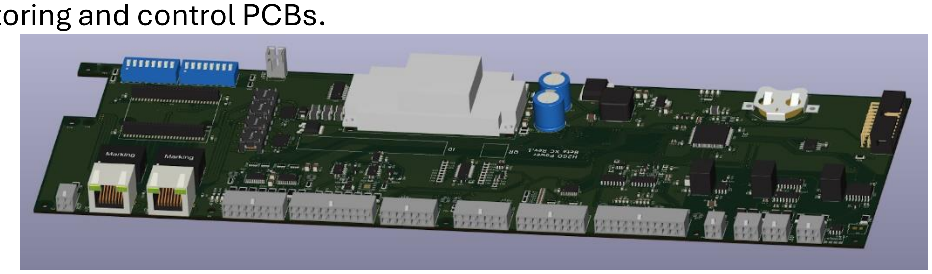


Figure 63: Embedded Control Board

The “HJB” module level monitoring and control boards (Figure 64: HJB Modular Control Board) allowed local modular interfacing to solenoid valves and analogue sensors associated with a single storage reactor, with a single wire interface back up to the intermediate “cross-controller”.

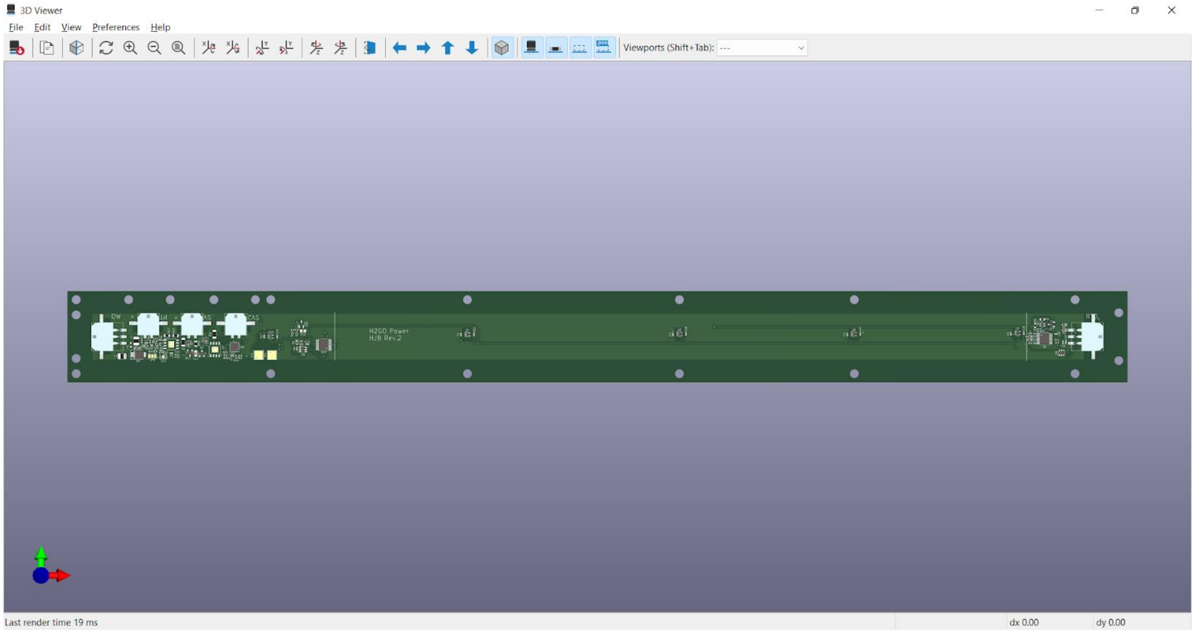


Figure 64: HJB Modular Control Board

Finally, to allow reliable control of the high-pressure solenoid valves within the system, a driver board was developed to amplify the control signals from the cross-controller, which were limited by power over ethernet current restrictions.

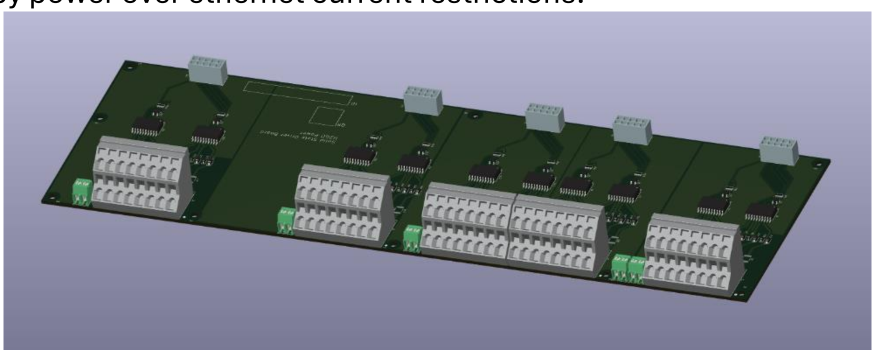


Figure 65: Driver Board

All custom PCBs went through a rigorous design, layout and design rule checking process to allow manufacture.

At the system level, the electrical design was conducted to meet the requirements of the Machinery Directive. Each system contained a primary electrical panel, integrating a large number of off the shelf electrical components with the system control PLC described above. In order to maximise learning during build of the hydrogen storage system, the primary electrical panel was built in-house using qualified electrical technicians as shown in Figure 66: Electrical Panel Manufacturing at H2GO Power Facilities and Figure 67: Finalised Electrical Panel.

Figure 66: Electrical Panel Manufacturing at H2GO Power Facilities

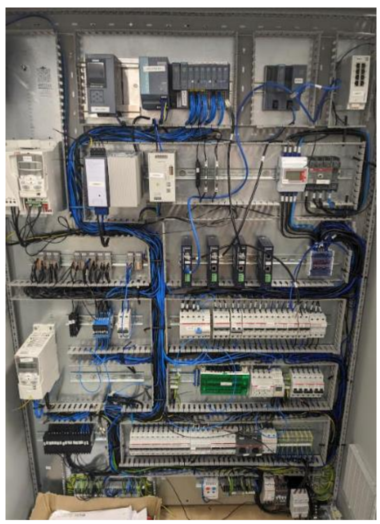


Figure 67: Finalised Electrical Panel

For the HiAB system, an outsourced manufacturing strategy was selected, allowing internal resource to focus on the core technology. Following the design release of the HiAB electrical panel, all components were purchased and kitted in preparation for build.

16.0 PLC development

With the system that was developed within the SHyGaN project, being designed as largely automated, developing the suitable PLC to support this level of automation was necessary. Each container was designed to be controlled by a separate PLC unit in order to achieve better control over the system's operation. The main activities of the PLC design were undertaken by H2GO Power where the main outputs of this work were two PLC control philosophies (1 for each container) together with the necessary EE architecture documents. MTC participated in this work steam by reviewing both control philosophies in order to provide feedback to H2GO Power, and creating a PLC software design document that would clearly describe the PLC system hardware (including configuration and parameters) and software components. The applied PLC software was to fully implement the operating modes of the system for both containers, and system IO control logic as defined in the mentioned control philosophy documents. In addition to this, HMI design and development was undertaken for assessing the PLCs' usability and alignment with the control philosophy documents, together with an offline simulated test of PLC software.

During the execution of these tasks, the control philosophy documents were reviewed and feedback was provided to H2GO Power to further improve the respective control philosophies. During the PLC software development the configuration of a fail-safe PLC hardware and safety interlocking logic between the two containers was implemented. An overall PLC (+ safety) software executable file in Siemens TIA Portal native package was also created. The pictures in Figure 68: PLC software development provide snapshots from the PLC software development work. For the execution of the scheduled tests, two offline simulated tests of the PLC software and HMI were performed with Siemens PLCSIM application. Test reports were produced verifying the implemented functionality based on system requirements. The PLC software design documentation activity was deliberately left for last as changes requests to the PLC software design/development work would be expected as a consequence of the changes on the overall design. By doing so, rewriting of the documentation was mitigated and/or avoided. This activity was initiated just before the project's premature termination, as a result only little progress was made on this.

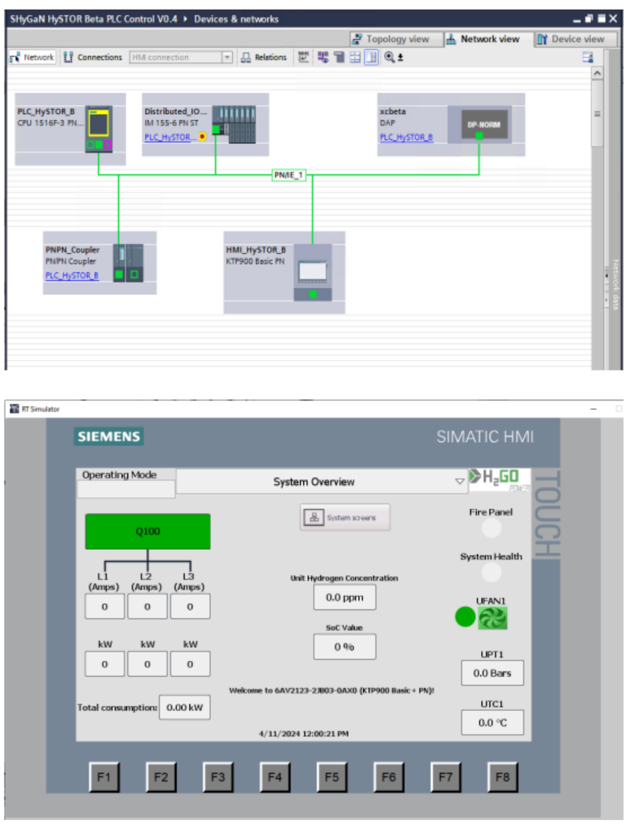


Figure 68: PLC software development snapshots

 [redacted]

17.0 Design verification activities

As discussed in 10.4 design verification activities were carried out to assess performance of subsystem components. Progress was made into stage 1 and the early stages of 2 and 3 according to Figure 30. The most noteworthy verification activities are that of the core reactor technology presented as follows.

17.1 Reactors verification

The first batch of four modular reactors were received and quality inspected. One modular reactor was filled with storage material from the same manufacturing batch that would be used in the SHyGaN deployment, with the aim of validating the design and performance. For monitoring strain during activation several cycles were performed under different hydrogen flow rates, including the same conditions expected during SHyGaN operation (e.g. 12.5 L/min release rate per reactor to account for the SHyGaN flow requirements). The reactor was connected to the testing rig to monitor temperature, pressure, hydrogen flow rate and hoop strain (Figure 69).

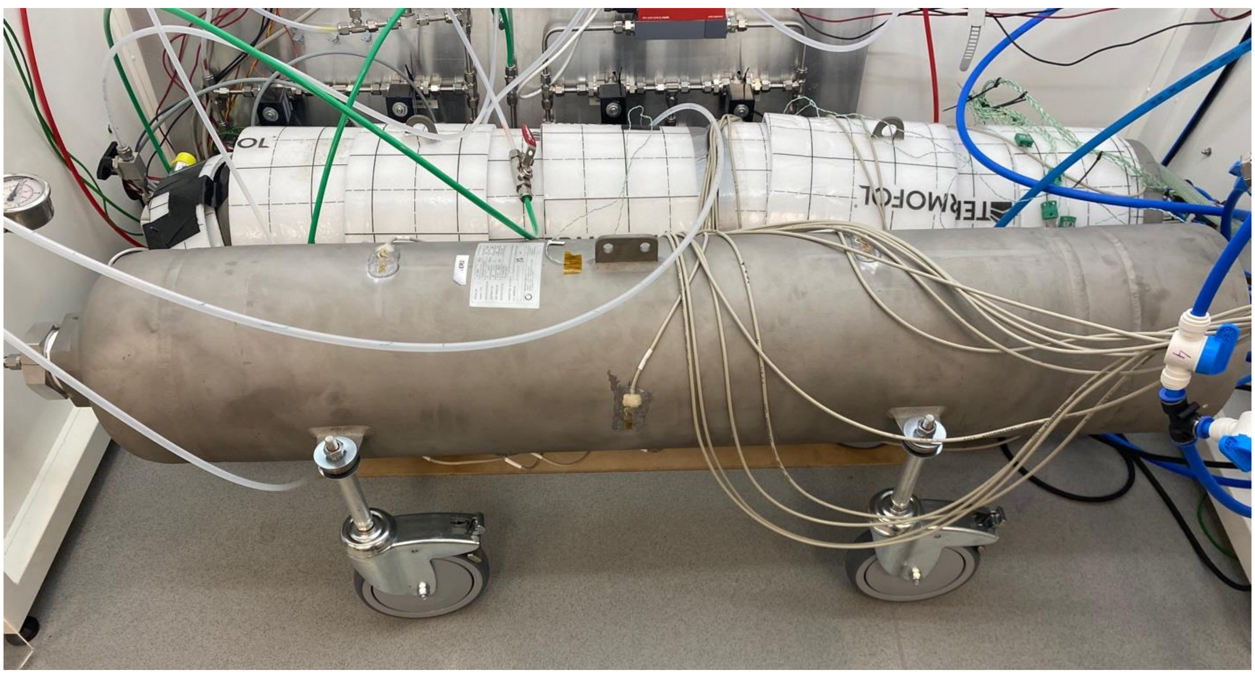


Figure 69: SHyGaN modular reactor (front) in testing enclosure.

The amount of absorbed hydrogen was manually controlled and gradually increased in order not to exceed a pre-determined value of the hoop strain on the reactor walls. Higher strain values were generally observed during the first five cycles and this is due to initial expansion of the storage material following exposure to hydrogen. As cycles progressed, the vessel capacity stabilised at ~90% of the theoretical maximum capacity.

The desired flow rate was maintained for over 23 hours until the internal pressure of the reactor decreased due to full release of hydrogen. This “squared” profile is particularly desirable to allow a steady flow of hydrogen into the boiler. It was noticed that the relatively low flow rates for this application (when compared with the maximum flow performance that can be achieved with the H2GO technology) allowed for hydrogen release to occur immediately, completely removing the need of warming-up the reactor while maintaining high enough internal pressure. Immediate release of hydrogen is particularly important to account for transient behaviour during the system operation. The lab testing of the modular reactor validated the expected performances and confirmed that an immediate steady hydrogen flow of 260 L/min once the unit enters discharge mode.

18.0 Environmental, safety and regulatory considerations and requirements

The systems were developed as part of a product development and demonstration project for integration on the NGN Site as discussed. Therefore, the primary codes and standards required for qualification of the installation are those related to NGN/PM/G/17 [16]. Further to this, the two systems have been designed to meet the codes and standards related to the CE and UKCA marking, where possible; however the system was deemed to not be certified to CE or UKCA as it was not required. For securing the system's compliance with applicable standards and legislation, DNV facilitated multiple HAZOP, HAZID and LOPA sessions with H2GO Power, NGN and MTC during the detail design phase. This work helped identify the appropriate H&S legislation and standards, for the SHyGaN system. These decisions were utilised in the Piping and Instrumentation Diagram (P&ID) generated by H2GO Power, which in turn was used by the MTC for the detail design CAD. The MTC were also tasked with conducting a secondary search of appropriate standards and regulations, to identify potential gaps in the design and to make any necessary design recommendations, for mitigating any regulatory risks. In addition, NGN worked on assessing the main on-site requirements and the necessary safety preparations. All the above mentioned work streams were running in parallel, and the main information is provided below.

18.1 Design regulatory assessment

Nine Standards and nine Regulations were deemed to be the most applicable and were therefore evaluated in more depth. These, along with other suggestions made by the MTC H&S team, formed the basis of a series of recommendations outlined within this chapter. As mentioned, DNV facilitated multiple HAZOP, HAZID and LOPA sessions during the course of the detail design phase, which identified hazards/risks, hazardous scenarios to determine, H&S legislation and standards, and therefore assisted with part selection and appropriate safety systems for use on the system. H2GO Power, NGN and MTC staff were in attendance for each of the sessions, and all outputs were detailed in relevant reports (issued by DNV) upon completion. These decisions from each report were utilised in the Piping and Instrumentation Diagram (P&ID) generated by H2GO Power, which in turn was used by the MTC for use within the detail design CAD. A brief outline of the tasks held for these sessions follows below:

Hazard Identification Study (HAZID)

- Determine likely hazards within the system.
- Focus on recognising hazards without going into detailed analysis of the consequences or likelihood.

Hazards and Operability (HAZOP)

- Identification of process hazards/risks present in the current design of the SHyGaN system.
- Determination of potential consequences of each identified hazard.
- Identification of existing safeguards and protective measures in place.
- Generation of recommendations for additional safeguarding measures to feed into the P&ID and subsequent design work.

Layer of Protective Analysis (LOPA)

- Determine residual risk from any potential hazardous scenario identified in the HAZOP.

The MTC design team conducted a fortnightly assessment of the design alongside the MTC H&S team, for determining potential H&S concerns whilst still in the design phase, prior to the build commencing. Some of the issues and concerns raised were listed within the HAZOP sessions and changes were implemented. These internal H&S sessions were a secondary review to catch anything that may have been missed during the HAZOP.

It's also important to mention that following DNV's recommendations, it was determined that H2GO should not pursue a UKCA marking for the system within the project's duration, as it would be classed as a research and development (R&D) activity, and therefore be exempt. This exemption applies to products that are exclusively intended for research and development purposes, as they are not intended to be made available for sale to the general public or used for consumer purposes. However, as a preparatory step for a potential commercialisation, the relevant safety requirements were assessed during the project.

18.2 Selected regulations

In Table 10: Selected regulations from MTC assessment below the nine final selected regulations that were deemed as most suitable are being presented

Table 10: Selected regulations from MTC assessment

Regulation	**Description**
Pressure Systems Safety Regulations (PSSR)	The Pressure Systems Safety Regulations 2000 are critical for ensuring the safe operation of pressure systems in the UK.
Dangerous Substances and Explosive Atmospheres Regulations (DSEAR)	The Dangerous Substances and Explosive Atmospheres Regulations 2002 (SI 2002/2776) set minimum requirements for the protection of workers

	from fire and explosion risks related to dangerous substances and potentially explosive atmospheres.
Control of Substances Hazardous to Health (COSHH)	COSHH applies to a wide range of substances which have the potential to cause harm to health if they are ingested, inhaled, or are absorbed by, or come into contact with, the skin, or other body membranes.
Potentially Explosive Atmospheres Regulations- (ATEX)	ATEX is part of the DSEAR Regulations involving risk of explosion from gases or substances.
Control of Major Accident Hazard (COMAH)	COMAH Regulations look to prevent major accidents involving dangerous substances and limit the consequences to people and the environment of any accidents which do occur.
Provision & Use of Work Equipment Regulations (PUWER)	The Provision and Use of Work Equipment Regulations 1998 (PUWER) are UK regulations aimed at ensuring the safety and proper use of work equipment.
Lifting Operations and Lifting Equipment Regulations (LOLER)	LOLER regulations aim to ensure that lifting equipment is safe to use and that lifting operations are carried out safely.
Supply of Machinery Safety Regulations	The Supply of Machinery (Safety) Regulations 2008 (as amended) is UK legislation aimed at ensuring machinery placed on the market or put into service is safe and meets essential health and safety requirements.
Electricity at Work Regulations (EWR)	The Electricity at Work Regulations 1989 (EAWR) is UK legislation designed to prevent death or injury from electricity in the workplace.

For each of the above regulations the main design considerations that were identified as necessary to be taken are being presented individually:

Pressure Systems Safety Regulations (PSSR)

The designer, manufacturer, importer or supplier should consider and take due account of the following, where applicable:

1. the expected working life (the design life) of the system;
2. the properties of the contained fluid;
3. all extreme operating conditions including start-up, shutdown and reasonably foreseeable fault or emergency conditions;
4. the need for system examination to ensure continued integrity throughout its design life;
5. any foreseeable changes to the design conditions;
6. conditions for standby operation;

7. protection against system failure, using suitable measuring, control and protective devices as appropriate;
8. suitable materials for each component part;
9. the external forces expected to be exerted on the system including thermal loads and wind loading; and
10. safe access for operation, maintenance and examination, including the fitting of access (e.g. a door) safety devices or suitable guards, as appropriate.

Dangerous Substances and Explosive Atmospheres Regulations (DSEAR)
Design considerations detailed in DSEAR for safety systems:

- Where power failure can give rise to the spread of additional risk, equipment and protective systems must be able to be maintained in a safe state of operation independently of the rest of the plant in the event of power failure.
- Means for manual override must be possible, operated by employees competent to do so, for shutting down equipment and protective systems incorporated within automatic processes which deviate from the intended operating conditions, provided that the provision or use of such means does not compromise safety.
- On operation of emergency shutdown, accumulated energy must be dissipated as quickly and as safely as possible or isolated so that it no longer constitutes a hazard.
- Necessary measures must be taken to prevent confusion between connecting devices.
- The employer should only use 'products' (equipment, protective systems, safety devices, components and their combinations) in potentially explosive atmospheres that comply with the specific essential health and safety requirements of Equipment and Protective Systems (EPS), unless the risk assessment states otherwise.
- Appropriate signage must be utilised on the system itself and any surrounding sub systems. Regulation 10 does not require everything to be marked or labelled, but the employer should decide, through their risk assessment, if and how contents of containers and pipes containing dangerous substances should be identified, whether appropriate identification is required and if so, the form it should take. The regulation allows a common-sense approach to selecting means of identification, which would depend on the work activity and take into account security implications. Suitable means could include labelling, the use of appropriate colour coding, or instructions and training.
- Appropriate information, training and instruction should be given to contractors and employees on the dangerous substances present together with information on the hazards, risks, precautions and actions necessary for them to remain safe.

Control of Substances Hazardous to Health (COSHH)
As per this standard, employers must not carry out work which can expose any of their employees to any substances hazardous to health until:

- A suitable and sufficient assessment of the risks to employees' health created by that work has been carried out.
- The steps needed to comply with the Regulations have been identified.
- The identified steps have been put into operation.

Therefore the related risk assessment should take into account the properties of the hazardous substance, how and when they can give rise to risks to health, and the degree to which those risks need to be taken into account. For the case of SHyGaN a COSHH assessment was carried out on the MHx, hydrogen and the electrolyte, to ensure all risks were assessed correctly. This applies for both storage prior to the build and when fully operational and contained within the system, to ensure all necessary control measures are in place. For the MHx material, the overall risk score is high, given the large quantities of material employed in the system, however adequate steps have been identified and put into operation (e.g. the use of a glove box when filling individual reactors). Once the reactors are filled, the probability of exposure of the operator is minimal, reducing the health risk.

Potentially Explosive Atmospheres Regulations (ATEX)

ATEX is the name commonly given to the two European Directives for controlling explosive atmospheres:

1. Directive 99/92/EC (also known as 'ATEX 137' or the 'ATEX Workplace Directive') on minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres.
2. Directive 2014/34/EU (also known as 'ATEX 114' or 'the ATEX Equipment Directive') on the approximation of the laws of Members States concerning equipment and protective systems intended for use in potentially explosive atmospheres.

In Great Britain the requirements of Directive 99/92/EC were put into effect through regulations 7 and 11 of the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR). As part of the UKCA changes, the ATEX directive is to be replaced by the new UK Ex scheme for products sold across the UK. As such, this should not be applicable for the current system but an EX certificate would be required for future products if there was a requirement for it to be put onto the market.

Control of Major Accident Hazard (COMAH)

The purpose of COMAH Regulations is to prevent major accidents involving dangerous substances and limit the consequences to people and the environment of any accidents that may occur. This includes not just the installations that handle dangerous substances but also the related infrastructure such as pipework and activities such as traffic movement which could be relevant to a major accident. In the case of SHyGaN as with the COSHH regulation, this could apply to MHx, hydrogen and the electrolyte used in the electrolysers. As per the COMAH regulation, the operator will need to notify the competent authority if the quantity of dangerous substances at its establishment will equal or exceed the thresholds described in the regulation. The electrolyte and the H2GO MHx storage materials are not subject to COMAH regulations, but hydrogen is. However, when the hydrogen is chemically bonded to the MHx used in H2GO storage systems, it has been discussed in Section 7.4.2 of this report, on how this could be interpreted.

Provision & Use of Work Equipment Regulations (PUWER)

As per this regulation, the following should be considered as part of the requirements for SHyGaN either through the design work, or as part of the build and testing activities:

- The system must be suitable for its intended purpose.
- The system must be kept in a safe condition with maintenance schedules followed and regular inspections held.
- Employees must be provided with adequate training on the use of equipment.
- Instructions for safe use must be available and communicated effectively.
- Measures must be in place to prevent access to dangerous parts of machinery.
- Controls should be clearly marked and easily accessible.
- Emergency stop controls must be fitted where necessary.
- The system must be provided with a means to isolate it from all power sources, which is clear and effective.
- The system must be stable and secure during use.
- The system should have clear markings, such as maximum load capacities, warnings and safety instructions.

Lifting Operations and Lifting Equipment Regulations (LOLER)

As per this regulation, the following would need to be considered for SHyGaN during the design or incorporated during the build stage:

- As the container itself was to be lifted, all necessary calculations would need to be performed to ensure that the lifting points are suitable for the mass when fully built.
- The overall container design must be analysed for stresses and strains that may be present amongst multiple components during lifting operations.
- Any auxiliary lifting equipment utilised during the build phase or transport must have been inspected by a competent person and is subject to regular inspections.
- All necessary signage/markings are placed onto the container including Safe Working Load, Centre of Gravity and suitable lifting strategy.
- Regular inspections on the equipment as part of a maintenance schedule.
- Completion of suitable risk assessments or lifting plans when required.

Supply of Machinery Safety Regulations 2008

This regulation, ensures that machinery placed on the market is safe for use by meeting stringent health and safety requirements. Compliance involves thorough risk assessment, proper documentation, CE/UKCA marking, and provision of clear instructions and safety information. As such, these regulations protect users by ensuring machinery safety from design through to operation. In more detail, these regulations would require that all machinery and equipment in scope:

- Are designed and constructed to be safe.
- Have a technical file.
- Have appropriate conformity marking.
- Are accompanied by a Declaration of Conformity (or, in the case of partly completed machinery, a Declaration of Incorporation).

- Are supplied with comprehensive instructions in English.

For the case of SHyGaN this would not be required as the system was a prototype and would not follow the UKCA marking process. However it was considered a good practice to still complete the technical file and compile lessons learnt for the future product that may be placed on the market.

Electricity at Work Regulations (EWR)
This regulation serves for ensuring the safety of electrical systems in the workplace. There are no voltage limits in this regulation and the relevant criteria focus on the probability that danger may arise. It is although appropriate for the regulation to apply even at the very lowest end of the voltage or power spectrum, as explosion risks for example, which may be caused by very low levels of energy igniting flammable gases. In the case of SHyGaN this could be caused from hydrogen. Thus, as per this regulation design considerations had to be taken for: earthing, spark arrestors, lightning protection, isolation techniques, prevention of access to live parts, procedures for maintenance, and use of the system in potentially adverse weather conditions.

18.3 Identified standards

MTC in addition to the applicable regulations, also evaluated what applicable current standards could apply to the SHyGaN design, and how this could influence any design decisions made. This work concluded with nine final selected standards, which are presented in Table 11: Selected standards from MTC assessment below, that were deemed to be the most suitable and were evaluated in more depth. Note it is important to clarify here that H2GO see a wider range of standards that are applicable to the technology; these standards independently researched by MTC were considered by H2GO and fed into the certification roadmap for the technology, along with the others that were additionally deemed applicable by H2GO, to ensure that the go to market design was able to satisfy all essential health and safety requirements upon placing the product on the market.

Table 11: Selected standards from MTC assessment

Number	Description
EN 13445-1:2021	Unfired pressure vessels – Part 1: General
EN 13445-3:2021	Unfired pressure vessels – Part 3: Design
EN 13480-1:2017	Metallic industrial piping - Part 1: General
EN 13480-3:2017	Metallic industrial piping – Part 3: Design and calculation
BS 1306:1975	Specification for copper and copper alloy pressure piping systems
EN ISO 12100:2010	Safety of machinery - General principles for design - Risk assessment and risk reduction
EN 1127-1:2019	Explosive atmospheres - Explosion prevention and protection - Part 1: Basic concepts and methodology

EN ISO 13849-1:2015	Safety of machinery — Safety-related parts of control systems — Part 1: General principles for design
BS EN 60079-10-1:2009	Explosive atmospheres. Classification of areas. Explosive gas atmospheres

For each of the above standards the main design considerations that were identified as necessary to be taken are being presented individually:

EN 13445-1:2021

This standard provided more of a general overview to risk reduction with references to the other standards, indicating that more relevant design information is contained within 133445 part 3 design. The associated hazard and risk reduction element has been conducted by DNV in relevant HAZOP and HAZID sessions.

EN 13445-3:2021

The specific standard is applicable to multiple types of systems, but several parts were discounted as not relevant to the nature of the project (e.g. corrosion over prolonged periods of time). The standard provided significant design data and experiments for loads, stresses, pressure and temperatures considerations. The Basic Design Criteria within section 5 of the standard were considered during the design.

EN 13480-1:2017

This standard was not applicable to internal piping of boilers or piping integral to pressure vessels, and had limited relevance to SHyGaN.

EN 13480-3:2017

Key considerations within the standard were on basic criteria, design stresses, design of piping components and ends under internal pressure, branch connections and pipe supports. The standard also highlighted that more in-depth calculations would be needed to be added to the design on parameters such as the ones below:

- Pipe bends and elbows (section 6).
- Flexibility in pipes (section 12).
- Pipe Supports (section 13).

BS 1306:1975

Several useful considerations were providing within the standard. Indicatively, some key considerations were as follows:

- Thickness of pipes (section 7).
- Thickness of pipe bends (section 8).
- Joint types (section 10).
- Expansion allowance (section 12).
- Flexibility (section 13).
- Supports (section 14).

- Drainage (section 15)
- Venting (section 16).

EN ISO 12100:2010
This standard provides a detailed analysis of machinery design principles to identify risks and hazards that can be rectified whilst in the design stage (mechanical, electrical and control systems). The standard has also considered an iterative loop process with reviews in order to implement suitable control measures. Through this, hazards and risks were evaluated based on machine specifications, applicable regulations, experience of use and ergonomic principles. The specific approach was considered to fall under the remit of DNV which was covered through the HAZOP/HAZID sessions.

EN 1127-1:2019
Thise standard identifies explosion hazards together with prevention and protection against them, and it also links to other standards depending on the situation and properties/behaviour of materials. Through this standard design considerations were made for the mitigation of such risks, while it also provided useful notes on the use of hand tools in the potential presence of hydrogen in certain zones during system operation.

EN ISO 13849-1:2015
This standard relates to safety related parts of control systems and the appropriate means of selecting and implementing the correct measures, for eliminating or reducing associated risks. Conformity with this standard was part of DNV's work during the HAZOP/HAZID sessions, and its outcomes fed into the MTC's design.

BS EN 60079-10-1:2009
This standard provided a classification of zone for explosive gas atmospheres. The standard outlines ways to reduce risks and reduce risks in the zones (e.g. through the use of forced ventilation). Conformity with this standard was part of DNV's work during the HAZOP/HAZID sessions, and its outcomes fed into the MTC's design.

18.4 NGN safety preparation and processes

NGN's existing safety management system was sufficient to manage the project and therefore existing NGN procedures were followed to mitigate project safety risks. The two main NGN procedures that the project needed to adhere to were:

1. NGN/PM/G/17 - The Management of New Works, Modifications and Repairs Incorporating Commissioning, Operational and Asset Acceptance
2. NGN/HAZ/9 - Management Procedure for Process Safety Assessment Studies

These are presented in the following subsections.

18.4.1 NGN/PM/G/17

NGN/PM/G/17 is Northern Gas Network's procedure for ensuring that new works are designed and managed in accordance with regulatory requirements. The G17 design process is based on the Institute of Gas Engineers and Managers (IGEM) guidance document IGEM/GL/5 which was created to provide guidance to support the Gas Safety (Management) Regulations (GS(M)R) and the Pipelines Safety Regulations (PSR). IGEM is the professional engineering institution for gas whose technical expertise is recognised by organisations such as Ofgem and HSE. The G17 procedure incorporates the philosophy outlined in the IGEM guidance document IGE/GL/5 "Managing new works, modifications and repairs" setting out the processes for appraising and approving modifications to a gas transmission system and its associated support systems. Whilst still applicable to comply with GS(M)R and PSR, this minimum standard of documented procedures for managing new works, modifications and repairs to any plant or system associated with the supply of fuel gas is to be implemented to ensure compliance with the Pressure Systems Safety Regulations (PSSR), the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR), the Electricity at Work Regulations (EWR), and the Control of Major Accident Hazard Regulations (COMAH) where applicable. This Standard applies to other plant and systems, for example control systems and software. Integral to the procedure is the assignment of responsibilities to nominated personnel who, where appropriate, have been trained and assessed to ensure technical competence and suitability for their roles.

IGEM/GL/5, and therefore NGN/PM/G/17, also ensures compliance with:

- Pressure System Safety Regulations (PSSR) - These Regulations cover the safe design and use of pressure systems. The aim of PSSR is to prevent serious injury from the hazard of stored energy (pressure) as a result of the failure of a pressure system or one of its component parts. The only hazard under consideration is that due to pressure and associated stored energy. Hazards due to the flammable or toxic characteristics of the relevant fluid are not covered by the Regulations.
- Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) - DSEAR are concerned with protection against risks from fire, explosion and similar events arising from dangerous substances used or present in the workplace. DSEAR require that risks from dangerous substances are assessed, eliminated or reduced. They contain specific requirements to be applied where an explosive atmosphere may be present and require the provision of arrangements to deal with accidents, emergencies, etc. and provision of information, training and use of dangerous substances. DSEAR also require the identification of pipelines and containers containing hazardous substances.
- Electricity at Work Regulations (EWR) - These Regulations were made under the Health and Safety at Work etc. Act 1974. The Regulations require precautions to be taken against the risk of death or personal injury from electricity in all work activities. The Regulations cover all electrical equipment, which includes switchgear, control panels, distribution boards, electrical accessories, portable tools and equipment

and cables. The Regulations apply to all electrical systems including portable generators, batteries and instruments containing or operating from a source of electricity. The Regulations impose legal duties on persons in respect of work on or near electrical systems, equipment and conductors. They state the responsibilities shared by managers, supervisors and employees to ensure electrical safety.

- Control of Major Accident Hazard Regulations (COMAH) - These Regulations aim to prevent major accidents involving significant quantities of flammable, environmentally hazardous or toxic substances and if they happen, require Asset Owners to limit the effects on people and the environment.
- Provision & Use of Work Equipment Regulations (PUWER) - These Regulations apply to all work equipment (which includes pipelines and pipework) requiring equipment to be suitable for the intended use, safe for use and maintained in a safe condition. In certain circumstances, equipment is to be inspected to ensure the equipment remains in a safe condition. In addition, equipment is required to be used only by people who have received adequate information, instruction and training, and accompanied by suitable safety measures such as protective devices, markings and warnings. The primary responsibility for compliance with legal duties rests with the employer. The fact that certain employees, for example "responsible engineers", are allowed to exercise their professional judgement does not allow employers to abrogate their primary responsibilities.
- Construction (Design & Management) Regulations (CDM) - These Regulations apply to the whole construction process on all asset construction projects from concept to completion and beyond. Duty holders include clients, designers, principal designers, principal contractors, contractors and individual workers. Foreseeable risks, such as those that may arise during construction work or in maintaining and using the asset once it is built are required to be eliminated, reduced or controlled.
- ATEX Directive - part of the DSEAR Regulations involving risk of explosion from gases or substances and was covering in principle two European Directives for controlling explosive atmospheres. In Great Britain the requirements of this directive through regulations 7 and 11 of the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR). Despite being covered by DSEAR (which was presented above), ATEX is separately mentioned here due to the significance of compliance with that Directive for gas-related works and also for being one of the most significant safety requirements for gas-related works including hydrogen.
- Health and Safety at Work Act (HSWA) - HSWA applies to all persons involved with work activities, including employers, the self-employed, employees, designers, manufacturers, suppliers etc. as well as the owners of premises. It places general duties on such people to ensure, so far as is reasonably practicable, the health, safety and welfare of employees and the health and safety of other persons such as members of the public who may be affected by the work activity. All persons engaged in the design, construction, commissioning, operation, testing, servicing, maintenance, alteration, disconnection and decommissioning of pipework/systems are required to be competent to carry out such work. Competency is achieved by an

appropriate combination of education, training, practical experience and exhibiting appropriate behaviours.

- Pipelines Safety Regulations (PSR) - These Regulations apply to all pipelines, both onshore and offshore, but excluding pipelines that are: i) wholly within premises, ii) container wholly within caravan sites, iii) used as part of railway infrastructure, iv) used to convey water. In general, these regulations place emphasis on pipeline integrity and have specific additional requirements for pipelines of MOP exceeding 7 Bar, including the production of a Major Accident Prevention Document (MAPD) and the requirement for the Local Authority to produce emergency plans. The Regulations complement (GS(M)R) and include the: i) definition of a pipeline, ii) general duties for all pipelines, iii) need for cooperation between pipeline operators, iv) arrangements to prevent damage to pipelines, v) description of a dangerous fluid, vi) notification requirements, preparation and maintenance of a Major Accident Prevention Document, and vii) arrangements for emergency plans and procedures.

The G17 procedure therefore ensures that any New Works, Modifications or Repairs are undertaken in accordance with relevant regulatory requirements. The G17 legislative framework is illustrated in the figure below.

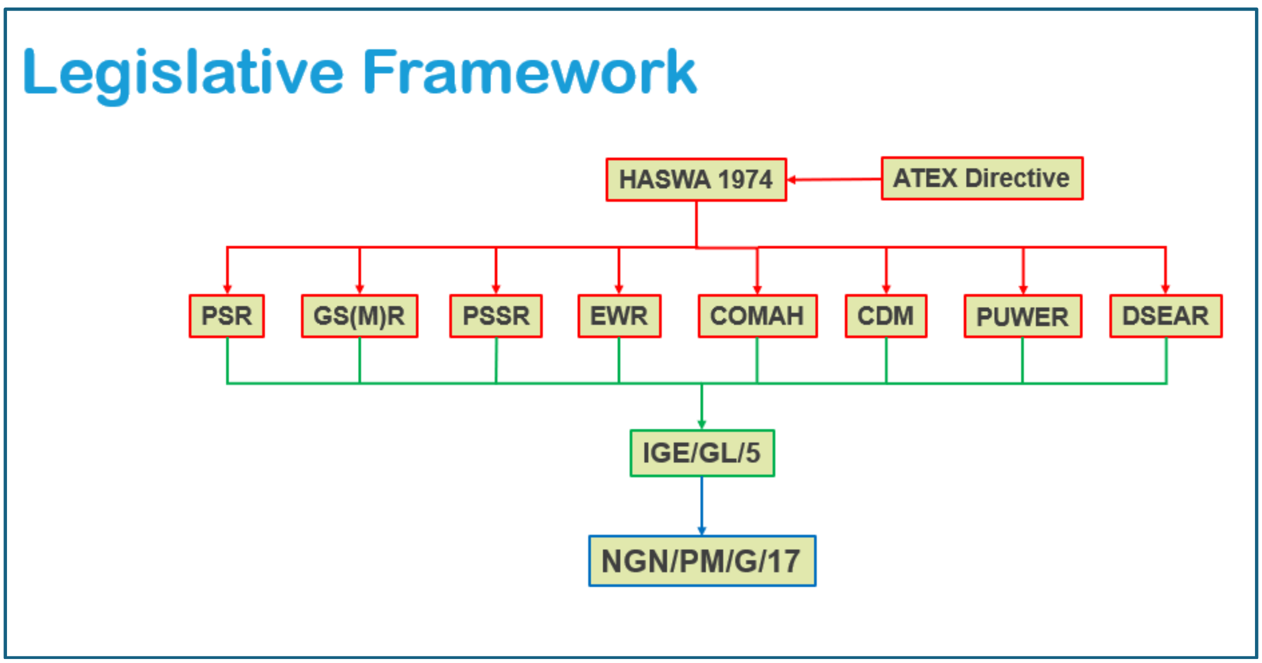


Figure 70: G17 legislative framework

The G17 procedure as mentioned, applies to the management and control of new works, modifications, repairs and demolition of assets utilised for the transportation, distribution and metering of gas. Therefore the G17 has to be applied to the following:

- Gas transportation systems, including pipelines operating above 2 bar or with slam shut protective devices set above 2.7 bar.

- Design Appraisal of other plant such as below 2 bar equipment and systems considered appropriate at the discretion of the user.
- Supply point metering installations with an inlet pressure above 2.0 bar
- Gas storage installations.
- Pressure vessels operating above 0.5 bar and a stored energy capacity exceeding 250 bar litres.
- All electrical, instrumentation, configurable equipment and control systems and any associated software.

G17 encompasses all disciplines (Mechanical, Gas Engineering, Electrical, Cathodic Protection, Instrumentation and Control, Civil/ Structural, Safety and Software) and applies to both in-house and outsourced activities. In the life of all projects that require compliance with the G17, there are six distinctive stages:

1. Initiation
2. Design Approval/Appraisal
3. User Acceptance
4. Installation Completion
5. Commissioning Completion
6. Records & User Acceptance

For ensuring that each project meets its overall objectives engineering controls are required at each stage. These controls ensure that the responsible persons agree that the objective of each stage has been met. Since the project was terminated prior to the finalisation of the design, only the first stage was completed.

The G17 as a process considers the role of the Competent Design Authority for the assessment of any design and appraisal work to be conducted and for having the authority to exercise controls within the overall design process. In this way, it is ensured that all design work will be compliant with the applicable regulatory requirements. For the SHyGaN project, DNV were the Competent Design Authority appointed by NGN, having responsibilities for assessing the organisations undertaking designs for NGN. All site upgrade requirements were confirmed by the G17 design with all works being subject to design approval before they could commence.

Specific to the project, a number of process safety studies were undertaken by DNV to ensure that the health and safety risks associated with the project were appropriately managed. Studies included HAZIDs, HAZOPs, LOPA, and a Fire & Explosion QRA. A Health & Safety Plan and CDM Risk Register was also prepared for the project. The project was HSE notifiable under The Construction Design and Management Regulations. All site construction, commissioning and management operations would be subject to the CDM Regulations and NGN operational procedures.

18.4.2 NGN/HAZ/9

The application of Formal Process Safety Assessment techniques is essential at the design stage of new projects with major hazard potential to ensure appropriate levels of process safety. The techniques are equally applicable during modifications. This procedure is expected to align with the Gas Networks' Major Accident Prevention Policy (MAPP) where they have one in place, and the Gas Networks' HSE/process safety policy to ensure that all potential major accident hazards are identified at design stage for new projects or modifications to enable appropriate control and mitigation measures to be put in place. Once in place, these risk prevention measures, if suitably operated and maintained in line with the Gas Networks' safety and environmental management system, should ensure that the risk to employees and the public is minimised. Some of the techniques are also suitable for considering hazards to the environment.

The application of standards and codes is important to minimise hazards, but even with a 'standard' design there may be elements of that design utilising new components, new techniques or new layouts which could have safety implications. The main strength of Formal Process Safety Assessments is that they allow all the disciplines involved in a design to review the design together as a team, to ensure that design objectives are achieved.

A Formal Process Safety Assessment Plan is developed prior to Feasibility and Conceptual Design and is then updated at the end of Conceptual Design for implementation into the detailed design and final handover. In exceptional circumstances, updates to the Formal Process Safety Assessment Plan may be required throughout the Feasibility process in preparation for the Conceptual Design stage. Safety and operability is delivered in the design process through a number of Formal Process Safety Assessment exercises. A Formal Process Safety Assessment is a planned and structured process which shows how all hazards and operability issues relating to an installation during its complete life cycle from design through to decommissioning are: i) identified and eliminated, or ii) reduced; or iii) isolated; or iv) controlled.

Each Formal Process Safety Assessment addresses different aspects of the project, applying a range of techniques to ensure that hazards are comprehensively identified, assessed and controlled. Formal Process Safety Assessment activities should be planned from the outset of a project, and there should be ongoing monitoring of progress against Formal Process Safety Assessment requirements. The emphasis should be on resolving any issues at the design phase of a project, rather than at construction / commissioning (when fixes can be costly or difficult to implement). Sufficient time should be allowed in the project timeline to plan and deliver Formal Process Safety Assessments, and close out any actions occurring from them.

The complexity of, and need for, the Formal Process Safety Assessments depends upon the complexity of the facility. There may be multiple Formal Process Safety Assessment activities during the same project phase. The project-specific requirements should be determined at the project outset at the Formal Process Safety Assessment planning meeting and then incorporated into the project plan. Functional Safety shall also be integrated into all project delivery activities. The internationally recognised standard for management of functional safety in the process industry, IEC 61511, recommends a lifecycle approach to functional safety management. Phase 1 of the safety lifecycle (SLC) is the identification of hazards and using a risk assessment to evaluate the risk reduction required by safeguards used to mitigate hazardous scenarios. Of particular interest are safeguards that part of electrical, electronic and programmable electronic systems (E/E/PES). These would be further assessed in Phase 2 of the safety lifecycle. The FPSA studies that constitute Phase 1 activities in the functional safety lifecycle include the HAZID and HAZOP, whilst Safety Integrity Level (SIL) determination, achieved using techniques such as Layers of Protection Analysis (LOPA), Fault Tree Analysis etc, covers Phase 2 of the safety. Following identification of any E/E/PES controls used to protect against hazardous scenarios in the FPSA studies.

18.5 On-site Planning

A number of NGN, GIS, IGEM and BS standards are related to the NGN/PM/G/17 – Management of New Works, Modifications & Repairs process. Where relevant these requirements were fed into the requirements for the system. In addition, standards have been derived from the following applicable directives where applicable which feed into the regulatory framework for G17 compliance.

- Machinery Directive 2006/42/EC (the Supply of Machinery (Safety) Regulations 2008 No. 1597 in GB)
- The Electromagnetic Compatibility (EMC) Directive 2014/30/EU (the Electromagnetic Compatibility Regulations 2016 No. 1091 in GB)
- The Pressure Equipment Directive (PED) 2014/68/EU (the Pressure Equipment (Safety) Regulations 2016 No. 1105 in GB)
- The Ecodesign Directive 2009/125/EC (the Ecodesign for Energy-Related Products Regulations 2010 No. 2617 in GB)
- The Restriction of Hazardous Substances (RoHS) Directive 2011/65/EU (and the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Regulations 2012 No. 3032 in GB)
- ATEX Directive 2014/34/EU

All site works were to be designed in accordance with the requirements of relevant IGEM and NGN Standards. Table 12. Principal Design Standards and Codes examples principal standards and codes that were required to be complied with.

Table 12. Principal Design Standards and Codes

Document No.	Document Title
IGEM/TD/13 Edition 2	Pressure regulating installations for Natural Gas, Liquefied Petroleum Gas and Liquefied Petroleum Gas/Air
IGEM/SR/25 Ed 2	Hazardous Area Classification of Natural Gas Installations
NGN/SP/E/28	Design of Pressure Regulating Installations with Inlet Pressures not exceeding 100 bar
NGN/SP/TR/18	Engineering of Pipelines and Installations Operating > 7 barg
NGN/PM/G/17	Management of New Works, Modifications & Repairs
NGN/SP/TR/23	Conceptual design of pipelines and installations operating at above 7 bar.
NGN/SP/TR/24	Detailed Design of Pipelines and Installations Operating > 7 barg

In support of the project, a 262kWh solar PV array was installed to provide low-carbon electricity to power the electrolyser equipment. A battery building was also constructed on-site by Northern Powergrid with the purpose of providing electrical storage so that electrolytic demands could be met at all times. The existing site infrastructure and newly installed solar PV array could meet equipment demands.

Decisions on whether to grant planning permission were made in line with national guidance (in the form of the National Planning Policy Framework) and the local planning policies set out by the local authority. Planning permission refers to consent from the local authority for construction of a proposed building, alterations to an existing building or change in use of an existing building. Upon the project's initiation NGN examined if such a permission would be required for the case of SHyGaN, and by following the relevant process, Gateshead council confirmed on the 10th of March 2023, that the proposed works comprising the installation of the system and associated pipes, would comprise permitted development under the Town and Country Planning (General Permitted Development) (England) Order 2015. The project also falls under existing permitted development in line with the rights for gas transporters, on the basis that the hydrogen heating system would ultimately heat the existing gas supply. On this basis, and as agreed with Gateshead Council, permitted development rights mean the development did not require planning permission.

In order to review the permitted development rights available, the project has assessed Schedule 2, Part 15, Class A (Gas transporters) of the Town and Country Planning (General Permitted Development) (England) Order 2015 (as amended).

It is considered that the development could comprise 'permitted development' under one of the following descriptions, subject to the agreement of Gateshead Council:

(a) the laying underground of mains, pipes or other apparatus; - This relates to the buried works – 8 weeks' notice would be required to be given to Gateshead Council

And

(b) the erection on operational land of the gas transporter of a building solely for the protection of plant or machinery; - This would be if the container was considered to be a building not exceeding 15 metres in height. The approval of the details of the design and external appearance of the building being obtained from Gateshead Council.

And/or

(c) any other development carried out in, on, over or under the operational land of the gas transporter. – This would be subject to it not being considered to be a building, and it would involve the installation of plant and machinery which does not exceed 15 metres in height.

Gateshead Council confirmed that the proposed works was to be carried out under NGN's permitted development rights, as a registered gas transporter on operational land, under the Town and Country Planning (General Permitted Development) (England) Order 2015.

Additionally the project was required to liaise with the Environment Agency as works may affect receiving sites such as watercourses and groundwaters. Works have the potential to be subject to approval such as flood consent or discharge consent. The project was assessed using form NGN-CPTF-F02 for environmental permitting and consent requirements. This includes but not be limited to:

Permit Type	**Description of Requirement**
Trade Effluent Consent	A Trade Effluent Consent must be obtained for discharges of process water or contaminated water. The Consent will have parameters with regards to flow rate, pH and constituents which must be complied with. Sites with existing Consents must be reviewed to ensure the consent meets the requirements of any project occurring onsite.
Environmental Permit – Surface Water Discharges	Environmental Permits are required for any discharge to surface waters with the exception of rainwater run-off. The Permit will have parameters specified by the Environment Agency with regards to flow rate, pH and constituents which must be complied with. Sites with existing Permits must be reviewed to ensure the permit meets the requirements of any project occurring onsite.
Environmental Permit – Waste Operations	Works to be completed onsite will be assessed against the requirements of the Environmental Permitting Regulations to determine the need for any form of permit, consent or exemption as listed in Schedules to the regulations.

It was previously confirmed by NGN, regarding authorisation requirements for the discharge of electrolytic process water that the de minimis exemption rule as advised in the Environment Agency Guidance be applied for the project; this was advised on the basis that the maximum discharge rate of electrolytic process water was 1 L/h. It transpired, during the detailed design phase, that the maximum discharge rate would be 80 L/h and the de minimis exemption would no longer be applicable, and therefore required NGN to make an application to the Environment Agency for the discharge of effluent to Groundwater. As this finding came into light upon the design's finalisation, and shortly after the project's termination was announced, NGN did not proceed with the application to the Environmental Agency.

18.6 DNV Sessions and Assessments

As mentioned, DNV was assigned as a subcontractor to undertake the necessary regulatory assessments to determine the system's compliance against applicable regulatory requirements. Towards this end, DNV led multiple HAZOP, HAZID and LOPA sessions with H2GO Power, NGN, and MTC during the detail design phase, generating the relevant reports. The main outcomes from these sessions are presented below:

18.6.1 HAZID

A HAZID study is intended to highlight potential hazards at an early stage of design such that they can be addressed following well-defined risk management processes. Carrying out a HAZID would also contribute towards compliance with NGN's Safety Management System. The key aims of the HAZID study were to:

- Identify hazards, the associated unwanted events, and the possible causes of those unwanted events.
- Identify the consequences that could result.
- Identify barriers / control measures that will prevent the hazards leading to unwanted events or mitigate the consequences.
- Highlight uncertainties in the design and identify any actions or areas for further study to address them like for example: i) Aspects of the project that are novel or not covered by recognised codes and standards / good practice; ii) Design elements that could have a significant impact on safety where the safety philosophy is not yet well developed; or iii) Cases where different options were being considered within the design and the choice of option could have a significant impact on safety.
- Risk rank the hazards using the NGN 5x5 Risk Assessment Matrix (RAM).

The HAZID study followed the guidance in ISO 17776: Petroleum and natural gas industries — Offshore production installations — Major accident hazard management during the design of new installations. A summary of the main hazards identified is provided in **Error! Reference source not found.**. The table summarises the unwanted event considered, and the maximum risk rank. The maximum risk rank for each hazard is largely the same across the two systems due to the similarity in design and the presence of the same hazardous substances.

Table 13: HAZID Study Hazard Summary

Hazard	Unwanted Event	Maximum Risk Rank
Hydrogen	Ignited Release – General	High
	Personnel Exposure to Hydrogen	High
Nitrogen	Release into vessel during commissioning	Medium
People at height	Fall from height	Medium
Equipment with moving or rotating parts	Contact with moving or rotating equipment	Low
Electricity	Contact with live electrical equipment	Low
High light Levels	Light pollution	Medium

As a response to the hazards identified, the study concluded with a list of actions that had been identified during the related workshops. These actions were mainly related with: i) further reviewing specific system and site requirements, ii) updating key design documents such as P&ID and PFD, iii) confirming and reviewing with boiler provider and electrolyser manufacturer, certain capabilities and specifications of their technology, iv) ensuring certain assessments (e.g. cybersecurity, lightning, noise, etc) to be made prior to the commissioning of the system, v) ensuring that relevant ventilation would be installed and be operational prior to the system's installation and commissioning, and vi) reviewing the potential benefit of installing static oxygen depletion sensor within the system's units. Following the study's completion, the consortium worked in undertaking the related actions for addressing further any identified hazards.

18.6.2 HAZOP

The Hazards and Operability (HAZOP) study for the SHyGaN system had a scope is limited to the design of the SHyGaN system (electrolysers, hydrogen storage, ventilation, process vents, etc.) but considered the potential impacts of deviations and incidents upon the wider NGN facility. At the request of H2GO Power, the HAZOP approach aimed to clearly delineate between each of the system's containers, to facilitate the utilisation of the results of the assessment in future applications of each technology.

The main objectives of the HAZOP study were as follows:

- Identification of process hazards/risks present in the current design of the SHyGaN system, as to be installed at the NGN site.
- Determination of potential consequences of each identified hazard, with consideration of impact upon the safety of personnel, the safety of the public, the environment, security of natural gas supply, and the assets of all primary stakeholders.

- Identification of existing safeguards and protective measures in place to prevent the occurrence of each hazardous scenario and qualitative discussion of the suitability of these measures.
- Generation of recommendations for additional safeguarding measures or other changes that may be required to manage the risk of each hazardous scenario to ALARP (meaning that any effort towards further risk reduction would be unreasonably disproportionate to the additional risk reduction that would be obtained).

As per the NGN procedure, the HAZOP did not include any consideration of scenario likelihood/frequency or associated risk ranking. It did however include a formal ranking of consequence severity as per NGN severity definitions, in order to determine which scenarios would require further analysis. The NGN severity definitions used are shown in Table 14: NGN HAZOP Severity Definitions.

Table 14: NGN HAZOP Severity Definitions

Level	**S**	**S**	**SoS**	**Fn**	**E**
	Safety (Worker)	**Safety (Public)**	**Security of Supply**	**Finance**	**Environment**
Severity Level 1	Minor injury / near miss negligible	No effect	Interruptive supplies disrupted /Negligible disruption	<£0.5m	Negligible
Severity Level 2	Lost time injury / HSE letter of concern / reversible injury	Minor Injury	Minor: Firm contract customer disrupted, minor disruption to operational systems	<£0.5m - £1m	Minor
Severity Level 3	Major injury / RIDDOR Reportable / irreversible injury	Serious Injury	Large: Tarrif customer disrupted, short term system failure	<£1m - £10m	Major incident / letter of concern from Environmental Agency (EA) or Local Authority
Severity Level 4	Fatality (<3) HSE Enforcement Notice	Major Injury/ Irreversible Injury	Major: Disruption outage for significant period of time	<£10m - £20m	EA Enforcement Notice / Improvement Notice Issued

Severity Level 5	Multiple fatalities (>3) HSE Enforcement Notice	Fatality (<3)	Severe: Disruption systems outage for a lengthy period of time	>20m	EA Prohibition Notice
Severity Level 6	N/A	Multiple fatalities (>3)	N/A	N/A	N/A

The scope of assessment was divided into 5 nodes, 2 for the HySTOR container and 3 for the HIAB container. The nodes were as follows:

- HySTOR Node 1 – Hydrogen Loading/Absorption
- HySTOR Node 2 – Hydrogen Unloading/Desorption
- HIAB Node 1 – Hydrogen Generation to Boiler
- HIAB Node 2 – Hydrogen from HySTOR to Boiler
- HIAB Node 3 – Hydrogen Generation to HySTOR

Due to the wide theoretical scope of a HAZOP, and a requirement to manage the assessment within credible limits, a number of assumptions were made and shared with the team prior to the commencement of the study: the HAZOP study of the HySTOR and HIAB systems focused on representative modules, banks, and scenarios to assess risks while assuming all equivalent elements and standard operations were uniformly applicable. Simplified system nodes, worst-case scenarios, and specific assumptions, such as proper equipment functionality, operator compliance with SOPs, and worst-case ignition for hydrogen releases, guided the analysis, excluding certain deviations and considering the system's unmanned nature and site isolation.

In summary the findings from the HAZOP analysis did not identify anything of significant concern apart from minor considerations to be taken to design, together with some subsequent actions that would minimise associated risks. These were taken into consideration during the project's course and applied to the extent that it was possible prior to the project's premature termination. However, the nature of the assessment performed, as outlined in the NGN HAZ/9 Guidelines, implied the requirement for a subsequent completion of Layers of Protection Analysis (LOPA) in order to determine in greater detail, the extent to which hazardous scenarios would be managed. During the HAZOP sessions, a total of 16 distinct scenarios, were considered to represent a potential major accident hazard. In all cases the defining risk category was Safety (Worker), with no credible major impacts upon the environment or members of the public.

Further information on the HAZOP can be read in the published report [17].

18.6.3 LOPA

The objective of the LOPA workshop was to determine any residual risk of any scenario identified in the SHyGaN HAZOP as representing a potential major accident hazard. The definition of these hazards, as per the NGN FPSA Guidelines /3/ included any scenario with a consequence severity of S4, S5, or S6 (see **Error! Reference source not found.**) according t o the NGN consequence definitions. As no safety instrumented functions were included within the SHyGaN design, there was no pre-study requirement for the determination of a safety integrity level and instead, for each scenario, the residual risk was determined and compared with an appropriate risk target to determine whether further risk reduction measures would be required for ensuring that the effect would be ALARP (As Low As Reasonably Practicable). It has to be noted that the Enapter-supplied electrolysers, which were to form part of the HiAB sub-system within SHyGaN, did not include any safety integrity level-rated instrumented systems. There was however no intention for any changes to be made to the vendor packages within SHyGaN and, as such, the assessment was not intended to perform the determination of a safety integrity level for these functions. It instead focussed on identifying any risk gaps that may be needed to be accounted for by H2GO Power without making changes to vendor scope.

As mentioned, during the HAZOP sessions, 16 scenarios, were considered to represent a potential major accident hazard. Out of these 16, only 5 were deemed as suitable for assessment through a LOPA study. Of these scenarios, two were combined into a single LOPA, following discussions during the session. The remaining 11 major accident hazards were subject to an "as low a reasonably possible" discussion among the LOPA Team to determine if the scenario was to be managed to a level of minimal impact, considering the safeguarding elements identified during the HAZOP and the completion of actions generated in the earlier studies.

For further information on the LOPA outputs refer to the LOPA report [18].

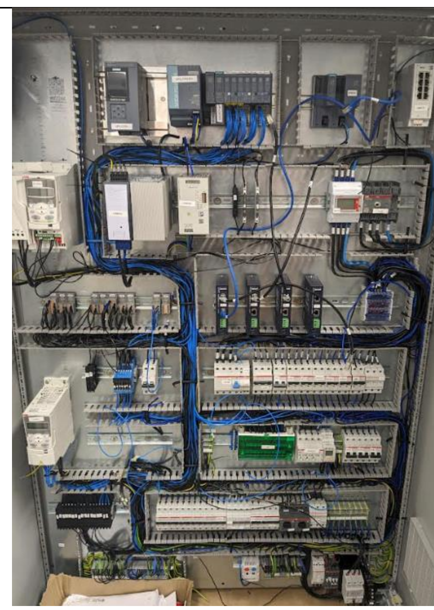
19.0 Status of system's build at termination

As mentioned, the project was terminated prematurely, at the stage when the majority of the design had been finalised and the system's manufacturing was to commence. As such, the assigned manufacturing partner did not undertake any activities, however as the containers were bespoke to the project's needs, the container supplier had already fabricated one of the units – i.e. work on the build had started but hadn't reached the status of being ready for delivery to the integrator. In addition to this, several key components of the system such as the hydrogen storage reactors, and the electrical enclosures were manufactured. Some photos from the components that were manufactured within the project's duration are provided below.

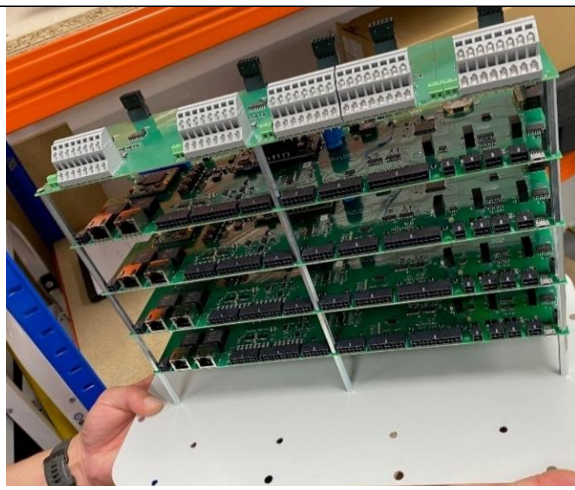
Electrical Enclosure during in-house manufacturing

Manufactured Electrical Enclosure

Electrical Enclosure during in-house manufacturing



Manufactured Electrical Enclosure

 Hydrogen Storage Container Customisation from Manufacturer	 Hydrogen Storage Container Customisation from Manufacturer
 Manufactured Control Boards	 HJB Modular Control Boards

20.0 Social value

Sustainability, social value and impact, are not an outcome of the work performed in projects such as SHyGaN, but the driving force for their implementation. Decarbonising industrial processes and increasing the applicability of hydrogen is substantial for facilitating the transition from the carbon-based economy to a sustainable future. The impact of such efforts can be shown by their alignment to the 17 Sustainable Development Goals (SDGs) adopted by the United Nations, where the UK plays a leading role in their fulfilment. The deployment a hydrogen-powered heating system as the one developed in this project would have a clear fit with several of the UN SDGs as follows:

- Good health and well-being from improved air quality (SDG 3 – Good health and well-being)
- Affordable and Clean Energy (SDG7)

- Decent Work and Economic Growth (SDG8)
- Introducing breakthrough technologies that push the envelope of innovation in the industry (SDG9 Industry, Innovation and Infrastructure)
- Decarbonising industrial processes and heat and reducing CO_2 emissions (SDG11, Sustainable Cities and Communities)
- Climate Action (SDG13)

Unfortunately, the abrupt ending of the project, and H2GO ceasing operations did not allow for the technology to reach its full potential and bring those benefits, however H2GO Power hopes that through dissemination in this report the further development of green hydrogen technologies could be indirectly supported. However, some social value had been realised through this project despite of being terminated before its scheduled end. These can be summarised as follows:

1. SHyGaN has brought social value by employing at H2GO Power over 10 highly skilled employees. All staff employed, as a direct or indirect result of the project were highly qualified personnel from several engineering disciplines.
2. The system showed high potential as an efficient hydrogen-powered heating solution which facilitate the decarbonisation of the overall heating sector which is considered as the most challenging to abate. Despite that the demonstration was not conducted, the potential has been evident through the work performed and H2GO Power firmly believes that similar efforts have a lot to gain from the insights obtained through SHyGaN. Affordable and efficient hydrogen-powered heating could significantly decarbonise several processes across the globe.
3. Hydrogen-powered heating is often encountered with scepticism due to safety concerns related to hydrogen storage and usage. As per the safety assessments that were performed within the project's duration, it became clear that materials-based hydrogen storage can minimise such concerns and make hydrogen deployable and safe. Despite that the demonstration had not taken place, the findings from the work performed prior to project closure could benefit policymaking regarding the usage of materials-based hydrogen storage as well as improve the public's perception on hydrogen.

21.0 Budgeted vs actual costs

SHyGaN was a project of a budget of around £3.8m, out of which the grant-funded component was of around £3.1m. Out of this budget a large proportion (around £1m), was on the purchase of associated materials and capital equipment necessary for the demonstrator, and a subcontractor budget of around £350k had been considered mainly for the on-site activities necessary for the integration of the unit at the NGN site. It is also important to state that all costs provided are VAT exclusive as VAT that could be recovered was not an eligible cost for the Industrial Hydrogen Accelerator programme, and as such no VAT was included in the proposal's budget.

As mentioned previously, unforeseen costs and issues encountered during implementation arose which were not anticipated at the project's budgeting at the proposal stage. However through the consortium's best efforts significant cost fluctuations were avoided. The most notable differences between the budgeted and actual costs, together with the related mitigation measures for associated risks are provided below:

- During the proposal stage, 1 container was considered for the system, which however following the first design iterations, became apparent that the system would be better to be developed using 2 separate containers for further flexibility on the design and mitigating design challenges. During the project's implementation and in collaboration with the consulting partner HSSMI, several container suppliers had been assessed and achieved the best possible value for money to mitigate this deviation.
- Despite that a subcontractor budget had been considered for ensuring the system's regulatory compliance with safety standards during the project's implementation it was observed that the safety requirements at a heavily regulated site as per NGN's were much higher than initially considered and further assessments would be necessary to be conducted by the independent third party that was contracted for these tasks (DNV). Having observed this at an early stage and through continuous engagement with DNV, the consortium utilised the least costly option that would not compromise safety compliance.
- Following several delays that were experienced during the system's design and MTC's confirmation that they couldn't manufacture both containers within the scheduled timeline, as mentioned above H2GO Power tendered for alternative manufacturers that could handle the systems build. After multiple discussions with potential manufacturers, H2GO Power was able to find a manufacturer that could manufacture both containers within a schedule that would be accepted by the Industrial Hydrogen Accelerator Funding Programme's restriction and within a tolerable cost. Specifically, it's worth mentioning that the received offer for both containers, was not higher than what had been budgeted by the manufacturing partner during the proposal stage for one container. As it can be understood, the corresponding budget for the new contractor was moved from the partner that was to undertake the manufacturing initially, to H2GO Power, in order to undertake the contractor's payment.
- The electrolysers considered during the proposal stage from Enapter were budgeted based on previous experience and costs of individual electrolysers that had been bought previously. However, as the project required an order of 40 electrolysers, a lower unit cost was able to be achieved through a larger bulk order that helped mitigate other cost-related risks.
- Related to the point above, the MHx to be used for hydrogen storage, and the associated reactors were budgeted from experience with lower volume procurement, where during SHyGaN as part of sourcing for the most suitable suppliers, H2GO Power was able to achieve a better unit costs compared to the value initially budgeted.
- As a general rule for the implementation of this project, and mainly after acknowledging the need for using two smaller containers instead of one larger one,

a strong focus was put on the procurement activities. As such, the market was evaluated to identify new and more cost-efficient suppliers, negotiation with existing suppliers, and with the support of the engineering team to work meticulously over reducing the system's balance of plant. These activities were also undertaken as a preparation for H2GO Power's commercial entry that was anticipated following the system's demonstration. Through these activities additional cost savings had been achieved that helped in their turn to mitigate cost-related risks.

- Despite that on-site design had not progressed through the approval process at the time of termination, estimates provided from the contractors that would undertake the necessary civils and mechanical work showed that cost savings by design could be achieved.

As shown above, several mitigating actions had been developed which allowed for a reasonable expenditure up to the time that the project had ended, considering the following:

i. the project was terminated at the 7th quarter of its lifetime with an end scheduled at the 10th quarter. The initial duration was of 24 months (8 quarters) but a further extension of 6 months was requested and signed off.
ii. most of the procurement-related expenses had been completed.
iii. Within the following 4-5 months it was anticipated that the manufacturing of both containers to be completed and the demonstration to commence, hence most of the resource intensive activities had already been completed.
iv. Moving the manufacturing budget from the initial manufacturing partner to the new contractor, together with the fact that the design activities were mostly complete, would not require any significant spend from the MTC partner for the rest of the project.
v. The most resource-intensive activities were expected to be the site preparation activities and the system's integration which hadn't taken place up to the point of termination.
vi. The project partner HSSMI as a consulting role in the project was not affected by the delays encountered on its work and was expected to deliver all associated work by the end of Q8.
vii. Baxi's main budgeted activities were up to the preparation of the boiler and their involvement on the system's design, thus most of their scheduled work had been completed and their role from that point would involve support during the demonstration. Specifically the budgeted activities from Baxi's side involved: i) their active participation and guidance in the system's design to ensure that the boiler could be properly integrated to the system, ii) the preparation and of handling the boiler for integration (including the drafting of a demonstration agreement, training to H2GO personnel and internally), and iii) being available to support any issues encountered during the physical demonstration. As the project was terminated at the time that system build was to start, Baxi's involvement from that point would be solely related to providing any support on the physical demonstration.

The project's expenses to the point of termination was £2,236,247.85 which is around 72% of the total budget, and considering the above points, the expenditure had been within the consortium's expectations.

22.0 Forecasted technology costs

Forecasted costs for the core solid state storage technology have been discussed previously in in section 7.2. When considering the impact on the LCOH for the SHyGaN system, the forecasted costs for the H2GO storage should consider the cost predictions for the red data points in Figure 14 which include efficiency gains from heat recuperation. In addition, for the SHyGaN application the HiAB system needs to be considered along with the HySTOR system. It is important to note that the SHyGaN solution requires no design amendments to the H2GO storage (HySTOR) design, as in the scale up the ability has been considered to integrate with external sources that can provide the ability to heat or cool the system. Therefore LCOH would be calculated from the additional costs required from the electrolysis and the hydrogen boiler.

The most significant cost for the HiAB functionality is the inclusion of electrolysis and this is where the majority of the impact to the LCOH would be experienced. The hydrogen boiler would have a negligible impact on the overall system cost, as the associated costs would not be expected to be too far removed from a Baxi natural gas boiler of a similar type (in the region of a few thousand pounds). This estimate although comes with the caveat that the hydrogen boiler market requires like for like market conditions with the natural gas boiler market. As the addressable market conditions are currently uncertain, the hydrogen boiler's end price could vary. Thus, when considering scaling costs it makes the most sense to look at the HiAB and HySTOR as follows:

- Water cooled electrolysis
- Hydrogen Boiler plus balance of plant
- H2GO solid state storage.

AEM water cooled electrolysers are commercially available[1], and therefore in scaling it would be prudent to take advantage of the already integrated systems that are on their way to achieving cost competitiveness in industrial applications; it is important to note here that the business model of H2GO was not to be a technology integrator, but a technology developer, hence the procurement of an already integrated electrolyser system would be the desired approach, However in a nascent market and for demonstrating a first of a kind innovation, the integration in the SHyGaN project was necessary.

Therefore, at a commercialisation stage, H2GO would at most focus on the integration between technologies, and it would be envisaged that the boiler and it's minimal BoP would be containerised separately into a small enclosure to link up a commercial off the shelf

[1] https://www.enapter.com/aem-electrolysers/

electrolyser and the H2GO storage, to make the solution a reality. The additional cost for the boiler capability would not impact the costs significantly as it's a small proportion when compared with the electrolysis and storage costs.

Forecasted costs for the system would be as follows:

Table 15. SHyGaN system costs

Product	Current costs (£/kgH2)	2030 costs (£/kgH2)
HySTOR[a]	1.17	0.34
Electrolysis [19]	5.79	0.96
Boiler plus BoP[b]	-	-
Total LCOS	6.96	1.3

[a] See section 7.2.

[b] The Baxi boiler does not currently see sufficient demand to warrant setting up a production line and commercialised costs at this stage are unknown. However as discussed above this can be expected to be at a similar range of a natural gas boiler of the same type. Having therefore, a small proportion of the finalised system and a negligible extent on the LOCS.

23.0 Scaling up and replicability considerations

The system had been inherently designed to be flexible and adaptable to several case studies beyond heating. Through the modular design approach and separating hydrogen storage into an individual container the SHyGaN concept can be extended into almost any use case that could use H2GO's hydrogen storage technology together with other hydrogen assets for production (e.g. electrolysers, steam methane reforming etc.), or utilisation (e.g. hydrogen fuel cells, hydrogen boiler, direct hydrogen supply etc). Therefore, the general concept that was to be demonstrated through SHyGaN could be applicable to any use case that would require compact, high density and safe hydrogen storage even for challenging uses such as heating. This would be due to proving that the H2GO hydrogen storage technology could be compliant and fully operational under strict safety standards, and that the technology could be perfectly integrated to other assets. This could be further enhanced through the integration of H2GO's HyAI software platform that and its unique smart management approach. With HyAI being hardware agnostic, this integration could be applicable to almost any alternative configuration.

It should also be considered that the modular design and approach that was followed for all main system assets (e.g. using a series of stackable hydrogen reactors and electrolysers to match the system's hydrogen demand), allowed for a flexible system to support any customer demand; by increasing the number of reactors and associated assets, or containers in the case of much higher demands. In the case that the system could be demonstrated, the design of the hydrogen storage container, could be replicated following enhancements from lessons learnt during the demonstration and be able to serve higher or lower demands thanks to this modularity. Therefore, the specific system (or similar configurations) could be used for any site that generates renewable energy or hydrogen directly, and as such be replicated across several sectors assisting the acceleration of decarbonisation.

23.1 Overview of SHyGaN scaling up activities

Despite that the system not progressing to build, the engineering work performed and assessments such as HAZOPs and LOPA demonstrated that the system was viable from a regulatory, safety and performance stand point and exhibited expected benefits that were identified in this report under the benefits of the core solid state storage technology. Further development of the technology could contribute to the UK Government's commitment to net zero carbon emissions by 2050. As H2GO were targeting through this project to mature the storage technology to enter the market, an entire work package, led by HSSMI, had been focused on defining the product and H2GO scale up strategy for placing a product on the market and begin system manufacturing for commercial orders in higher volumes. The work performed covered a broad range of considerations, including sourcing requirements, design for manufacturing, definition of processes and requirements. HSSMI within the SHyGaN project was tasked with supporting H2GO Power into defining their manufacturing strategy and taking the necessary considerations towards the scale up journey that was anticipated to begin during the demonstration of the SHyGaN system. Together with this, HSSMI supported H2GO on tasks related to the system's design and manufacture by providing their expertise and knowledge. Before proceeding further into this section, a summary of the main activities undertaken in the SHyGaN project by HSSMI are presented:

Design for Manufacture (DfM)
Considerations and assessments of the system's key components at commercial volumes was an ongoing key activity within the SHyGaN project. HSSMI worked closely with H2GO and the MTC teams in the design of the hydrogen storage reactors, reactor stack frame and related system components. HSSMI also worked on a modular stack design that would be suitable for future high volume manufacturing capability and suitable for use in a proposed reactor filling facility. This work resulted in a set of approaches and features that would significantly improve the volume manufacturability of the system's containers.

Manufacturing strategy
HSSMI's main tasks included determining an effective manufacturing strategy for the SHyGaN system which could enable a wider roll-out of the technology. This work included the definition of a high-volume manufacturing process, a supply chain analysis for the key system components and future opportunities to improve the design for manufacture characteristics.

Build book
To track and implement the SHyGaN container build processes, HSSMI proposed the development of a system “build book”. The key purpose of this document was to record all activities pertaining to the manufacturing and assembly of the SHyGaN units. This document provided a comprehensive guide to the whole build process and would enable H2GO to manufacture subsequent iterations of the system’s containers. Within the project’s lifetime the build book for the HySTOR container was completed and a first draft of a build book for the HiAB container had been generated.

Quality Management System (QMS) activities
To support H2GO Power in their manufacturing scale up activities, HSSMI emphasised to H2GO the importance of having a process in place that would ensure delivering high quality products to their customers. To achieve this, the design and implementation of a rigorous quality management system (QMS) would be substantial for H2GO Power not only to deliver high-quality products but also to facilitate acquisition of certifications such as ISO 9001. The first workshop towards setting the basis for a robust quality management system was delivered in Q5 of the SHyGaN project. This was a one-day workshop involving senior management and key H2GO Power employees. The key aim of the workshop was to present the importance of implementing a quality management system and the method of achieving certification. A second one-day workshop was delivered in Q6 of the SHyGaN project which was focused on the development of H2GO Power’s core technologies – the hydrogen storage and HyAI platform. During the workshop, a quality management system roadmap and ambitions were defined in order to be integrated into the product development activities for the respective products. These results were preliminary and served for defining initial ambitions and actions to be taken towards the set-up of a quality management system. A third workshop was planned to take place, but as the project was prematurely terminated, all activities related to the establishment of a quality management system ended.

23.2 Manufacturing processes

In this sub-section a reference is made to some of the most significant processes for the manufacturing of the system and provides some considerations on their potential replicability and enhancement at commercial scale.

23.2.1 Electrolyser installation

As stated, for the prototype system, stackable and modular AEM electrolysers developed by Enapter were considered. For the desired system scale that would correspond to 8 racks of 5 individual electrolysers each, and at each rack one drier would be connected in series, together with all the piping and components associated with it. Each rack was expected to be linked in series to provide the required hydrogen output. The size of each rack may vary depending on the desired supply and system sizing, justifying the selection of modular electrolysers. The process is simple and required only the testing of the electrolysers and their connection to H_2 and O_2 pipes, water tubes, and any associated electrical and electronic components.

23.2.2 Hydrogen boiler installation

For the project’s needs a prototype hydrogen boiler developed by Baxi was to be applied to the system. This model was the H2 Quinta, which was based on an existing 45 kW natural gas Quinta boiler that had been developed by Baxi and held a CE-mark. The boiler had also been tested previously at a Kiwa test facility, demonstrating that it is suitable for a trial. The connection of the boiler is also a simple process as it’s a ready-made product that needs the correct connections (e.g. gas supply, flue etc). Also, for a higher heat output, Baxi has previously designed modular heating systems by placing boilers in cascade, which could also align with the flexible and modular concept of SHyGaN. This was a concept that H2GO Power considered exploring further after the demonstration.

23.2.3 Hydrogen Storage container (HySTOR)

The hydrogen storage container was to include 21 reactors filled with hydrogen storage materials (MHx) and assembled into a 3x7 stack. For the assembly of the hydrogen storage area within the container three main operations have been defined: i) reactor filling, ii) reactor activation and conditioning, iii) reactor stack assembly. For developing an initial bill of processes for the specific activities the following assumptions had been made:

1. The reactors are sourced from third-party suppliers and assembled.
2. The filling operation is carried out using a glovebox rather than an automated filling system.
3. No pipe cutting or welding operations have been considered - all metal pipes and parts are cut to length prior to the assembly operations
4. Due to the weight of the filled reactors (200 kg approx.) lifting equipment is used for the stack build.

The above were suitable for the needs of prototype manufacturing but at commercial scale in-house reactor manufacturing could be considered depending on the evolution of H2GO Power’s manufacturing strategy. In a similar fashion, depending on the definition of a final manufacturing strategy pipe cutting and welding should also be defined. However, the transition from manual filling through a glovebox should change with an automated filling system as it would undoubtedly reduce times and associated costs during reactor filling. As such, with the containers for the prototype being bespoke, following the demonstration and having defined a final manufacturing design, the process would become more standardised allowing for mass production and replication. Towards this end, a build book was being developed and served as a document that tracked in a standardised way all the necessary manufacturing activities and processes, and was considered as an essential step towards manufacturing readiness. By having a complete build book, a manufacturer can understand the build process better, allowing outsourcing to be more efficient, to disseminate clear requirements from what is expected, especially with regards to quality and safety and in compliance with any relevant standards. Also creating a standardised build book at a pilot stage allows for areas of inefficiency to be highlighted and to identify improvement areas where changes are required for reasons such as reducing costs, build times, bottle necks and generally data points for choosing areas to optimise for scale up and commercialisation.

At termination the build book was a working draft that identified steps throughout the build. The draft would have been refined during the build phase. The build book was separated into the different subsystems of the product and covered:

- Reactor filling
- Reactor activation
- Stack frame build
- Hydrogen panel builds (RHS, roof, LHS and panel integrations)
- Coolant system
- Electrical cabinets

23.2.4 Reactor filling

Within the project's duration as mentioned, reactor filling was manual and conducted using a glove box. The associated bill of processes is provided in Figure 71: Reactor Filling Bill of Processes for more clarity. The operations do not only include reactor filling but also glovebox setup and cleaning, etc.

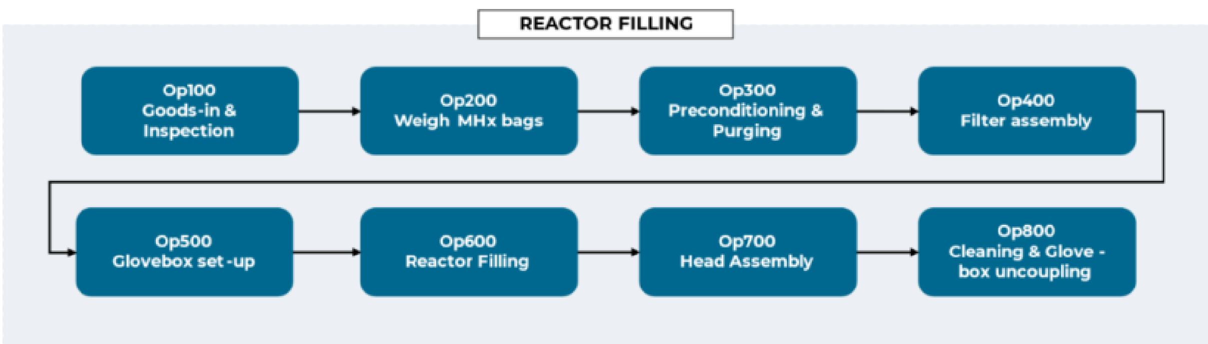


Figure 71: Reactor Filling Bill of Processes

As shown this process was simple, but it was time consuming. During a prototype manufacturing as in the case of SHyGaN, it would not be feasible to conduct an automated process as the associated costs would be much higher. However upon commercialisation, the introduction of automatic filling would significantly reduce costs and a standardisation of the process.

23.2.5 Reactor activation and conditioning

MHx materials store hydrogen in solid state through absorption, and hydrogen is released through the reverse process - desorption. This absorption - desorption cycle requires cooling and heating of the storage materials for chemically bonding or releasing hydrogen respectively. The first absorption - desorption cycle is called activation and during the process the reactors are filled with hydrogen. Once all hydrogen had been adsorbed, the material would be heated to start hydrogen release. The associated bill of processes is shown in Figure 72: Reactor Activation and Conditioning Bill of Processes.

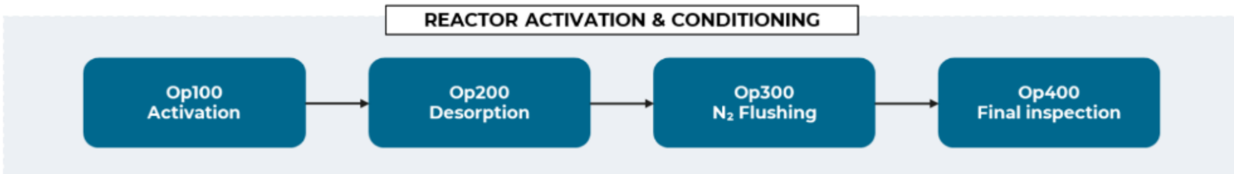


Figure 72: Reactor Activation and Conditioning Bill of Processes

This process is not demanding provided that suitable equipment is in place and could easily be further standardised and streamlined with refined production lines and quality control processes.

23.2.6 Stack build

As stated, the hydrogen storage container was to include 21 reactors mounted onto a 3 (L) X 7 (H) stack frame. Following the activation of all reactors, they were to be assembled into the stack frame and subsequently fitted into the container. The bill of processes in Figure 73: Stack Build Bill of Processes shows the operations necessary for building the stack.

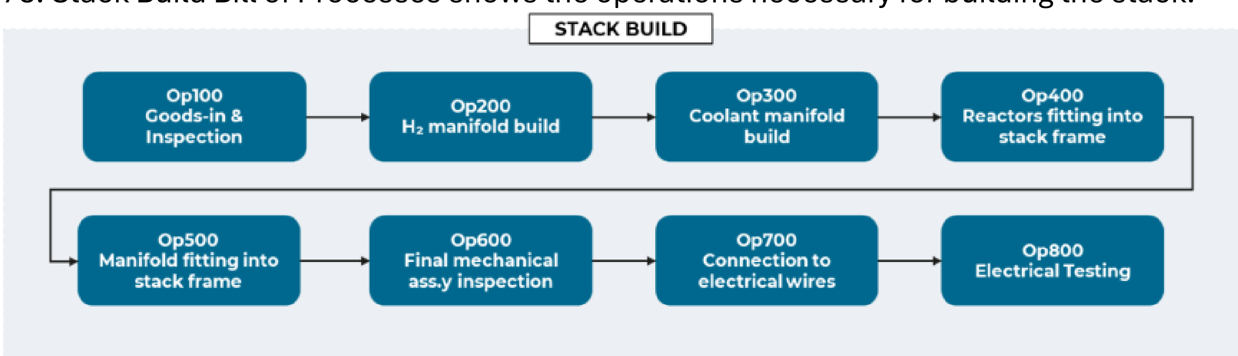


Figure 73: Stack Build Bill of Processes

This corresponds to the latest stack frame concept that was used within the SHyGaN project. However as shown below in H2GO Power's design for manufacturing considerations, areas of improvement that would further streamline operations at commercial manufacturing had been identified.

23.2.7 Electrical cabinets

The process was straightforward is it mainly involved the build of the mechanical cabinet, cable kitting, wiring and electrical testing and as such it would be easy to replicate. For the project's needs, the cabinets were manufactured in-house to reduce costs and to also have control over the overall configuration as it was a continuously evolving concept. Should the technology had been commercialised the probability of outsourcing them is high as it can be provided easily by many manufacturers.

23.2.8 Container build

Once all major system components were to be sub-assembled, they were expected to undergo a final assembly in the respective containers and integrated, to result in the end product. For the case of the container hosting the electrolysers and the boiler, the build would mainly involve the installation of the electrical cabinet, the electrolyser stack, and the boiler, together with the necessary ventilation, hydraulic, and electrical configurations and connections. In the case of the hydrogen storage container the reactor stack would be integrated followed by supporting balance of plant. Overall, the process for both containers should be a standard system integration process and upon conducting it on a prototype it would be easy to be replicated. For facilitating this as mentioned, a build book was being developed throughout the project.

23.2.9 Container connection

As expected, both containers would require direct connection for the system operation. The boiler was to be connected with the electrolysers and the hydrogen storage container. Designed to be a dual operation system, it would have the capability to fuel the boiler either directly through the electrolysers, or through the hydrogen storage container. The process would involve the necessary pipe connections between i) the containers for transferring hydrogen to the hydrogen storage unit, ii) the electrolysers and the boiler, and iii) the hydrogen storage unit and the boiler. Following this, the integration of all electronic components is required for operation.

23.2.10 Final factory acceptance testing

As the proposed system was to be a first of a kind, it would be imperative to carry out a series of tests, before the installation of the system at the NGN site. Attention would focus on the testing of the connections between the two containers, in order to determine the necessary protocols for the system's seamless operation. Therefore, it would be crucial ensuring that all connections between the two containers are secure. Once both containers are connected, the unit requires testing as a whole to check all the electrical, hydraulic and gas connections for integrity. Should the project had continued H2GO Power would have collected all the lessons learnt during that testing and standardised the process to facilitate scale up.

23.3 Design for manufacturing considerations

During the project some Design for Manufacture (DfM) considerations had been taken to refine the design post-project, with the objective of reducing manufacturing costs and further improving the end product. As no product was manufactured within the project, these considerations were partially assessed. The main insights obtained per system component are provided below.

23.3.1 Reactor stack frame and manifolds

1. The stack frame material that was to be used in the project was stainless steel. However, investigating other materials such as powder coated steel to potentially reduce costs during the welding process were considered.
2. The stack frame could be integrated with the coolant manifold frame to further reinforce it, as the weight of all reactors would exceed 4 tonnes.

3. Securing and reinforcing the stack frame to both the bottom and the side of the container, would minimise any movement during transport but also further reinforcing the stack itself.
4. An additional space should be created at the bottom of the stack frame (120mm minimum) to facilitate lifting by a forklift. In this sense, it could be beneficial to consider reducing the reactors to 18 (eliminating one row of 3) or more tightly packing them to maintain the same storage capacity.
5. Pipes' length and diameter should be standardised in the manifold to allow for pre-cut supply, including cleaning prior to assembly.
6. For the external parts of the water-glycol pipes, it would be beneficial to switch from steel to copper and plastic for achieving overall weight and cost reduction and allowing for plug-in fittings.
7. Pipe dimensions in manifolds should be standardised, to allow for pre-cut/NC-formed pipes to be externally procured including cleaning before assembly.
8. The stack frame should follow a modular design approach, by manufacturing sub-frames which could then be assembled. This would reduce manufacturing time and make the overall process more streamlined. Further details on this are provided on a separate sub-section below.

23.3.2 Storage reactors

1. Overall reactor size could be increased by considering a longer vessel. This would allow for increased storage capacity with near minimal effect on the associated BoP.
2. In a scaled-up manufacturing facility an automated reactor filling system should be applied, for improving the filling process.

23.3.3 Hydrogen storage container

1. The storage frame could be strengthened to allow for the external fitment of reactors in vertical orientation in sub assembly area.
2. The storage frame could be fitted to a trunnion type fixture and be assembled with the associated pipework, manifolds and electrical looms prior to the installation into the container.
3. The BoP room could be redesigned so that the majority of the components built externally, could be loaded to the room for final connection. The usage of pre-assembled studs in cabinets would also be beneficial by assisting the fitment of heavy sub-assemblies.
4. The electrical cabinets could be built externally while a platen should also be assessed for improving the cabinets' build. Pre-assembled studs in the cabinet would also assist the fitment of the heavy sub-assemblies

23.4 Alternative electrolyser options

23.4.1 Sourcing options

For the demonstration system, AEM electrolysers manufactured by Enapter were considered due to their modularity that supports the flexibility of design that H2GO had envisioned, as well as being readily available. For the system's manufacturing strategy regarding on how to receive, store and assemble the electrolysers into the system three scenarios had been considered:

Scenario 1: The modular electrolysers to be directly sourced from the supplier (Enapter). H2GO would then receive, store and assemble the electrolysers in a separate assembly station putting 5 electrolysers per rack. For a 1MWh storage system, 5 racks per container would be required.

Scenario 2: In the second scenario, H2GO would receive completed racks from the supplier and then assemble the received racks into the finished container. In this scenario, Enapter may need to send the electrolysers to one of their suppliers for assembling them into racks before shipment to H2GO.

Scenario 3: The third option would be to source additional electrolyser suppliers that also meet the specified requirements.

For the first two scenarios a Strengths/Weaknesses analysis was conducted, and its outcomes are in Table 16: Strengths/Weaknesses Analysis Between Sourcing Scenarios 1 and 2. For the third scenario as suppliers and their attributes vary an individual assessment was held and presented as a sub-section.

Table 16: Strengths/Weaknesses Analysis Between Sourcing Scenarios 1 and 2

Weaknesses	Strengths
Scenario 1	
✗ Larger manufacturing footprint (sub-assembly stations) ✗ Increased material handling need ✗ Complex logistics due to increased parts requiring storage and handling ✗ Increased BOM ✗ Testing of the completed rack would be required	✓ Increased control over the design

Scenario 2	
✗ Completed electrolyser racks could be more complex in terms of logistics (bigger and heavier) ✗ In the longer term could be more expensive than in-house manufacturing option	✓ Reduced manufacturing and logistics operations required (less frequency) ✓ Lower initial CAPEX investment

As shown above, the second scenario should be more appropriate upon an initial scale-up as it would require a lower investment, and the overall logistics and material handling would be less complex. However, in case that a commercial launch together with large volume production, the first scenario could be explored as in-house manufacturing at large volumes can usually reduce further costs and allow for increased control over the design.

23.4.2 Alternative electrolyser manufacturers

Of the currently available electrolyser technologies, conventional Alkaline, AEM, PEM, and Solid Oxide technologies are considered by manufacturers as the most promising options to produce 'green' hydrogen. By evaluating these technologies, the following insights have been gained:

1. Alkaline and AEM electrolysers are currently the most cost-effective
2. The key cost drivers include stacks, power electronics, gas conditioning and balance of plant
3. PEM are the most expensive electrolysers where key stack components, as the bipolar plates are made from expensive materials
4. For Alkaline Electrolysers, the diaphragm and the electrode are the most expensive components.

A list of the most significant suppliers and their corresponding hydrogen production rates are provided in Table 17: Main Electrolyser Suppliers and Corresponding Metrics, while the main findings and suitability to the SHyGaN concept for each manufacturer follow the table. These manufacturers have been anonymised for the scope of this report.

Table 17: Main Electrolyser Suppliers and Corresponding Metrics

No.	Manufacturer	Country	Electrolyser Type	Hydrogen Production Rate (Nm^3/h)
1	Manufacturer 1	Germany	AEM	0.5
2	Manufacturer 2	UK	Solid Oxide & Alkaline	~ 36

3	Manufacturer 3	Germany	Alkaline	750
4	Manufacturer 4	France	Alkaline	0.4 ~ 10
5	Manufacturer 5	Denmark	Alkaline	800
6	Manufacturer 6	Norway	PEM	0.27 ~ 1.05
7	Manufacturer 7	USA	Solid Oxide	478
8	Manufacturer 8	USA & India	PEM	~ 66 (6 kg/h)
9	Manufacturer 9	USA	PEM	200
10	Manufacturer 10	China	PEM & Alkaline	200
11	Manufacturer 11	China	Alkaline	800

23.4.2.1 Manufacturer 1

Their main strengths are their scalability and modularity which fits perfectly with the SHyGaN concept, and the overall modular philosophy that H2GO Power was following, making them also ideal for being linked with multiple renewable energy sources. Furthermore, they are considered having low maintenance and installation requirements. They use cost-efficient materials and release high purity hydrogen at high efficiency. The only downside that was observed, is that they require more pipe joints/connectors compared to other types, which may make servicing difficult and increases integration costs. The above, were among the key considerations that were taken for selecting electrolysers for the project.

23.4.2.2 Manufacturer 2

They are known for their high performance and longevity, while their unique design allows for a simplified maintenance. Also, their differential pressure operation can lead to decreased operational costs and increased safety. However, compared to the ones offered by Manufacturer 1 they are less modular on production rate and size, which could limit their flexibility. This made them unappealing for the prototype, but Manufacturer 2 could have been considered as a commercial option depending on the use case scale and characteristics.

23.4.2.3 Manufacturer 3

These should be used at larger scales and industrial applications due to their high hydrogen production rate and flexible resource usage (they can utilise industrial waste heat to reduce electricity demand, and steam instead of liquid water for hydrogen production).

Furthermore, they have a low environmental footprint as they do not use PGM (Platinum Group Materials) like conventional electrolysers. However, despite these strong points, they are much less compact and modular compared to the ones offered by Manufacturer 1 in both terms of production rate and size. In this sense, they could not be applicable for a pilot demonstration as they do not fit the modular design philosophy. Nevertheless, they could be a good fit for a similar configuration to SHyGaN, but they offer limited flexibility and modularity.

23.4.2.4 Manufacturer 4

These electrolysers, have a compact design which can allow for increased flexibility, their supervision and maintenance can be remote and they have shown a good cost efficiency (5.5 kWh to produce 1 m^3 of hydrogen). Also, the technology is completely plug and play, making it very much fitting with the SHyGaN concept. As Manufacturer 4 offers one of the widest ranges in hydrogen production (from 0.4 to 800 Nm3/h) they could be highly suitable for the SHyGaN modular concept. However, their significant downside is that their output pressure is comparatively low (1-8 barg) which could not satisfy potential hydrogen flow demands. Besides that, they can be a very promising alternative to Manufacturer 1 should the output pressure specifications be aligned with a system's energy supply needs.

23.4.2.5 Manufacturer 5

These electrolysers are modular and scalable, but as they come in larger sizes, they are less compact compared to the ones offered by Manufacturer 1 in terms of production rate and size. On the other hand, due to their high efficiency (they are considered as the most efficient alkaline electrolyser in the market), and that they have been designed to accommodate the input fluctuations that come with renewable energy sources, they could be considered for projects of a much larger scale and energy demand. However, due to their large sizes they would not be as flexible as in the way that the SHyGaN concept was envisaged.

23.4.2.6 Manufacturer 6

These electrolysers are of the PEM (Proton Exchange Membrane) technology, that gives them several advantages (e.g. low maintenance needs, fast response time, and flexibility on production rates), but they are much more expensive than alkaline or AEM electrolysers. Having also the feature of automatic fault detection and system depressurisation, they can be a very suitable option for demanding projects. Nevertheless, as of now that the hydrogen market is still at a nascent stage, the cost factor makes them unsuitable for being used in such a system. Another factor that makes them not that suitable, is that PEM electrolysers are still a developing technology, which would result in several uncertainties during product development. Should the market be more developed their suitability could be re-examined.

23.4.2.7 Manufacturer 7

These utilise solid oxide technology achieving high temperature electrolysis, that can split steam molecules with less energy and leaving no oxygen in the hydrogen stream (eliminating the need for deoxygenation units). This makes them a cost-effective choice, and their low reliance on rare earth materials, brings a competitive environmental footprint. Their downside although, regarding their compatibility to the SHyGaN concept, is that despite being modular, their sizes are for large applications, making them less compact than electrolysers such as the ones offered by Manufacturer 1. Thus, as in similar cases, these could be suitable for an industrial application of a much larger scale and energy demand.

23.4.2.8 Manufacturer 8

Like the electrolysers offered by Manufacturer 6, these electrolysers use the PEM technology making them competitive in terms of efficiency. Hydrogen production can be customised to meet varying purity and moisture content requirements, while due to its dynamic operation it can respond quickly to intermittent renewable energy resources. Their advanced monitoring tools can also secure seamless operation, but similarly to the ones offered by Manufacturer 6, they are of higher cost and not appealing for the current hydrogen market conditions. Lastly electrolysers manufactured by Manufacturer 8 as in other cases, are of larger sizes and thus not that flexible and suitable for the SHyGaN concept.

23.4.2.9 Manufacturer 9 & Manufacturer 10

Another PEM electrolyser. The same conclusions as with the electrolysers offered by Manufacturer 8 apply.

23.4.2.10 Manufacturer 11

A strong advantage for these is their highly automated configuration. They demonstrate a three-level control management featuring production management, DCS monitoring, PLC equipment management, chain alarm and automation control to improve efficiency, together with an automatic shutdown capability. Their alkaline bath design effectively reduces unit system cost of hydrogen production. Regardless of the above, their size is too large, making them suitable only for very large projects, and as in other cases they lack the flexibility that is one of the main value propositions of SHyGaN.

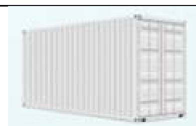
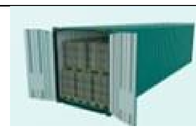
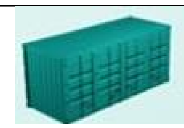
23.4.3 Conclusion

The majority of the above electrolysers are of a relatively large size for a prototype while they also lack the flexibility and modularity envisaged for SHyGaN. This feature was highly important for the project as it could ensure undisrupted operations. If for example an electrolyser breaks down, by isolating the faulty electrolyser the system could continue operating and allow to better understand the system during demonstration. Some of the options however, due to their performance, could be considered as an alternative configuration for large-scale projects following a cost-benefit analysis, and assessment of the specific project requirements. In principle, as it has been proven through H2GO Power's design, the storage technology could be highly flexible for almost any scale and configuration and depending on the use cases' requirements several configurations could be examined. It is although important to consider that as the market is still immature, associated prices and costs would be expected to change significantly should the market flourish, and any assessment of technologies etc should be done from scratch.

23.5 Container considerations

The diversification of the supply chain, and especially by identifying alternative manufacturers/providers is essential for a scale-up to be resilient towards commercialisation. In a similar fashion with the electrolysers, the relevant options for containers upon commercialisation had been assessed. This considered the basic requirements that would need to be fulfilled for the specific system, which include: i) Capability of transportation by sea, road, and/or rail freight, ii) Resilient against negative effects from the external environment (e.g. corrosion), iii) Capability of enhanced ventilation within the container. An overview of the available different container types and standard sizes is in Table 18: Overview of container types and standard sizes:

Table 18: Overview of container types and standard sizes

 **Dry Containers**	 **High Cube Containers**	 **Pallet Wide Containers**	 **Double Door Containers**	 **Side Door Containers**
20 ft container 7.8ft W x 7.9ft H Length: 20ft – internal 19.4ft Tare weight: 2,300kg Payload capacity: 25 tn Cubic capacity: 33.2 m^3	**20 ft container** 7.7ft W x 8.9ft H Length: 20ft – internal 19.4ft Tare weight: 2,315kg Payload capacity: 28.16 tn Cubic capacity: 37.28 m^3	**20 ft container** 8ft W x 7.84ft H Length: 20ft – internal 19.32ft Tare weight: 2,400kg Payload capacity: 28.08 tn Cubic capacity: 34.34 m^3	**20 ft container** 7.7ft W x 7.7ft H Length: 20ft – internal 19.4ft Tare weight: 2,700kg Payload capacity: 27.780 tn Cubic capacity: 33 m^3	**20 ft container** 7.7ft W x 8.9ft H Length: 20ft – internal 19.4ft Tare weight: 2,315kg Payload capacity: 28.16 tn Cubic capacity: 37.28 m^3
40ft container 7.8ft W x 7.9ft H Length: 40ft – internal 39.5ft Tare weight: 3,750kg Payload capacity: 27.6 tn Cubic capacity: 67.7 m^3	**40ft container** 7.8ft W x 8.1ft H Length: 40ft – internal 39.5ft Tare weight: 3,900kg Payload capacity: 28.6 tn Cubic capacity: 76.3 m^3	**40ft container** 8ft W x 7.84ft H Length: 40ft – internal 39.5ft Tare weight: 3,800kg Payload capacity: 26.68 tn Cubic capacity: 69.86 m^3	**40ft container** 7.4ft W x 7.5ft H Length: 40ft – internal 39.5ft Tare weight: 4,700kg Payload capacity: 27.3 tn Cubic capacity: 64 m^3	**40ft container** 7.8ft W x 8.1ft H Length: 40ft – internal 39.5ft Tare weight: 3,900kg Payload capacity: 28.6 tn Cubic capacity: 76.3 m^3
	45ft container 7.8ft W x 8.1ft H Length: 45ft – internal 44.5ft Tare weight: 4,800kg	**45ft HC container** 7.9ft W x 8.85ft H Length: 45ft – internal 44.5ft Tare weight: 4,280kg	**40ft HC container** 7.8ft W x 8.9ft H Length: 40ft – internal 39.5ft Tare weight: 5,200kg	**45ft HC container** 7.8ft W x 8.1ft H Length: 45ft – internal 44.5ft Tare weight: 4,800kg

	Payload capacity: 27.7 tn Cubic capacity: 86 m^3	Payload capacity: 29.72 tn Cubic capacity: 86.2 m^3	Payload capacity: 28.6 tn Cubic capacity: 76.3 m^3	Payload capacity: 27.7 tn Cubic capacity: 86 m^3

As it can be seen above the specifications of containers do not vary significantly among the available container types, and hence the final selection would be mainly dependent on agreements and negotiations with the suppliers regarding costs, supply etc.

The system considered for the demonstration would require the following sizes of containers:

1. A 12ft container for hydrogen storage
2. A 25ft container for encompassing the electrolysers and the boiler

None of these containers are of a standard size, so the approach taken during the project, was to modify a standard 20ft and 40ft containers respectively by modifying it to the required size and customising it according to the system's requirements (e.g. the internal partition into areas, addition of louvre doors for ventilation, etc). Through this approach H2GO Power maximised the density of the storage efficiency in the hydrogen storage efficiency and the packing efficiency of the electrolysers and boiler in the other container. By using non-standardised container sizes, the application of a flat rack (platforms used for transporting cargo of unique size) would be required, which in turn would require the following to be considered:

1. **Cost**: Using "flat racks" when shipping non-standard containers increases the cost by only a few hundred pounds, which does not significantly affect shipping costs. However, sea freight costs may increase (See point 3)
2. **Time**: No major impact on lead times if using "flat racks"
3. **Sea freight:** Non-standard container walls might be higher than the walls of the "flat rack", resulting in stacking constraints. In this scenario the container would need to be placed in a separate area that could increase associated costs.
4. **Regulations compliance**: Certification of non-standard containers may add extra time and costs.

As for the demonstration's needs the system was required to be bespoke, H2GO Power proceeded through this approach which also provided control over the design. For commercial orders, a specific agreement with the container manufacturer could take place depending on the volume of orders to reduce costs but also standardise the system. However at commercial scale, considering that the system capacity would be much higher, it would be much likely to proceed with standardised container sizes so that the system could be more compatible with requirements applicable to the market.

23.6 Manufacturing facility considerations

As part of the work conducted in SHyGaN, some considerations for scaling up to a large-scale manufacturing facility were made. This work was not concluded as the project was terminated, but the main insights acquired are presented within this chapter. The assumptions for these considerations were made by assessing two different scenarios:

1. A facility where H2GO would manufacture all components including the electrical cabinets, wiring looms, BoP room, reactor coolant system, etc. All these components would be then assembled within the containerised solution. This option would allow for control over all components, but it would be more difficult to manage due to the need of overseeing several processes and differentiated teams.
2. To follow a subassembly approach where all necessary components would be externally manufactured and then assembled internally. In this case, control over the IP of all critical components (e.g. reactors) would be imperative, but the non-IP critical components could be completely outsourced. This approach would be less complex to manage and potentially ensure higher quality due to the involvement of selected manufacturers.

These two scenarios represent a simplified categorisation considering that there could be several possibilities between these two, depending on the final decision of what would be manufactured in-house and what would be outsourced. This decision could occur following the manufacturing of the pilot system, together with the demand for products, investment to be raised, etc. This decision should also be dependent on the IP-critical processes for the manufacturing of specific components, if any specific IP protection measures could be applied when outsourcing manufacturing, etc. In general, the more components to be made in-house the higher the investment would be, while in a similar fashion, the more components to be outsourced, the higher the manufacturing costs would be.

Regardless of the selection of process(es) to be outsourced, reactor-related manufacturing activities should be clearly separated at a different space than the manufacturing of other components and container assembly, due to the different requirements that the reactors have. Specifically, reactor manufacturing would require a clean environment that would allow the proper handling of the powder-like hydrogen storage materials, which are being filled within the reactors. Furthermore, the reactors were the main technology component, and thus their production volumes would be much higher than of any auxiliary components, while also due to the IP-sensitive nature, access should be limited. Moreover, automated reactor filling systems should be explored to automate the process and allow producing reactors at commercial demand.

On the other hand, the manufacturing of auxiliary components and their integration into the container were not expected to be manufactured at such high volumes and a clean environment would not be necessary. However, depending on the amount of outsourced activities, relevant storage spaces would need to be taken into account for storing spare parts and the associated tooling. Storage should also be considered for the hydrogen storage materials as they are both heavy and expensive. In this sense, assuming that a stock equal to at least the monthly demand for hydrogen storage materials would need to be stored, the consideration of a silo-type storage directly connected through pipes to the filling equipment (or an intermediate buffer storage), could be the most viable option. This would allow for storage of large volumes of material in a space efficient way and would minimise operator intervention, making it a safer storage alternative. These however, should also be assessed against the supplier’s capability of providing materials in bulk quantities. Alternatively, the material monthly stock could be stored in a separate facility and the equivalent daily amount delivered daily to the filling facility, which however could be a logistics challenge.

23.7 Considerations for stack frame and reactor filling

For the preparation of the end product, reactor filling and stacking are key procedures that should be further improved in terms of costs and associated time for streamlining further the product preparation process. Furthermore, both the reactors and the hydrogen storage materials are heavy and their handling can be cumbersome. To this end, H2GO Power worked on examining alternative designs for the stack frame that would follow a modular approach, allowing for a seamless transportation of empty and full reactors, and their filling and assembly into the container. During this assessment, the following three configurations were considered:

1. Filling and stacking reactors individually

This was the process undertaken during the SHyLO and SHyGaN projects and was assessed solely for understanding better the benefits of an alternative approach. Through this the stack frame was to be installed into the container, while all reactors would be filled individually and assembled one by one. As it can be easily understood, this could be a suitable approach for a prototype manufacturing but not for undertaking commercial orders, as the process is time consuming and under high volume orders assembling many reactors could complicate further the associated logistics.

2. Modular reactor filling 3x1

In this approach, reactors would be assembled to sub frames of 3X1. This would require the reactor manufacturer to deliver the empty reactors in sub-frames of 3X1, while for their filling automatic equipment should be applied, that would fill three reactors at the time. Figure 74: 3x1 Sub-frame Configuration shows a schematic of this configuration.

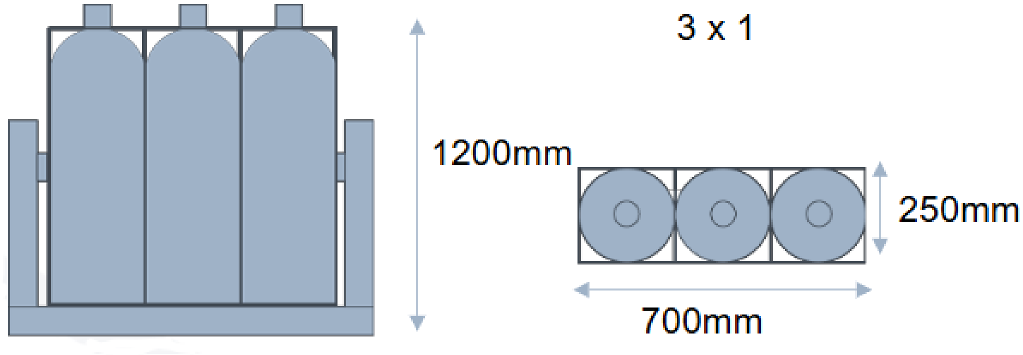


Figure 74: 3x1 Sub-frame Configuration

This approach would considerably reduce logistics, but the number of sub-frames could be still high considering that several orders of complete containers would need to be delivered. On another note, these sub-frames should be designed to be stacked one of top of the other, allowing for a modular assembly. Each frame would also need to have lifting points for a forklift to manoeuvre it, while for an accurate positioning of the 3x1 sub-stack frame, a locator/positioning (poka-yoke) feature would be required as well.

3. Modular reactor filling 3x2

This approach is similar to the one demonstrated above with the main difference being that the reactors were to be assembled into sub-frames of 3x2. Similarly, the reactor manufacturer would need to deliver the empty reactors in sub-frames of 3x2, while automatic filling would also be necessary. However, for this configuration, the automatic filling equipment to be used, would fill six reactors at the time. Figure 75: 3x2 Sub-frame Configuration shows a schematic of this configuration.

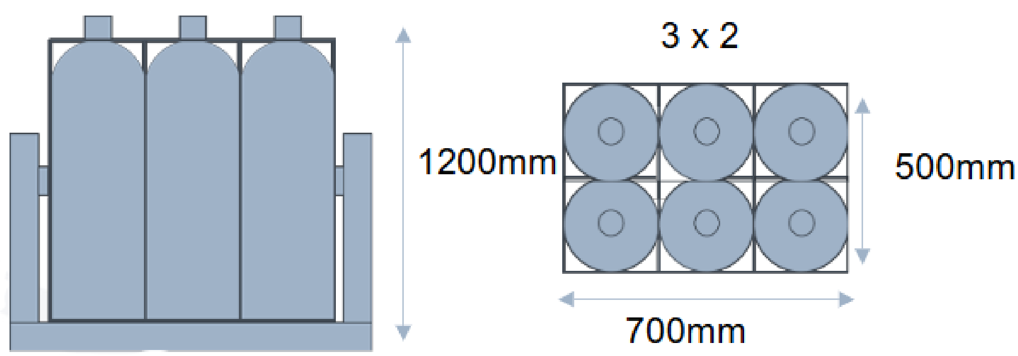


Figure 75: 3x2 Sub-frame Configuration

Compared to the above (3x1), the logistics here can be further reduced, and this size of sub-frame is still suitable for modular assembly. Similarly, this should also be designed to be stacked one on top of the other to allow for the desired modularity, while lifting points would also be needed.

Based on the above, the usage of sub-frames together with an automated filling system would undoubtedly improve the overall process and reduce manufacturing times, as at the period of the SHyGaN project, H2GO Power was still at a prototype manufacturing stage where most operations were conducted manually. The selection of the most suitable approach however at a scaled-up scenario would be dependent on multiple factors such as the anticipated demand for sizing a manufacturing unit, the amount to be invested, etc.

24.0 Benefits, risks, issues and challenges

In this section some of the most important benefits that the system could bring with commercial adoption are presented, together with associated risks, issues and challenges that could be encountered, or were already encountered during the course of the project.

24.1 Benefits

24.1.1 Safe and efficient storage of hydrogen

For industrial decarbonisation, hydrogen is an essential energy storage vector. However, there are many safety considerations over the use of hydrogen where the risk may be increased, and/or industrial settings where safety requirements are among the most stringent. In addition, efficiency in storage and hydrogen usage are substantial for making any proposed hydrogen technology appealing. The system that was proposed within SHyGaN, by applying the solid-state hydrogen storage technology developed by H2GO had a notable advantage against any other hydrogen storage mediums. Specifically, the storage system alone presented an efficiency of >90% due to an ability to utilise waste heat streams.. For the heat-in-a-box case that was examined through SHyGaN, only a small amount of heat generated from the hydrogen boiler would be used to release hydrogen from the storage system, while heat recuperation from the site would also be investigated to boost further system efficiency. During the system's design several simulations on the system's process flow were conducted, which examined all the possible operational modes that could be applied to the system (regarding storage charge, bypass, discharge, etc). In most of these modes the efficiency was calculated above 90%

24.1.2 Flexible design allowing for adapting to multiple use cases and scales

The SHyGaN system was conceived from its very beginning for demonstrating that H2GO's proprietary hydrogen storage technology could be applicable to multiple use cases, together with a completely scalable modular design. The selection of a heating application was also to demonstrate that this technology could be applied to the most challenging hydrogen use cases such as heating. Firstly, through the modular reactor design that H2GO had developed, provided the capability to achieve any scale and satisfy any storage demand by increasing the number of reactors, and/or containers depending on the use case. Also, this modular approach allowed for operational flexibility:if, for example, in the case that one of the reactors develops a fault, it could be isolated up until being replaced or fixed, without affecting the system's operation. This is also the reason for selecting modular AEM electrolysers for the case of SHyGaN to have a level of flexibility for hydrogen production. Further to this, the demonstration was to prove that this storage technology could be effectively integrated with other assets. So, for example, instead of the hydrogen boiler a similar configuration could be applied for use cases that would need a hydrogen fuel cell. Lastly the decision to separate storage assets from the rest of the system's assets, in another container was to achieve further flexibility in the design and making the proposed system adaptable to further configurations.

24.1.3 Smart operations and control

HyAI had been a one-of-a-kind product as it was the first ever AI-enabled software platform for the optimisation of hydrogen systems, in terms of energy efficiency and environmental footprint during system design and operation. Its optimisation considered not only a system's internal operations, but the broader deployment environment such as grid prices, grid emissions, local weather and temperature together with the effect of other site operations, making it a global solution for hydrogen systems. As HyAI could be integrated into any type of asset, it could control all system's assets and thus securing maximised system operations and efficiency. Therefore, SHyGaN's value proposition involved a fully automated plug and play system.

24.2 Risks

24.2.1 Underdeveloped market

Despite the system's competitiveness over other hydrogen technologies, the hydrogen market is still underdeveloped, which would not guarantee that the system could enjoy a wider deployment following the scheduled demonstration. Unfortunately, this was proven to be the most significant risk that the system encountered as H2GO were unable to secure additional funds to continue operations and scale the technologies, ultimately resulting in the project's termination. As mentioned above, through H2GO Power's intense engagement with stakeholders from the wider innovation, and energy ecosystem, H2GO Power received strong feedback regarding the technology, but also strong scepticism was encountered from potential investors, as they expressed concerns on the immaturity of the market.

24.2.2 Additional hardware required

During proposal submission, the use of one container instead of two had been considered, which accompanied the risk of additional costs for the system's manufacturing. In addition, some smaller components were not considered as their identification was made during the detailed design stage. However, during the project's implementation a high level of effort was put on the procurement of items in order to secure best value for money. A cost buffer had also been considered during the costing of materials and capital equipment, at the proposal stage. These two actions allowed H2GO Power to mitigate this risk during project implementation.

24.2.3 Additional requirements’ compliance required

Prior to SHyGaN, H2GO Power’s experience through the SHyLO project involved the manufacturing of a demonstrator that was to be demonstrated at the EMEC site. Having selected the NGN site for the SHyGaN demonstration, which was a heavily regulated site, the involved processes for demonstrating compliance against the NGN site requirements were far more onerous. This resulted in the need for undertaking much more work than the initially scheduled with the selected compliance subcontractor (DNV) and could result in cost and time overruns. However through cost savings and involving DNV early mitigated the risk.

24.3 Issues

24.3.1 Design uncertainties

As the envisaged system was a first of a kind, several uncertainties on the design were to be encountered. In addition, the need for two containers instead of one would require further design work. These resulted in several delays from the project’s design and manufacturing partner (MTC) followed by a confirmation that they wouldn’t be able to undertake the system’s build within the project’s timeline. This put the project at a major risk which H2GO Power was able to overcome by finding a third party experienced in manufacturing , that were able to undertake the whole system integration within the available budget and time. To mitigate secondary risks, H2GO Power also considered keeping the MTC engaged on providing support and guidance on the system’s build.

24.3.2 HiAB container design challenges

As the HiAB container was a novel and complex concept, numerous challenges were encountered throughout its development due to the significant complexity arising from having a large number of interconnected systems. As the SHyGaN operating philosophy and control systems were unable to be frozen at the initial intended point, several design iterations were needed which resulted in frequent changes. As the design progressed, the required pipework was complex and with tight packaging clearances. This caused unplanned additions/relocations of valves / drains / junctions etc as a result of a gradually increased understanding from MTC and H2GO Power of the system’s function and safety requirements, which in return caused significant disruption and rework. In addition to this, despite best efforts from both the MTC and H2GO Power, Enapter the electrolyser manufacturer demonstrated a slow engagement which also brought the need for a considerable redesign of the rack-level pipework after MTC and H2GO Power were advised that previously published design guidance from the manufacturer, was inappropriate for a system of this scale. Also once Enapter became more engaged in the project, they stated that operating the HiAB container in a UK winter environment, which would likely result in sub-zero ambient temperatures, meant that a heating system to protect the electrolysis systems from permanent damage was needed. This was investigated in the HAZOP and caused further delays that were followed later by wider container changes to introduce insulation, with respective layout changes. These encountered issues were a main cause of extending the duration of the design activities.

24.4 Challenges

24.4.1 Design uncertainties

As explained in the issues sub-section the issue of design uncertainties had materialised and resulted in time delays. Minimising these delays and overcoming any uncertainties at a fast pace was a challenge that the project encountered during the design. This was actively addressed by moving some key members of the H2GO Power team to the MTC facilities to overcome any challenges being encountered early on and/or actively discuss the issues by the time that they appeared. In addition to this, a series of design meetings was being held at a weekly basis, while design review meetings involving the whole team were being held at a monthly basis. Specifically for the case of the TCL design for both containers, several changes in requirements and design modifications to neighbouring systems in the same space, and changes to ancillary equipment specification, necessitated additional redesigns of key areas to ensure all systems would fit together seamlessly and were to the latest design specification.

24.4.2 Ambiguity during regulatory assessments

During the assessment of regulations and standards the MTC experienced several challenges and ambiguities mainly due to the fact that there were two separate work streams regarding the regulatory assessment – the one conducted by the MTC and the other by DNV. The main challenges that arose as a result of this can be summarised as follows: i) poor communication experienced in both MTC and DNV meetings regarding the regulatory assessment which resulted in unnecessary work and time wasted, ii) As multiple reviews took place in both work streams, resource allocation was challenging and significant time and effort was dedicated to involve teams in both meetings, iii) in some occasions there was an ambiguity regarding responsibilities between DNV and MTC which led to delays and potential oversights, iv) arranging meetings for all involved teams (which represented at most time the whole consortium and DNV), at times that could be convenient for all stakeholders was difficult and challenging, v) significant effort was put in coordination of those meetings to ensure that decisions that were made during the meetings led by the MTC, were consistently applied and followed up in meetings led by DNV.

25.0 Key successes, findings and lessons learnt

Despite that the project was terminated prematurely, a considerable amount of work had been conducted up to the system manufacturing stage and allowed for notable information and insights to be acquired, regarding the technical and non-technical aspects of the technology. These are summarised as follows:

25.1 Successes and findings

25.1.1 Technology and balance of plant

- Despite the design uncertainties and challenges encountered considering the project was related to the design and development of a first of a kind system, the main system was designed and simulations showed promising results.
- Despite the project's design and manufacturing partner (MTC) confirmed inability to build the system on time, H2GO Power sourced a third party that was capable of delivering within the envisaged cost and schedule.
- The overall system design was found to be technically and commercially feasible in relation to key benefits identified. With regards to increased efficiencies, the energy and mass balance assessments carried out (section 10.3) identified a competitive advantage for solid state hydrogen in heating applications. With regards to cost these increased efficiencies allow for a lower cost as discussed in sections 7.2 and 22.0 through the ability to recuperate heat. Furthermore the safety studies (HAZID, HAZOP, LOPA) corroborated with the narrative that the technology was inherently lower risk that other methods of storing hydrogen, due to the low pressures and hydrogen chemically bonded.
- Compared to the hydrogen storage container unit developed within the SHyLO project, in SHyGaN a significant reduction in the required balance of plant was achieved. This was achieved through a better understanding of the technology and system design through iteration leading to an ability to optimise (reduce) supporting BoP, optimise manufacturing and assembly processes and a better understanding of risks and how to apply the regulations to the system and reduce conservatism in the design. The results of these improvements can be directly seen in the cost reductions between 2024 and 2025 costs in section 7.2.
- For five out of the six operational modes assessed, the system was shown to achieve efficiencies >86% indicating that the hydrogen storage unit had minimal impact on overall system efficiency.
- The direct storage mode showed an efficiency of around 60% as waste heat could not be recuperated into the heating of the site's water.
- The storage system alone showed an efficiency of >90% as it required only a small amount of heat to release hydrogen from the MHx.
- An improved control board design was developed for the system's operation. Compared to the initial product design where the boards controlled the reactor operation from a relatively distanced location, in SHyGaN separate boards that each would correspond to one individual reactor were implemented. This allowed for better control of the system through moving control capability to the reactors, which reduced a significant amount of wiring through co-location, and reduced issues that could occur such as assembly issues, wire damage, debugging and interference.

- For the control boards the Profinet communication protocol was applied in SHyGaN, which is a more appropriate industrial standard and could facilitate the system's to commercialisation.
- The power supply for the control boards was done through PoE which combined data and power into a single cable, and therefore reduced the amount of cabling required, compared to the previous configuration.

25.1.2 Regulatory compliance and permitting

- The installation of the demonstration unit as a project fell under permitted development which showed that no significant permits would need to be obtained for the demonstration to occur.
- The environmental impact of the unit's operation at site was assessed, and no significant impacts were identified. This excludes the water discharge requirements that were identified when the design was finished. At this point the project was terminated, and NGN did not proceed further into assessing this and the related compliance requirements.
- Regulatory requirements were more excessive than initially envisaged due to the addition of the G17 appraisal which was unknown at the time of application. As discussed in this report the system was exempt of CE/UKCA marking however due to the deployment at a gas network G17 needed to be met. Despite the need for compliance with G17 the independent assessment from DNV showed that the system was able to be deployed without any significant regulatory restrictions, thus further demonstrating suitability for commercial applications.
- The presence of hydrogen in the plant requires specific safety measures which had been well documented and understood and are significantly mitigated due to the nature of technology (hydrogen storage in solid state).
- The generation of flammable gases, such as hydrogen, naturally introduces hazards and potential fault scenarios. These types of hazards however are well understood in the gas industry and several industries with heating needs. Thus, even if the system's introduction could result in additional faults and increased risk, these could be assessed and appropriately managed in line with the current safety measures applied at an industrial site.
- Should the demonstration have taken place, H2GO Power would be able to show in real-world conditions the high levels of safety that the technology could offer.

25.1.3 Market and business

- Being a first of a kind system showing such a potential attracted the interest from several stakeholders engaged. Within the course of the project, H2GO Power participated in numerous events for the dissemination of its technology (please refer to Appendix 6), while also engaged directly with stakeholders from the overall innovation and energy ecosystems. Through these actions it's estimated that the technology was disseminated to over a hundred organisations ranging from energy companies, supply chain partners, consultant firms, and engineering firms, from the UK and abroad. The received feedback was highly positive despite that any physical demonstration had not been concluded.

- The market has been proven to be immature for the wider adoption of hydrogen solutions despite the high interest received. Engaged investors even while expressing interest on the system's potential their concerns on the market's state were raised. During the project's duration, H2GO Power engaged intensively with investors as part of the company fundraising attempts. Discussions were held with over 200 potential investors that represented a diverse range of sectors (such as energy, materials, and engineering), and profiles (from venture capital to investment departments of multinational corporations). A subsequent externally ran M&A process where nearly 270 organisations were presented the value proposition also didn't materialise to present a deal in a timely manner. In most cases despite the positive feedback received, concerns were raised regarding the currently low number of complete and operational hydrogen projects and the financial situation that has affected climate-related work globally.
- Should the market become more mature in the future, hydrogen production will be expected to be more cost-efficient resulting in turn, to an adequate number of hydrogen projects being operational. Under these conditions, such a system would be much suitable for applications requiring high-safety and efficient hydrogen-powered heating, and appealing for deployment.
- Despite gas preheating was linked to quite a small market, the system could enjoy applicability on many industries applying low to mid-heat industrial processes. These include a broad range of industries such as the wider food and chemical industries. Specifically, industrial processes requiring low to mid-heat are often overlooked as the main focus has been set on the so-called carbon intensive industries (cement, steel etc) which require high amounts of heat for their processes. However, despite their lower need for heat, such processes in total are responsible for a significant portion of annual CO_2 emissions and energy consumption. Some indicative industrial sectors and processes are as follows: Metal processing (welding pre-heating), Automotive (drying and moulding), Chemicals (air and feedstock pre-heating, heating of water and other process fluids, solvent recovery, etc), Food (evaporation, distillation, drying, roasting, etc), and many more. Due to the fact that such processes are dispersed in a wide range of industries, the quantification of their impact has been rarely assessed. However, as per a paper published by the University of Bath and the Institute for Sustainable Energy and the Environment [20], these sectors represent at least 25% of the UK's annual GHG emissions, while low temperature processes and drying processes in the UK alone exceed an annual consumption of 250 PJ (or around 69,444 GWh). In addition, through a research which assessed the wider EU industrial sector and the intensity of its processes [21], heating processes that were of a lower heating demand than 500 ^{o}C exceeded 500 TWh annually, while processes applying heating of above 500 ^{o}C were calculated at 1,035 TWh annually.

- The system could also be highly suitable post demonstration to commercial heating applications with considerable demand, such as hospitals, shopping centres, etc.
- Having demonstrated the system through SHyGaN and the associated safety benefits of the technology, hydrogen-powered heating could be encountered with less scepticism compared to the present.
- Following demonstration, H2GO Power intended to explore integrating the storage technology to high-heat industrial processes so that H2GO Power could demonstrate further the technology's universality and explore new markets.

25.2 Lessons learnt

- FEED work inevitably involved design iterations, considering that the technology being developed in the projects was a first of a kind application. This caused some delays due to uncertainties encountered, but using several formal touch points per week allowed for regular reviews by the cross-consortium team and facilitated decision-making.
- Through these iterations and collaborating directly with the consortium allowed further refinement of the design and reduced complexities in the system. For example, a reduction in the required balance of plant without compromising product quality and efficiency was achieved.
- Developing a first of a kind system and especially deploying it at a heavily regulated site such as at NGN's involved compliance with numerous standards that needed to be reviewed thoroughly. This resulted in design stage overruns and for a project of this complexity, adequate time for a compliance review would have been beneficial prior to undertaking system design activities.
- The scale up work undertaken in collaboration with HSSMI could facilitate the commercialisation of the technology should the project have continued. The activities undertaken for setting up a Quality Management System were much beneficial for H2GO as a whole but also for the project's implementation.
- As per the above point, the work undertaken developing a build book for the SHyGaN system, facilitated the work that needed to be undertaken with MTC, but also allowed more effective communication with third-party manufacturers.
- The energy and mass balance simulations performed by the MTC were significant in assessing the system's potential and estimated performance, resulting in validation of H2GO Power's technology expectations regarding process efficiencies.
- Based on the work performed up to the project termination, the system's integration at the NGN site was demonstrated to be technically feasible without any significant technical or safety concerns.
- No significant safety issues were identified, although further actions would be required to finalise the work with DNV and the on-site design. The relevant studies by DNV (HAZOPs, LOPA etc.) showed no significant concerns that could not be easily managed or mitigated. Moreover, the assessment of hazardous areas with DNV provided no significant issues.

- The development of two fundamental aspects of the system's design in parallel i.e. HiAB & HySTOR container and the site upgrade design would have reduced the risks of overruns and ideally have been avoided. Running in parallel the HiAB & HySTOR containers' design with the site upgrade design became very difficult due to unknown parameters/requirements of the system. Provision of a complete HiAB & HySTOR design would have the site upgrade design less onerous.
- Initiation of the HiAB & HySTOR containers' design prior to engaging with NGN meant that the NGN design requirements were not considered at the outset and this resulted in design inefficiencies. Therefore the engagement should have taken place earlier.
- The role of DNV on the assessment of regulatory requirements would need to be defined at proposal stage more clearly so that clear distribution of roles among the MTC and DNV would be set. The engagement of DNV even earlier in the project would also reduce hurdles and delays experienced as presented in the related challenges encountered.
- With the issues experienced during the design of the HiAB container and experiencing a slow engagement from the container's manufacturer it became apparent that the electrolyser manufacturer would have benefited the project if it had been a member of the consortium. Considering the novelty of the system and uncertainties that were experienced, a proper engagement of the manufacturer as consortium member would increase their responsibility on the project but also encourage R&D efforts from their part.
- This was an ambitious project that was achievable in the initial timeframes planned. However risks had not been accurately considered regarding the speed at which project partners could mobilise upon contract award. While the project was rescheduled from the outset to try and account for the fast mobilisation this did not consider the inertia that larger companies have in allocating staff to projects and conflicting priorities.
- During the design phase it became apparent that MTC had under costed the build of the system which required a pivot to an external vendor. While this issue was mitigated contingencies should be better identified at project submission. A recommendation could be for funding programs to clearly request as a separate budget for contingencies.

Appendix 6 – Exploitation and dissemination

Dissemination is an integral part for projects such as SHyLO and SHyGaN as they allow for the sharing of knowledge to a wider audience towards the facilitation of an innovation ecosystem, but also a significant opportunity for creating and/or strengthening exploitation opportunities. Since both projects were implemented in parallel, and dealing with H2GO Power's main technical development, the dissemination of both projects was directly linked with the company's overall publicity. For this reason the activities performed are being presented together within this Annex.

The conducted dissemination activities, utilised multiple channels to increase the visibility of the technology being developed through both projects, as well as highlight the competitiveness of H2GO Power's hydrogen storage technology as a separate entity but also as part of a system used in demanding applications such as heating. The activities performed included the participation to a series of events ranging from commercial exhibitions, conferences, and high impact events from addressed to the wider innovation and environmental communities. Specifically for the case of SHyGaN, a joint press release with the provider of the hydrogen boiler technology (Baxi) also took place, together with some related publications. In addition, during the lifetime of both projects media coverage on the activities being performed was achieved. Notable mentions of media coverage include the announcement of the ShyLO project on Forbes and The Engineer, and the announcement of the collaboration with Baxi on media such as Hydrogen Fuel News, H&V news, and hydrogen central.

Both projects received positive comments, from a broad range of stakeholders from the quadruple helix (academia, industry, public sector, and media) which justified the technology's potential. During the lifetime of both projects, H2GO Power also engaged intensively with potential investors as part of H2GO Power's fundraising activities where a big part of this engagement corresponded to providing the latest updates from these projects. Even though the received feedback had been positive, any further conversations on investments, were not successful due to the market's immaturity and scepticism from investors.

Since the SHyGaN projects had to be terminated prior to the manufacturing of the demonstration unit, the opportunity to realise completely the scheduled activities didn't come into fruition. Out of these a significant part would focus on demonstrating both technologies to interested parties for maximising the project's impact. Should the manufacturing under SHyGaN have been completed, H2GO Power was scheduling with the demonstration partners to arrange site visits for interested stakeholders (such as investors, industry & supply chain actors, and from the policy making community) to showcase the system's capabilities and competitiveness. The NGN site in addition to the Kiwa site would have been an excellent additional dissemination platform that could maximise the number of engaged stakeholders.

For the case of ShyLO, the Kiwa UK hydrogen production plant in Cheltenham, is linked to Kiwa's new test labs by the UK's first low pressure hydrogen distribution pipeline, and demonstrates the feasibility of producing hydrogen from a locally produced syngas from a biogas source, through the application of a Steam Methane Reforming process. With Kiwa being a globally renowned industrial gas testing, inspection and certification body the integration of the ShyLO at their site could also be disseminated directly to Kiwa's network through well-established communication channels. Moreover, this site has already received interest from other technology developers wanting to demonstrate their products such as hydrogen purifiers, gas analysers, and local carbon capture technologies which justify H2GO Power's site selection, but also shows the outreach that a demonstration at that site would achieve. Moreover, following the operation of the unit on site, H2GO Power was considering the preparation of a white paper and exposure through various media for the dissemination of the demonstration to a wider audience.

In the case of SHyGaN, NGN could maximise the number of engaged stakeholders visiting the demonstration site (the Gateshead-based InTEGReL) as it is a fully integrated whole energy systems development and demonstration facility, where several new technologies had been tested attracting a notable number of international visitors annually. An outstanding example of such demonstrations are the hydrogen-powered homes installed at the InTEGReL facility attracting visitors from around the globe. Further to this, the SHyGaN partner Baxi following the unit's installation at NGN site, was expected to disseminate the project through their well-established communication channels. Lastly, for the case of both projects, the participation through events such as the ones that H2GO Power had already participated so far would be continued until the project's scheduled closure.

Information on some of the most notable dissemination activities being conducted before the project's premature ending is provided in the table below. Some indicative pictures are also provided after this table.

Table 19: Indicative Dissemination Activities

Activity	Category	Description	Stakeholders engaged	Date
Media coverage on SHyLO project launch	Media coverage	Publications on media such as the Engineer, and Forbes presenting the scheduled demonstration within SHyLO	Engineering, energy and technology professionals, Entrepreneurs, General audience	Mar. to May 2022
Hyvolution 2023	Exhibition	Exhibition stand, engagement with prospective customers and collaborators	SMEs, investors, industry and supply chain partners	Feb. 2023
Cleantech for UK initiative	Exhibition	Pitching and exhibition stand. Leadership presented the technology to the PM of that	Industry and government officials	Feb. 2023

		time (Rishi Shunak) and Bill Gates who attended the event		
H2GO Power/Baxi joint event	Project and Partnership Launch event	Joint event by H2GO Power and Baxi to announce publicly the collaboration through the SHyGaN project.	Media and technical press representatives, government representatives	Feb. 2023
Publications on magazines presenting the Baxi/H2GO Power collaboration	Media coverage	Publications on several magazines and media following the joing event with Baxi. Magazines include Heating Ventilating and Plumbing Magazine, Electrical Contracting News, Hydrogen Central, Manufacturing and Engineering Magazine and more	Engineering, energy and technology professionals	Feb. 2023
CIBSE Journal article	Publication	Publication on CIBSE (Chartered Institution of Building Service Engineers) Journal on the SHyGaN system	Engineering professionals	Mar. 2023
CERA week (Houston Texas)	Panel discussion, networking	World's largest energy conference. CEO participation	Energy companies, technology end-users, investors, innovators, government officials	Mar. 2023
Hydrogen UK Heat working group	Working group and discussion	Event hosted by Hydrogen UK to present the latest updates on hydrogen-powered heating applications and technological developments.	Energy & Utilities companies, Hydrogen supply chain actors	May 2023
All Energy Exhibition	Exhibition and networking	The UK's largest low carbon energy and full supply chain renewables annual event attracting exhibitors from over 15 countries.	Renewable energy industry representatives, investors, end-users and Government officials	May 2023
Hydrogen and Storage APPG	Panel Discussion	Event hosted by the All-Party Parliamentary Group on Hydrogen, bringing together hydrogen and gas sector experts to examine the current state of the UK's hydrogen storage technologies.	Government officials, stakeholders from the gas and hydrogen sectors	May 2023
Hydrogen for life 2023	Panel Discussion and networking	Showcase event presenting the latest advancements in the UK's hydrogen innovation and technology, hosting relevant	Energy & Utilities companies, Hydrogen supply chain actors	Jun. 2023

		panel discussions and dedicated networking time. H2GO Power CEO participation		
Cadent Global Technology Conference	Panel Discussion and networking	The first Global Technology Conference organised by Cadent, the largest gas distribution network in the UK, for bringing together international gas and technology companies to support Cadent's mission towards decarbonisation and digitalisation. H2GO Power CEO participation.	Energy & Utilities companies, Renewable Energy Industry representatives	Jun. 2023
Energy Asia	Panel Discussion and networking	Global impact event organised by PETRONAS, a global Malaysian energy group with presence in over 100 countries bringing together energy professionals, industry representatives and policy makers through actionable solutions for accelerating decarbonisation. H2GO Power CEO participation.	Energy & Utilities companies, Industrial stakeholders, policy makers	Jun. 2023
Climate Week NYC 2023	Panel Discussion and networking	Global impact event attracting key stakeholders. H2GO Power CEO co-hosted a roundtable discussion on the scale up of hydrogen technologies, and networked with attendants of the event.	Renewable energy industry representatives, investors, end-users, policy makers	Sep. 2023
NZIP Innovation Showcase	Demonstration event/ Networking	Exhibition stand and presentation to audience as the SHyGaN project lead (funded under the NZIP Portfolio). Engagement with multiple stakeholders through dedicated meeting sessions. A delegation of H2GO attended and presented the project and associated technology.	Government representatives, industry, supply chain partners, SMEs	Oct. 2023
Hydrogen Investment Forum	Conference / Networking event	The 2ndHydrogen Investment Forum in the UK jointly organised by Hydrogen UK and DESNZ. Conference and networking event organised for	Policy making stakeholders, investors, supply chain partners,	Feb. 2024

		facilitating conversations between government, investors, hydrogen project developers and supply chain companies, providing a platform for collaboration to grow the UK's hydrogen economy. H2GO Power leadership participation.	hydrogen stakeholders	
Hydrogen UK Annual Conference & Awards 2024	Conference / Networking event	Conference and awards event organised by Hydrogen UK annually. Considered the UK's largest hydrogen-related event. Participation from H2GO Power leadership.	Policy making stakeholders, investors, supply chain partners, hydrogen stakeholders	Mar. 2024
CERAWeek 2024	Round table discussion and networking	Considered to be the most prestigious annual gathering of CEOs and Ministers from global energy and utilities, as well as automotive, manufacturing, policy and financial communities, along with a growing presence of tech. H2GO Power CEO participation in two panel discussion related to the clean energy transition, and disruptive technologies in the wider hydrogen sector.	Business, political, academic, and other societal leaders, including representatives from the overall renewable energy industry, investors, and policy makers	Mar. 2024
CEME Hydrogen Summit: Hydrogen Innovators and the future	Panel discussion, networking	Annual Hydrogen Summit for assessing the current hydrogen landscape and associated timely challenges. CTO and co-founder participation.	Hydrogen developers, hydrogen supply chain partners, industry stakeholders	Jun. 2024

Pictures from dissemination events

H2GO Power team at Hyvolution 2023

H2GO Power team presenting the technology to the Rt Hon Rishi Sunak MP, Prime Minister of the United Kingdom 2022-2024 and Bill Gates.

H2GO Power CEO and Co-founder, with Baxi's MD in front of H2GO storage reactor and Baxi's 100% hydrogen boiler at the joint event

H2GO Power team presenting the SHyGaN concept to attendees of the joint event

H2GO Power at All Energy 2023 event with the Rt Hon Humza Yousaf MSP, First Minister of Scotland 2023-2024

H2GO Power CEO and Co-founder Enass Abo-Hamed, speaking at the panel of Hydrogen for Life 2023 event

H2GO Power presentation of the SHyGaN project at the NZIP Showcase event

H2GO Power delegation at the NZIP Showcase event

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Solid State Hydrogen Storage

Reporting on DESNZ funded projects under the Low Carbon Hydrogen Supply 2 and the Industrial Hydrogen Accelerator programmes