HYS2204 - DELIVERABLE 1.21 - FINAL PROJECT REPORT

07 AUGUST 2025

P U B L I C

THIS DOCUMENT HAS BEEN PREPARED BY GEMSERV LTD, AND THEIR PARTNERS [H2SITE, EQUANS, THE UNIVERSITY OF BIRMINGHAM, YARA AND TYSELEY ENERGY PARK], AS AN OUTPUT OF THE AMMOGEN PROJECT, FUNDED UNDER THE DEPARTMENT FOR ENERGY SECURITY AND NET ZERO'S LOW CARBON HYDROGEN SUPPLY 2 PROGRAMME.

Gemserv
a TALAN company

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1 Executive Summary

In order to meet the expected demand for hydrogen and more importantly green hydrogen, alternative hydrogen carriers are appealing. Ammonia (NH3) could be a good carbon-free and sustainable option if the green ammonia production capacity can be increased to meet requirements, and an existing supply chain is in place for global trade. Ammonia cracking technology is thus of considerable strategic interest. Ammonia is recognised as an attractive potential hydrogen carrier due to its relatively convenient physical properties, the possibility of using the existing value chain, and lower transportation and investment costs over long distances compared to other hydrogen carriers. In particular,

- Ammonia has the unique feature of being a CO_2-free energy storage medium unlike other hydrogen carriers such as methanol, formic acid or Fischer-Tropsch products which release carbon oxides during their use.
- Ammonia has been produced industrially for over 75 years, with a large existing infrastructure and offtake. Ammonia is considered to be the most practical hydrogen carrier suitable for long-distance transport globally.

Ammonia cracking is the process of converting ammonia into hydrogen gas. It allows users to leverage ammonia's transport efficiencies and hydrogen's fuel properties. Ammonia cracking technology could therefore become crucial in the future hydrogen economy, particularly if it enables lower cost cracking.

The main challenges are the high cracking costs associated with converting ammonia back into hydrogen and the efficiency of the process. These were key areas of investigation in the AMMOGEN project.

At present, existing large scale industrial systems for ammonia cracking require reaction units and catalysts operating at high temperatures (600-950°C) for complete ammonia conversion. The required thermal energy is a restricting challenge making cracking costly and ammonia unattractive as an energy carrier. Moreover, cracker components' thermal losses, power consumed by balance of plant such as pumps, and loss of hydrogen due to imperfect recovery in conventional separation and purification section represent other important issues to address for next-generation ammonia cracker plants. The AMMOGEN project utilised a novel membrane reactor combined with a novel catalyst designed to overcome these obstacles.

The AMMOGEN demonstration has shown that its technology reduces the energy input required for cracking as the operating temperature of the reactor was just 450 °C, much lower than for state-of-the-art reactors currently used in industry. This means less fuel (NH3) is needed to reach the operating temperature, therefore minimizing the kg of NH3 needed per kg of produced H2. Since fuel consumption represents the largest cost share in economic analyses of ammonia cracking, a reduction in the fuel needed to produce hydrogen results in important **OPEX** savings. These are expected to become more significant for scaled-up technology.

Another advantage of the technology is the combined reaction and separation in the same unit, reducing the need for downstream processing to purify the hydrogen generated. This has important advantages, like site **footprint** and **CAPEX** cost perspective, as fewer system components should be required. AMMOGEN brings together the required catalyst and membrane reactor in an integrated system design. This provides significant benefits in terms of process intensification and efficiency, lower capital and operating expenses, higher quality of hydrogen product, less waste and improved process safety.

The scope of this project was to scale up and validate the novel membrane reactor and develop an ammonia to hydrogen plant to produce 200 kg/day ISO-Grade D pure hydrogen at more favourable operating conditions as a step towards more economical hydrogen production.

The AMMOGEN system was tested and operated over thousands of hours in the range of 375-450 ºC and 2-8 barg, which resulted in a minimum measured H2 purity of 99.98% and ammonia conversion levels always above 99.5%. The production rate, however, did not achieve the 200 kg/day target, mainly because of unexpectedly high pressure drops and temperature losses in the system. This prevented the ammonia cracker from working at the designed conditions. This can however be overcome in future thanks to the learning from the AMMOGEN project.

In summary during the AMMOGEN project:

- In total 2,068 test and operational hours were achieved.
- The average hydrogen quality surpassed the target of 99.97%, achieving fuel-grade hydrogen, indicating that the technology can be used for various offtakes which is a key KPI.
- 5,289 kilograms of hydrogen was produced during the test and operations.
- Zero safety incidents on site. Demonstrating the strong process safety in the design of all modules.
- Although the 200 kg hydrogen per day output target was not achieved, the lessons learnt during the operation provided H2Site the knowledge to overcome this issue in upcoming projects.

1.1 Glossary

ATEX - Atmosphere Explosible	**LOHC** - LIQUID ORGANIC HYDROGEN CARRIER
BOP - Balance of Plant	**LOPA** – Layers of Protection Analysis
BOM - Bill of Materials	**NH3** - Ammonia
CAPEX - Capital Expenditures	**NOX** - Nitrogen Oxides
CAD - Computer-Aided Design	**N2** - Nitrogen
CR – Change Request	**O&M** - Operations and Maintenance
COMAH - Control of Major Accident Hazards	**OPEX** - Operating Expense
DSEAR - Dangerous Substances and Explosive Atmospheres Regulations	**PFD** - Process Flow Diagram
DESNZ - Department for Energy Security and Net Zero	**PID** - Process & Instrumentation Diagram
FRA - Fire Risk Assessment	**PPE** - Personal Protective Equipment
FEED - Front-End Engineering Design	**PEM** - Polymer Electrode Membrane
FAT - Factory Acceptance Test	**PED** - Pressure Equipment Directive
GHG - Green House Gas	**PLC** - Programmable Logic Controller
GH2 - Gaseous Hydrogen	**PPA** - Power Purchase Agreement
GA - General Arrangement	**PPM** - Parts Per Million
HAZOP - Hazard and Operability safety study	**PMO** - Project management Office
H2 - Hydrogen	**RAID** - Risks, Assumptions, Issues, and Dependencies
HGV - Heavy Goods Vehicle	**RES** - Renewable Energy Sources
HRS - Hydrogen Refuelling Station	**SAT** - Site Acceptance Test

HRFT - Hydrogen Recovery Factor	**SIL** - Safety Integrity Level
I/O - Input and Output	**SOP** - Standard Operating Procedures
IP - Intellectual Property	**SCADA** - Supervisory Control and Data Acquisition
KPI - Key Performance Indicator	**TRL** - Technology Readiness Level
LH2 – Liquified Hydrogen	

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2 Project Overview

AMMOGEN is an ammonia to hydrogen project underpinned by **best-in-class** ammonia to hydrogen membrane based cracking technology and industrial symbiosis.

The technology aims to provide **low capital cost** for future dispatchable hydrogen deployments with favorable economics due to the ammonia storage characteristics, **low temperature operation** & **high conversion efficiency** of the AMMOGEN process. The development and operational testing through the AMMOGEN project provided the necessary data and learnings towards this outcome.

The project has been built upon a legacy feasibility & economic analysis, Front-End-Engineering & Design, procurement, construction, commissioning, and full system operations.

The complementary consortium to develop this project includes Gemserv, H2SITE, EQUANS, Tyseley Energy Park, University of Birmingham and Yara as leading industrial partners and collaborators (detailed in Table 1)

Table 1: Industrial partners and collaborators of the AMMOGEN consortium

Organisation Partner	Role in Project
Gemserv a TALAN company	Gemserv, a professional services company, were the principal developers of this project. They integrated all aspects together and served as the 'supplier' organisation to DESNZ Department for Energy Security and Net Zero.
H2 SITE Membrane reactors for H2 generation	H2SITE supplied their proprietary ammonia cracking technology.
EQUANS EMPOWERING TRANSITIONS	Equans, a technical service and EPCM, provided partial designs, constructed, operated, managed, and decommissioned the facility. Other design and construction elements were delivered by H2SITE.
tep TYSELEY ENERGY PARK	Tyseley Energy Park (TEP), spearheaded by Webster and Horsfall, provided the host location for the project,
UNIVERSITY OF BIRMINGHAM	University of Birmingham (UoB) provided knowledge transfer and dissemination support to the project.
YARA	Yara, a global supplier of industrial and agricultural products, provided a cylinder-based supply of liquid ammonia.

2.1 Ammonia as a Hydrogen Carrier

The Challenge: The transport of hydrogen adds a significant cost element to the economics of hydrogen generation and application. Ship and truck transportation of hydrogen are energetically and environmentally inefficient. Small and medium hydrogen consumers pay the price.

The Solution: Ammonia is one of the cheapest carriers to transport hydrogen and is more economical than pipeline transportation at larger volumes and distances (see Figure 1[1]) given the existing supply chains and infrastructure already in place globally.

Issues relating to the development of a sustainable hydrogen economy are the cost of production and transportation to point of use.

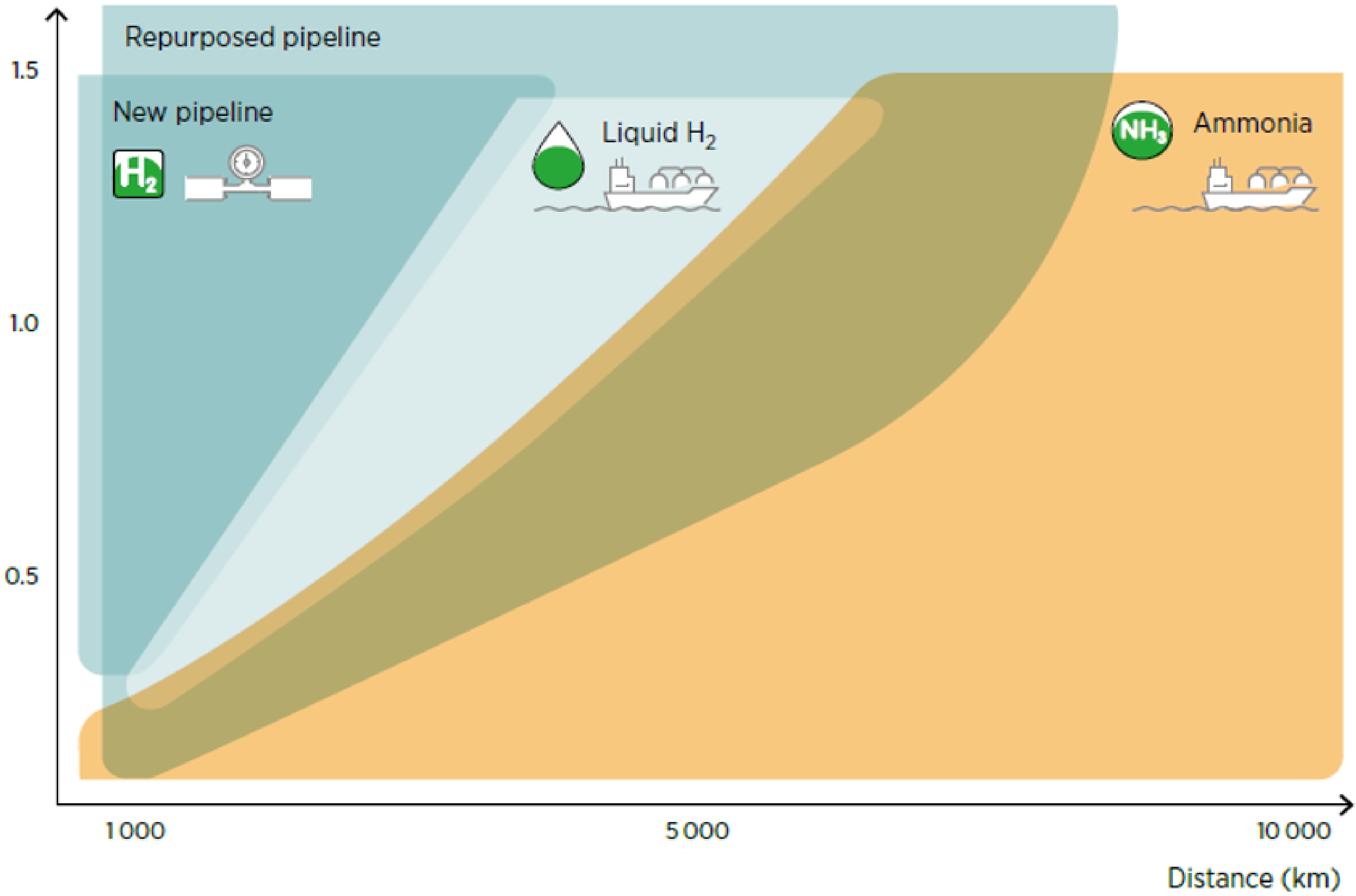


Figure 1: Economics of Hydrogen Transport over distance

[1] IRENA (2022) Geopolitics of the Energy Transformation: The Hydrogen Factor

Ammonia will play a role as a medium for shipping hydrogen globally. It has favourable physical properties - liquid ammonia's volumetric energy density is 50% greater than that of liquid hydrogen - and it is already traded globally.

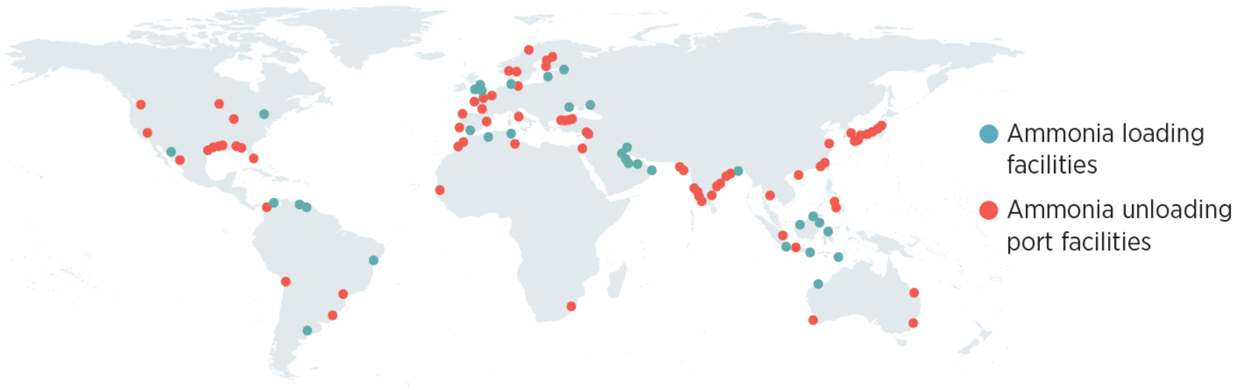


Figure 2: Existing global supply chain for ammonia production

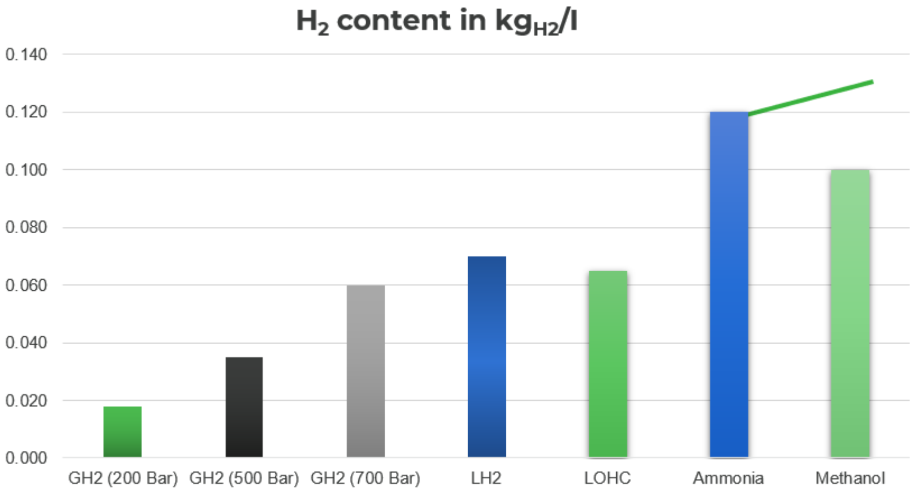
Figure 2 shows the existing global supply chain for ammonia production and transport[2]

Ammonia will provide an important link for deep-sea transportation of hydrogen and a comparison of hydrogen carriers is provided in Figure 3.

Key characteristics of ammonia as a hydrogen carrier compared to alternatives such as liquified hydrogen are:

- Existing mature transport infrastructure & knowledge
- Ammonia has highest H2-storage capacity followed by methanol and is also less expensive than storing liquid hydrogen
- More energy dense than hydrogen
- Lower long distance transportation costs
- The storage and handling technologies for Ammonia are well-known and proven. Ammonia is less flammable, easier to transport and stored at –33°C (instead of –253°C for liquid hydrogen).

[2] Reproduced from Royal Society (2020) & IRENA and AEA (2022), Innovation Outlook: Renewable Ammonia



- Liquid ammonia is able to store hydrogen in volumes much higher (121 kg-H2/m3) than liquid hydrogen (70.8 kg-H2/m3), **which is about 1.7 times as high**.
- Liquid ammonia can be stored at relatively low pressure (0.99 MPa at a temperature of -33°C), which is significantly lower than that of liquid hydrogen.

Figure 3: Comparison of hydrogen content for various hydrogen carriers

As highlighted in Figure 4, the AMMOGEN project focuses on the development and validation of the cracker technology to convert ammonia to hydrogen in a cost effective and efficient manner at the point of use to support the hydrogen economy.

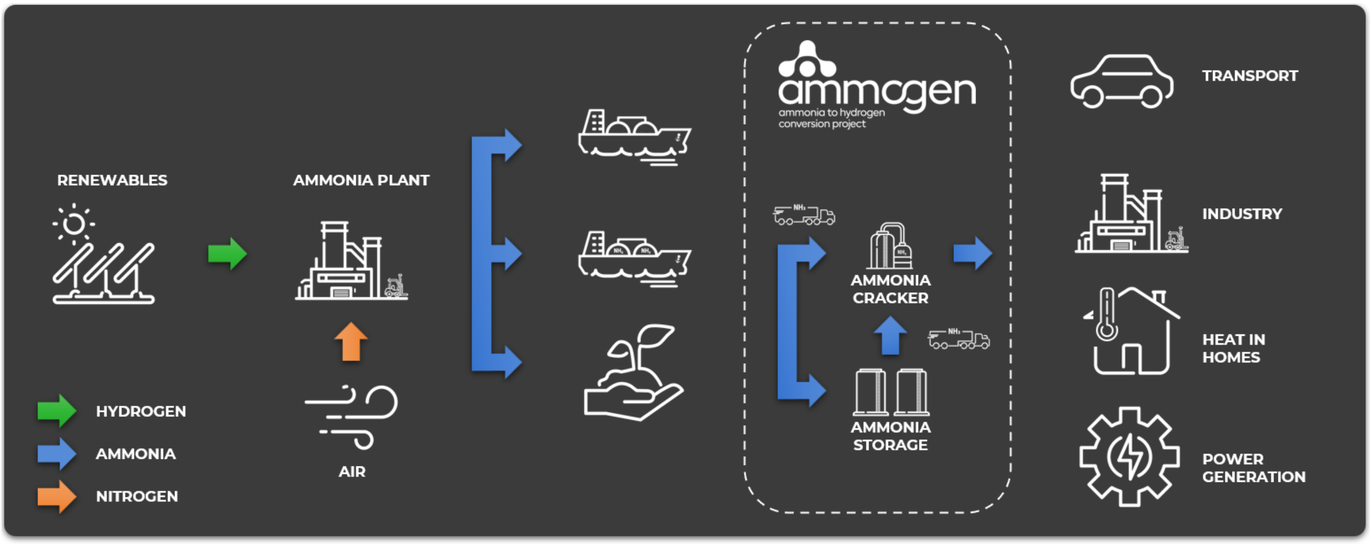


Figure 4: Situation of the AMMOGEN project within the hydrogen supply chain

2.2 Ammonia Cracking to Hydrogen

The cracking of ammonia is endothermic and requires the input of heat to drive the reaction to completion. The total energy input required to achieve and maintain ammonia decomposition depends on recovery rate and reaction temperature. The dissociation rate depends on temperature, pressure and catalyst, and is described by the chemical equation below:

$$2NH_3 \leftrightarrow N_2 + 3H_2$$

Typically, in small to medium scale commercial industrial systems, the dissociation of ammonia gas takes place at temperatures as high as 950°C in the presence of a special nickel catalyst within the electrically heated furnace. The cracked gas then goes through the heat exchanger to pre-heat the incoming gas. Depending on the end-use, the generated gas (75% H2, 25% N2) may or may not undergo a final purification step. These commercial units usually produce a forming gas (H2/N2 mixture) for various industrial applications. Rarely, additional steps to produce hydrogen at high purities are required for utilisation in fuel cells applications for mobility and other industrial applications.

Where ammonia would be used as an energy carrier, the development of efficient ammonia crackers able to generate pure hydrogen is required. It is necessary to develop a selective ammonia cracking unit which can effectively separate nitrogen and ammonia at lower temperatures and pressures to achieve better energy efficiency.

The AMMOGEN H2SITE membrane technology offers a novel method for ammonia cracking. In a membrane reactor, the chemical reaction and the selective separation of reaction product occur simultaneously inside the reactor.

2.3 Ammogen Aims and Objectives

The overarching aim of this project was to demonstrate the use of ammonia as a hydrogen carrier to reduce the delivered cost of hydrogen to the end user by designing, building, commissioning, and operating an ammonia to hydrogen conversion unit to produce 200kg/day of hydrogen. The AMMOGEN system was built and located at Tyseley Energy Park, UK.

Furthermore, the project aimed to improve the efficiency and economics of ammonia cracking and accelerate the future development of hydrogen solutions in the UK and position the country at the forefront of an emerging global market.

AMMOGEN's key KPI's include the following:

KPI	NARRATIVE	Ammogen Outcome
OBJECTIVE 1	Demonstration: Design, build, commission and operate a demonstration of grey hydrogen production from cracking industrial ammonia in a membrane reactor with integral purification at 200 kg/day scale and exceeding 75% availability. Note: during the project, the original KPI of 90% availability was reduced to exceeding 75% availability.	The production rate KPI was not achieved due to limitation on achieving optimal operation conditions. The 75% availability was not achieved mostly due to maintenance issues and several operational concerns. However, the learnings from the AMMOGEN project both, on the design of the equipment and organization of the operation will allow to achieve a higher availability in the second iteration under development.
OBJECTIVE 2	Quality: Produce grey hydrogen meeting ISO 14687 quality, suitable for transport and demonstrate if appropriate end user/off-taker is available, otherwise flare the hydrogen. Note: this KPI was adapted during the project, the original KPI stated 30bar ISO 14687 quality to demonstrate supply to ITM Motive refuelling station for fuel cell buses. However, due to change of ownership of the Motive refuelling station, this was not able to be considered in the project timeframe.	ISO grade hydrogen was obtained in a single separation stage, which exceeded the original expectations of the AMMOGEN system, which had planned for an additional purification stage after the first separation. This is a very positive and unexpected result, because it could simplify the system greatly and reduce CAPEX requirements.

OBJECTIVE 3	Efficiency: Improve efficiency of ammonia cracking with hydrogen recovery factor of >97% for electrification. Note: this KPI was adapted during the project, the original KPI stated an additional KPI of hydrogen recovery factor >82% with an integrated hydrogen burner. The gas burner was not implemented in the project due to time and cost constraints.	This KPI was not achieved, but fine tuning before new operation and corrective actions will increase the efficiency. The implementation of technical learnings to a modified reactor would increase efficiencies significantly and meet the KPI targets.
OBJECTIVE 4	Cost: Improve economics of ammonia cracking by demonstrating levelised cost of cracking ammonia of £2.54/kg of hydrogen excluding the cost of grey ammonia.	The economic KPI was not achieved as consequence of two main factors: external reasons that raised energy costs well over the expected values caused by the Ukraine crisis during the project lifetime, and the lower H2 recoveries compared to the target. This can however by overcome by optimizing the system and current energy prices.

Table 2: AMMOGEN's key KPI's

It should be noted that it was envisaged that during the project AMMOGEN would utilise green ammonia and therefore produce green hydrogen during the operational phase. However, this was not possible due to several factors that related to the availability of green ammonia from Yara in terms of timings and logistics from production sites and the cost element to the project. Ammonia costs during the project lifecycle spiked during the Ukraine crisis and impacted ammonia supply budgets, grey ammonia was the most cost-effective ammonia to carry out the validation of the AMMOGEN technology.

Moving forwards, working with key partners such as Yara, the viability of incorporating green ammonia in the supply chain and integrating it into future AMMOGEN type projects will be required to meet key end-user requirements for green hydrogen.

2.4 Project Schedule & Deliverables

The AMMOGEN project successfully completed 173 deliverables including detailed reports relating to: engineering (process, mechanical, electrical) safety, instrument and control, regulatory compliance, and project management activities as well as commercial analysis.

The project initially planned for 110 deliverables, but by the end of delivery, this number had increased to 173 deliverables. The increase was primarily due to Project Change Requests, which were used to maintain progress and align budget allocations with payment milestones. In cases where a single large deliverable was originally planned, it was sometimes broken down into smaller sub-deliverables to ensure steady cash flow throughout the project lifecycle. Additionally, some extra commissioning and safety-related activities were introduced during delivery — for example, tasks related to the introduction of a flare stack.

At the outset, the expected cost to deliver the project was £6.7m, but final delivery came in under budget by £740k, with a final spend of approximately £5.9m. This underspend was not due to cost efficiencies or savings in delivery, but rather a reduction in scope — most notably the decision to exclude the gas burner, due to engineering challenges and delays related to procurement lead times.

2.4.1 Project Timeline Summary (Completed Project)

This completed innovation project ran from **April 2022 to January 2025**, delivering the design, construction, and successful operation of a modular ammonia cracking system for low-carbon hydrogen production. Work was carried out across eight structured work packages, covering technical development, infrastructure delivery, operations, and public engagement.

2022: Foundation and Planning

- The project launched in April 2022, establishing governance structures and producing key documents such as the Project Execution Plan, Risk Register, and Site Planning Drawings.
- Initial engineering assumptions, system specifications, and health & safety assessments (HAZID) were developed.
- Planning applications and early land assessments were completed to support site readiness.

2023: Engineering, Procurement, and Construction

- Detailed engineering was completed for the ammonia cracker system — excluding the gas burner.
- Major components including heat exchangers, membranes, instrumentation, and control systems were procured and assembled.
- Extensive site mobilisation took place in phases, alongside the construction of the ammonia storage facility and enabling works.
- Electrical, mechanical, and insulation works were completed within the system container.

2024: Testing, Operation, and Knowledge Sharing

- The system underwent **offsite testing** and **pre-commissioning validation**, confirming readiness for operational use.
- Operational testing was conducted to assess system performance, hydrogen purity, and process stability.
- Knowledge transfer activities included **site visits**, **stakeholder workshops**, and **teaching material development**.
- Continuous monitoring of energy use and operational outputs supported data collection and analysis.

2025: Final Reporting and Close-Out

- In **January 2025**, the project concluded, and site decommissioned with submission of the **Final Project Report** to DESNZ.
- A commercial exploitation plan, future requirements assessment, and strategic recommendations were also delivered.

3 Design Considerations

3.1 Front End Engineering Design / Engineering System Design

The technical design of the project included design elements primarily comprised of the basic engineering package, the design package for the ammonia storage and vaporisation unit, the pre-construction information pack for the site and Pre-FEED / FEED reports.

The key elements in the design studies and activities included the following:

- Planning application
- Land contamination survey
- Site quantitative risk assessment
- Environmental permit
- Water discharge assessment
- Venting assessment
- Electrical design & electrical connection
- Civil works to install cable & electrical utility
- Internal electrical feeds within ammonia compound
- Main water connections
- Fibre and internet connections
- Nitrogen storage and connectivity
- Temporary construction services, such as fencing & site accommodation / welfare
- **Ammonia storage & vaporisation systems**, such as engineering for the ammonia vaporisation system, electrical, instrument, piping, structural insulation, civils and ammonia racking system
- **Core Technology (ammonia cracking**) equipment such as the compressor, post treatment, feedstock pre-treatment, heat exchangers, reactor, upgrading, demister, hydrogen post treatment, PLC & electric cabinet, instrumentation and online hydrogen purity measurement system
- ***Hydrogen Vent & Flare System**

*The hydrogen flare system was a necessary add-on to the plant design at a late stage of development due to the issues relating to timings of a potential hydrogen offtaker such as a refuelling station and lack of suitable compressor, storage and transport available to utilise the hydrogen produced by AMMOGEN. Despite the consortium's best efforts to find an alternative hydrogen offtaker, it was not possible to achieve this within the project timeframe.

The hydrogen flare was installed to ensure the hydrogen produced through operations was safely dealt with and to ensure safe operations on site. The decision to choose the hydrogen flare among other technologies was based on a safety analysis carried about by H2Site, which showed this was the best way to dispose of the produced hydrogen. On top of that, the Global Warming Potential of the AMMOGEN project was reduced, since burning the hydrogen prevented its effect if it were released to the atmosphere.

On top of that, the main challenge during the FEED stage was the design of an ammonia burner for integration in a membrane reactor. The development of this novel technology resulted in a search for some special materials and shapes to ensure corrosion compatibility and mechanical integration, which required a longer than expected time. This delay meant that producing the burner within the AMMOGEN project timeline and budget was not possible.

3.2 Consents and Permitting Applications

Site Permissions

The development of the AMMOGEN project and associated plant at TEP required appropriate stakeholder management to identify all the interested parties associated with this development.

Emphasis was placed on discussions with the adjacent Birmingham Bio-Power Biomass Gasification Plant and the other residents near the AMMOGEN plant such as Motive Fuels. This process ensured they were aware of the project developments to give them the opportunity to raise any concerns ahead of submitting the planning application.

EQUANS provided support for obtaining the necessary permissions and consents for the project to ensure compliance with the appropriate regulatory requirements.

Planning Permissions

This included ground investigation work and a land contamination survey in the proposed location for the ammonia storage and cracker compound. Discussions with the appropriate planning department to provide supporting information required with the planning application to ensure approval.

Environmental Permit

Discussions were held with the Environment Agency to identify any specific concerns about the location. The Canal & River Trust was also consulted regarding the AMMOGEN plant and on-site ammonia storage locations due to the proximity of the River Cole and the Grand Union Canal.

Based on the proposed design, the following documentation was developed for discussions and review with the appropriate agencies:

- Non-technical summary
- Environmental management system
- Site condition report
- Permit application
- Water discharge assessment
- Venting assessment / gas dispersion model (ammonia storage) developed by GEXCON
- Venting assessment / gas dispersion model (ammonia cracker) developed by GEXCON

Gas dispersion models were also developed to understand the safety analysis requirements for the HAZOP and to understand the potential impact of leaks or the catastrophic release of ammonia and hydrogen to on-site and local residential premises. The pre-construction information pack and pre-application planning submission were made to Birmingham City Council for the project installation of container units to house the ammonia cracker demonstration plant that would produce high purity hydrogen for transportation.

EQUANS, with the support of the consortium partners, led the planning discussions with Birmingham City Council who were receptive to the scheme and comfortable with the principle of use. Following on from the pre-construction information pack, a planning requirements document and planning application were developed.

No objections were stated by Birmingham City Council or the Canals Trust. A positive decision for approval was made on the 12th of January 2023. The response aligns with the project requirements and programme. Formal approval planning documents from Birmingham City Council are provided on the planning website[3].

Through discussions with the Environment Agency, it was advised that the consortium did not require a permit for the AMMOGEN plant to operate as it is exempt under the R&D rules which are stated below:

"The proposed activities (i.e., cracking of ammonia to produce hydrogen) would normally be regulated under the Environmental Permitting Regulations (EPR) as Section 4.2 Part A(1)(a)(i) - Producing inorganic chemicals such as gases – Hydrogen.

However, the EPR contain an exemption for installations or plant "used solely for research, development or testing of new products or processes." Based on the information you have provided we consider that this exemption applies to your case.

Based on the information provided, you will be storing 9,540Kg of ammonia, which is below the applicability threshold of 100 tonnes specified for the storage of anhydrous ammonia regulated by the local authority under EPR activity Section 4.8 Part B(a)(iii).

EPR R&D exempt activities conducted at installations used solely for research, development or testing of new products or processes don't need an environmental permit."

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[3] Birmingham City Council - Details Page for Planning Application

Even though the AMMOGEN plant and activities do not require an environmental permit, we conducted analysis and implemented procedures and practices to ensure AMMOGEN would not cause pollution or lead to environmental harm. Interventions included HAZOP and Gas Dispersion Modelling as well as utilising Standard Operating Procedures to handle the movement, storage and connections of ammonia and plant operations, including waste spillage and disposal best practice.

The Environment Agency also provided other advice which we considered to ensure we met our internal governance:

> *"The project will operate its activities according to a written environmental management system developed according to Develop a management system: environmental permits - GOV.UK[4]. The environmental management system is based on a comprehensive risk assessment covering both normal operating scenarios and accidents. It will also comply with the expected design and operation according to: Control and monitor emissions for your environmental permit - GOV.UK (www.gov.uk)[5] in order to prevent pollution; additional guidance that we are advised to consider includes: Inorganic chemicals sector: additional guidance - GOV.UK (www.gov.uk)[6]."*

The additional storage presence of ammonia and hydrogen would not constitute a change in COMAH status.

[4] Develop a management system: environmental permits - GOV.UK

[5] Control and monitor emissions for your environmental permit - GOV.UK (www.gov.uk)

[6] Inorganic chemicals sector: additional guidance - GOV.UK (www.gov.uk)

3.3 Ammonia Storage & Vaporisation Systems

Packaged 530 kg ammonia tanks are delivered by road tanker delivery to the AMMOGEN plant. These tanks are then stacked in a purpose-built cylinder racking system for storage until use.

The development of this supply and storage system applied Yara's expertise in working with ammonia. Yara provided feedback for the design of the ammonia storage compound from a safety perspective. The actual design, fabrication, supply, and commissioning was carried out by a subcontractor: Star Refrigeration Ltd.

Delivery of ammonia to the site was carried out by Yara through a selected partner i.e., Blended Products Ltd. in the UK.

The ammonia vaporisation system design included the electrical, gas detection and ventilation system specifications and associated package unit arrangement CAD drawings, as shown in Figure 5:

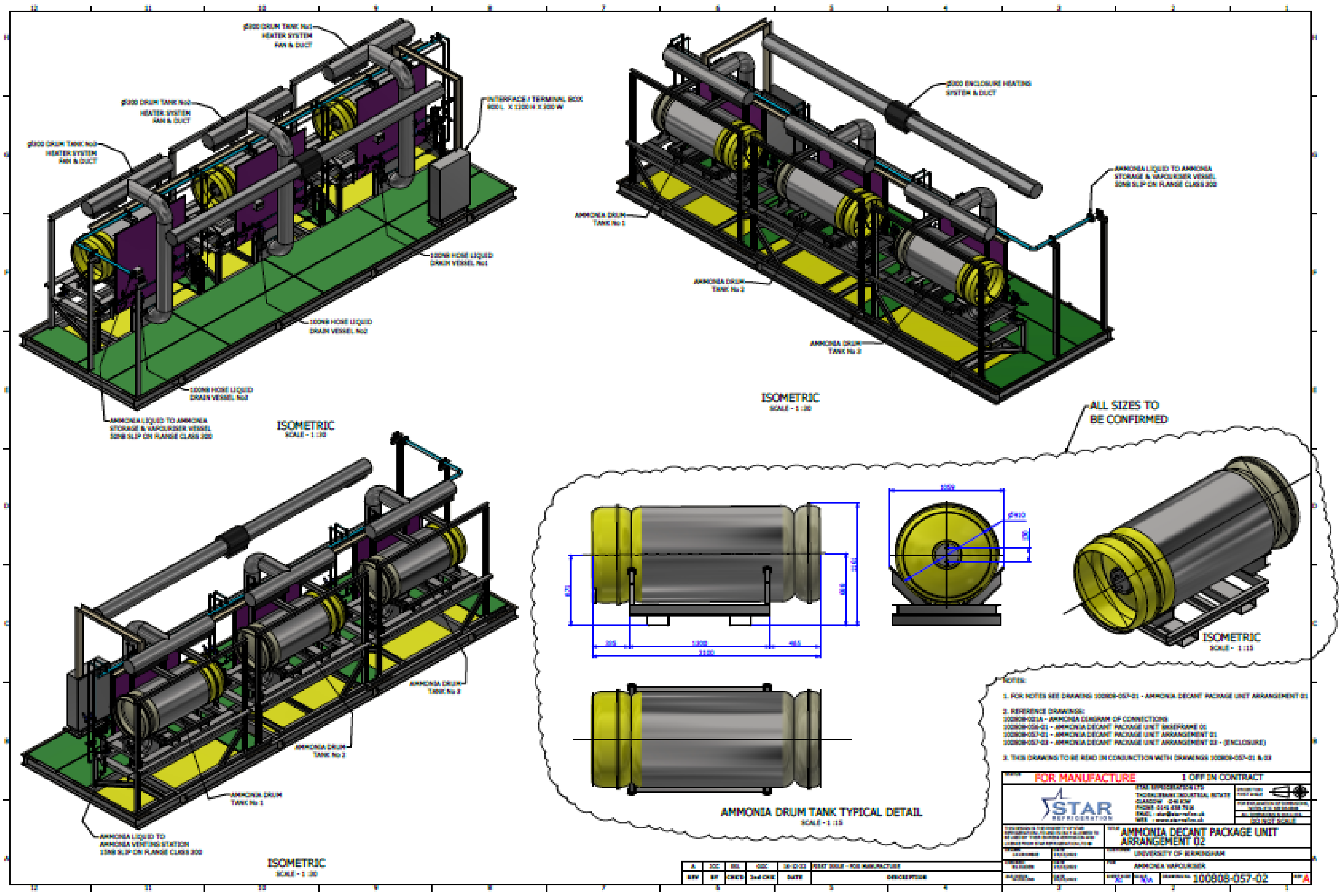

Figure 5: Ammonia decant package unit arrangement

Figure 6 shows the ammonia vaporisation system as built:

Figure 6: Ammonia decant and vaporisation units

The Ammonia storage and vaporisation systems are integrated parts of the AMMOGEN plant. The storage system is required to allow a continuous supply of ammonia for the process. The vaporisation system provides ammonia from drums to the ammonia cracking reactor.

The 2-off units that make up the vaporisation system as shown in Figure 7 are as follows:

- Unit 1 – Ammonia vaporisation unit
- Unit 2 – Ammonia drum decant unit

a) Control cabinet b) Pressure control tank c) Container for ammonia drums d) Integrated containers and ammonia drum

Figure 7: Ammonia decant and vaporisation units (unit 1 and 2)

As well as the ammonia vaporisation system installed on site, the ammonia storage/racking facility was constructed and installed as shown in Figure 8:

Figure 8: Ammonia storage and racking facility

The ammonia storage/racking facility was designed to hold the ammonia vessels next to the AMMOGEN plant in the dedicated storage racks for changeover, as required for continuous plant operation. A typical ammonia vessel is shown below being inserted into the ammonia vaporisation system (Figure 9):

. The carbon steel frame for positioning 530 kg drums of ammonia, with a 530 kg ammonia drum tank

Figure 9: Ammonia drum tank

Ammonia was sourced, transported by HGV using iso-containers, then transferred to the AMMOGEN vessels using ammonia cylinders provided by the vendor. These cylinders were dedicated for the pilot plant operation. An example of the iso-container is shown below in Figure 10:

Figure 10: Ammonia iso-container delivery to site

3.4 Ammonia to Hydrogen Cracking System

The FEED report synthesises the key outputs of all the engineering and design activities that have taken place on this project to date, covering:

- The ammonia storage & delivery
- Process and process safety engineering
- Safety considerations i.e., HAZOP and LOPA
- Piping
- Mechanical and electrical engineering
- Control
- Equipment lists
- Mass balance
- An overview of the process of the systems and site considerations

Detailed engineering development was conducted for the cracker technology, including the Process Flow Diagrams (PFD's), Process and Instrumentation Diagrams (P&ID's), process specifications, heat and mass balance, Hazard and Operability (HAZOP) node sheets, hydraulic design calculations and General Arrangement's (GA).

Included in the detailed engineering package was the technical description of the solution and system specifications as well as all the process, mechanical and electrical documentation to manufacture the ammonia cracker. The package considers the electrical heating option only due to the limited timeframe and costs to implement with speciality materials, therefore, this will be re-designed and the use of a gas burner for heat management is left for a second iteration for future system development.

In summary, the necessary engineering information for design and fabrication of the AMMOGEN cracker system included:

- System description
- Process flow diagram
- P&ID
- System specifications
- Heat and Material Balances
- Line list
- Valve list
- Instrumentation list
- Equipment list
- Equipment datasheets
- General Arrangements
- Isometrics
- Hydraulic calculations
- Electrical assembly architecture
- 3D electrical assembly
- Control philosophy
- ATEX study
- BOM mechanical assembly

The ammonia cracker developed by H2SITE is a membrane reactor deployed for ultra-pure and cost-efficient hydrogen generation. In the membrane reactor, the chemical reaction and the selective separation of a reaction product occur simultaneously. In chemical reactions limited by the thermodynamic equilibrium, like ammonia decomposition, the selective separation of one of the products (hydrogen in this case) will shift the thermodynamic equilibrium according to Le Chatelier's principle and will allow the system to go beyond this thermodynamic constraint.

This AMMOGEN ammonia cracker has several advantages over conventional systems:

- Pure hydrogen is recovered through the membranes and can be fed directly in fuel cells which avoids any costly downstream separation unit.
- The thermodynamic equilibrium limitation is circumvented, and it is possible to obtain full fuel conversion, reducing the downstream cleaning of unconverted species.
- The separation of hydrogen enables higher efficiencies at lower operating temperatures, which has a corresponding benefit from an energetic point of view.
- Since the whole process occurs in a single unit, the footprint of the technology is reduced.

For selective hydrogen separation, palladium-based membranes are typically used, which have a unique transport mechanism for hydrogen permeation. The reactor design for ammonia cracking is shown in Figure 11.

In the ammonia to hydrogen unit, gas phase ammonia coming from the storage facility is fed into the hydrogen generation cracker at a pressure of 8-10 bar(g). The ammonia flowrate is controlled *via* flow controllers. The feedstock temperature is increased by hot streams as described below.

The original AMMOGEN project considered an ammonia burner to provide the heat required by the ammonia cracker. However, the fact that this technology is in early development stages, encouraged the project to incorporate an electric heating system too. These different strategies enable operation under various specifications depending on the presence of electricity from the grid. When cheap, green energy is available, the unit can be heated using low-carbon electricity. When unavailable, the process is fully integrated: part of the feedstock energy content is used as a heat source in a dedicated gas burner.

Nonetheless, as mentioned earlier, the design of an ammonia burner led to the search for some special materials and shapes to ensure corrosion compatibility and mechanical integration, which required a longer than expected time. So, in order to ensure that during the demonstration of the AMMOGEN project the system operated at 450 ºC, and due to time constraints and costs, electrical heating was used.

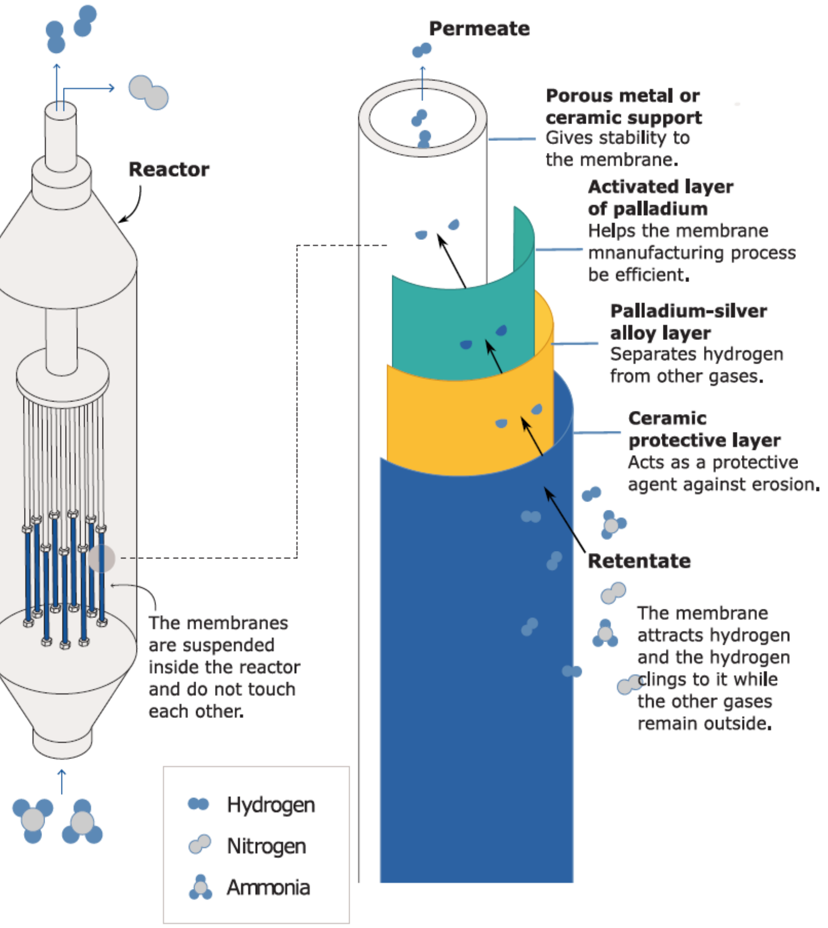

Figure 11: Membrane reactor design and its advantages for ammonia cracking

Even if the ammonia gas burner was removed from project KPI's, the knowledge generated during the AMMOGEN project has been vital to aid in the development of the ammonia burner, which will lead to cheaper and quicker manufacture in future projects.

In the cracker, the conversion of ammonia produces a hydrogen stream, which is purified by the membranes embedded in the reactor. To maximise hydrogen recovery, permeation is assisted by a hydrogen oil-rig vacuum pump, which increases the pressure difference between the reaction and permeation zones. At the pump outlet, hydrogen is released at atmospheric pressure with a purity of >99.97%. The residual contaminants are nitrogen oil and moisture.

To purify the product further, the hydrogen stream is sent to the upgrading section. In this section, the hydrogen is first sent to a zeolite bed that will trap any oil moisture and ppm of ammonia contaminants. This bed operates at ambient temperature and low pressure. Two beds are incorporated to operate the unit continuously. While the hydrogen stream is being polished in one zeolite bed, the other bed is cleaned with hot air coming from an air fan passing though electric heaters.

At this stage, hydrogen purity is monitored using an in-line mass spectrometer. If the **ISO 14687** grade specifications for fuel cell purity are met, the bed's pressure will be increased in a gas booster to 20 bar(g), as shown in Figure 12.

If the hydrogen purity is still not reached, or there is a slip of ammonia, the pressure of the hydrogen line will be increased to 40 bar(g) in the gas booster and will be sent to a membrane separator.

In the membrane separator, traces of nitrogen and ammonia will be retained.99% of the hydrogen present at the inlet of this unit will be extracted *via* the membranes to meet the ISO purity specification. However, during the operation of the cracker, it was observed that the ISO purity was achieved in the first membrane reactor, without the need for additional purification, which exceeded expectations. This is a significant result.

This process has worked well: the hydrogen produced was of the necessary purity levels during test and operations over the course of the project.

A system schematic of the key ammonia cracker module is shown in Figure 12.

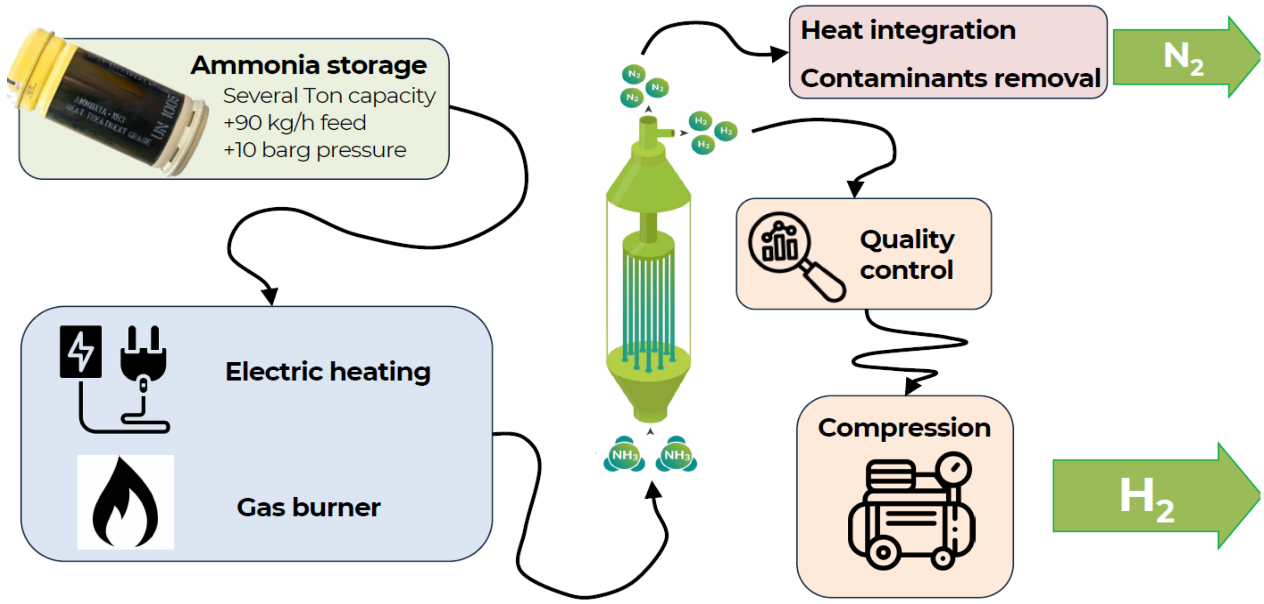

Figure 12: Overview of the AMMOGEN process

3.5 Civil Design

The design for the AMMOGEN site was completed and detailed in the associated deliverable civil and structural works design - demonstration plant and interconnection works, this includes the schematics for the site plan and general arrangement. An overview of the site for AMMOGEN is highlighted below with the finalised installation of the AMMOGEN plant (Figure 13 and Figure 14). It should be noted that that the "*Hydrogen Refuelling Station*" was not part of the AMMOGEN project.

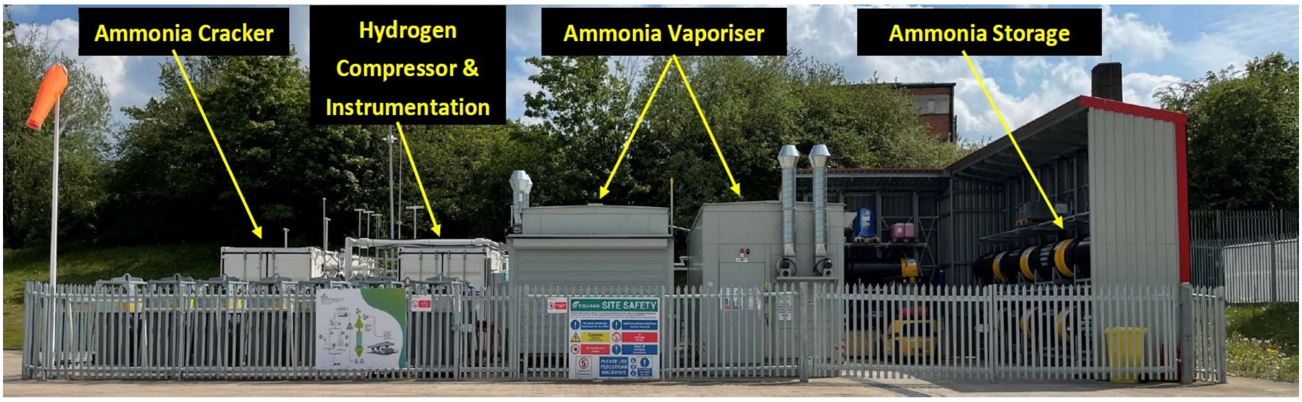

Figure 13: AMMOGEN site with infrastructure labelled

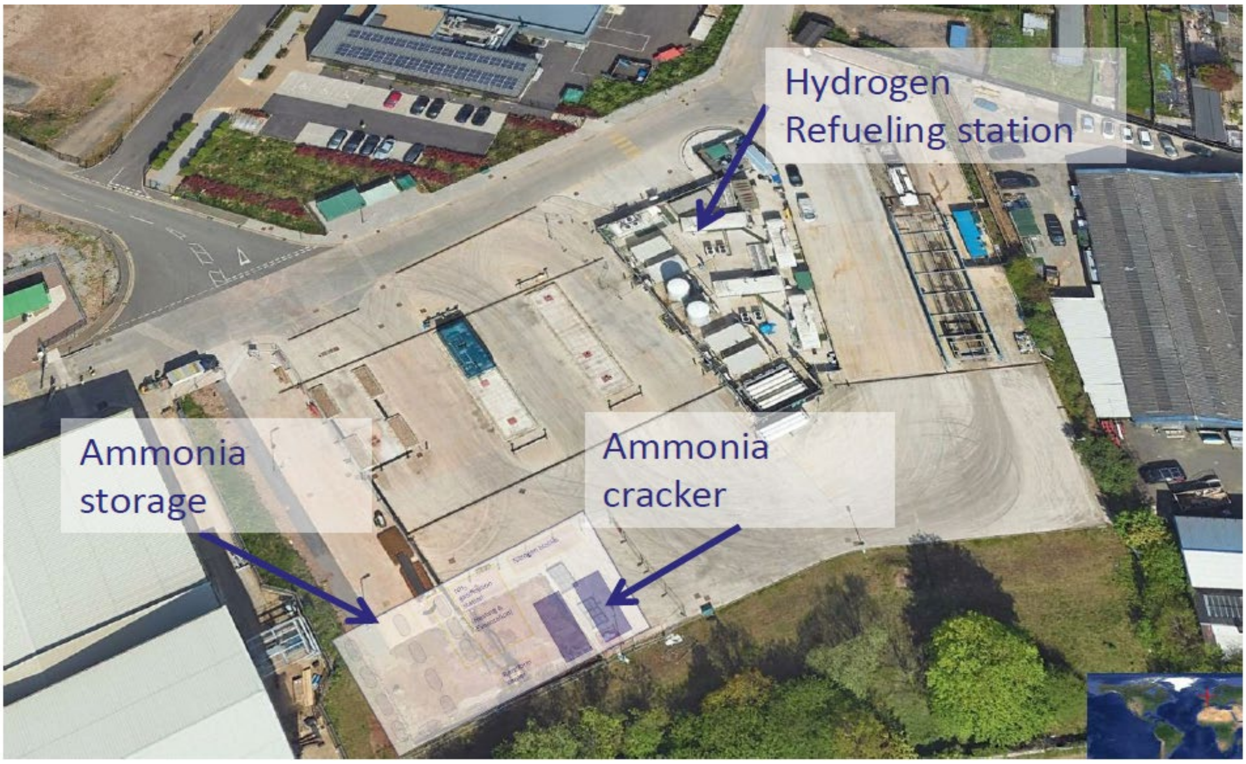

Figure 14: Installed AMMOGEN plant with infrastructure labelled

3.6 Health & Safety

A full HAZOP study was conducted to identity and mitigate hazards and operability concerns around the ammonia cracker and associated systems. The design was compartmentalised into 12 distinct nodes. The P&IDs and prerequisite documentation was updated accordingly. Outcomes from the HAZOP included the correct interaction between the ammonia storage and supply to the cracker, which is essential to ensure reliable and safe operation, as well as the potential interaction between the ammonia cracker and the hydrogen off-taker. The outcome of the HAZOP and safety recommendations were integrated into new P&ID's i.e., updated PID for the hydrogen generation unit after HAZOP and updated PID for the hydrogen compression and upgrading skid after the HAZOP reviews.

Design recommendations were implemented for the final construction and inspected at the as-built stage to ensure that HAZOP, and any changes, were aligned and reviewed. The main risks identified were Ammonia gas leaks which could potentially harm operators and hydrogen gas leaks, which could lead to a fire or deflagration scenario. Countermeasures to minimise these were taken and considered they would have to be efficient during any operation mode. This was implemented in the form of dedicated gas detectors that lead to an emergency shutdown in case of a leak, which stopped the feed of ammonia and production of hydrogen, whilst flushing all the equipment and lines with nitrogen towards the flare. The emergency stop required no human or machine intervention to happen.

Another aspect of the safety study was to include a purity risk analysis for the downstream application of hydrogen from the cracker. A thorough study was conducted to ensure that the quality of the hydrogen fuel that could potentially be delivered to the refuelling station meets the desired purity requirements.

The methodology followed for this study is based on the **ISO 19880:8:2019, Gaseous Hydrogen – Fuelling stations; Part 8: Fuel quality control**.

This standard is for specific applications to refuelling stations for road vehicles that use PEM fuel cells. The standard is based upon best practices and experience from gaseous fuels in the automotive and fuel cell industry. It discusses quality assurance plans as well as control approaches for routine and non-routine conditions, identifying the **ISO 14687:2** as the hydrogen quality reference for PEM fuel cells.

According to the risk analysis, it was concluded that all the gas transferred from the ammonia cracker unit to a refuelling station would meet the ISO specifications for hydrogen quality. Furthermore, in the event of a failure, the system monitoring procedures in place would prevent any damage to the PEM fuel cell vehicles.

The HAZOP and the SIL (Safety Integrity Level) analysis identified the main risks associated with the operation and interlocks between system and included recommendations and mitigation actions. The recommendations were integrated into the ammonia cracker design, ensuring safer operation.

The SIL analysis provided feedback for the integration process of several protection layers. The analysis consisted of equipment/instrumentation and/or procedures that are used in conjunction with other protection items to control and/or mitigate process risks. The standards applied are as follows:

- **ANSI/ISA-S84.01-1996: Application of Safety Instrumented Systems for the process industries.**

- **IEC 61508: Functional Safety of electrical/electronic/programmable electronic safety related systems.**

- **IEC 61511: Functional Safety of electrical/electronic/programmable electronic safety related systems for the process industry sector (Also available as a form of UNE-EN).**

Additionally, a thorough Dangerous Substances and Explosive Atmospheres Regulations (DSEAR), Gas Dispersion Modelling and a Fire Risk Assessment, was undertaken to meet compliance and safety needs. Broadly, the DSEAR study included analysis of the whole plant operations and its impact to the neighbours onsite. The dispersion modelling software was used to evaluate plant leakage / a catastrophic leak.

For further detail, the DSEAR and Fire Risk Assessment covered the following areas:

- Normal operations and emergency situations. The basis of safety for this type of system typically involves preventing the formation of flammable atmospheres within the equipment.
- Standard Operating Procedures (SOPs) and Personal Protection Equipment (PPE) for all activities.
- Written Scheme of Examination and Pressure Equipment Directive (PED) information for the interconnection.
- Emergency response plan including actions in the event of an ammonia/hydrogen alarm activation.
- Fire risk analysis of the subsystems and plant including an assessment of the risk to life from fire. Where appropriate recommendations are made to ensure compliance with fire safety legislation.
- Ammonia dispersion model.
- Hydrogen dispersion model.
- Operations and Maintenance (O&M) manuals for all equipment/systems.
- Emergency Response Plan updated with the response role of the emergency services and the responsibility of the West Midland Fire Brigade and Tyseley Energy Park.
- Any additional safety sensors or detectors needed to be integrated in the plant control system to monitor the system in terms of PPE.

An Atmospheres Explosibles (**ATEX)** inspection and analysis were conducted for the ammonia storage and vaporisation system and the ammonia to hydrogen cracking system. The objectives were:

- To ensure a thorough ATEX evaluation study.
- To Classify the hazardous areas of the ammonia cracking installation.
- Ultimately, to ensure that the system was compliant to the necessary regulations.

Ammonia and hydrogen gas are the hazardous substances in this system. The use of ammonia and hydrogen is likely to generate risk locations with dangerous concentrations of flammable gases or vapours. In these locations, the devices, equipment and their installations must be appropriate for use in this type of atmosphere. So, it is essential to determine the area classifications of said installations.

Therefore, the purpose of carrying out the ATEX evaluation is to classify the locations where the ammonia and hydrogen system components are integrated, and to establish the possible existence of explosive atmospheres (due to the airborne presence of these substances under atmospheric conditions).

To determine the classification of areas with risk of explosion and protection against explosions, the following provisions were considered:

- **BS EN 60079-10-1. Explosive atmospheres Part 10-1: Classification of areas - Explosive gas atmospheres.**

- **BS EN 1127-1. Explosive atmospheres. Explosion prevention and protection. Basic concepts and methodology.**

- **Other Codes and Reference Standards: CEI 31-35, NFPA 497A. - API RECOMMENDED PRACTICE 505 (RP 505), API RECOMMENDED PRACTICE 505 (RP 505).**

The main conclusions of the study included the need for ventilation of the systems and in the case of the ammonia cracker the need to install ATEX rated equipment within the containers. These requirements were included during the detail engineering phase and were considered during procurement to ensure compliance.

3.7 Control Logic & System Design

One of the activities performed to integrate the whole plant assembly and system was to design, procure, install and commission a Supervisory Control and Data Acquisition (SCADA) control system for the ammonia vaporisation plant and ammonia cracker plant. This system enables remote viewing of the plant status and can alarm team members operating remotely. A visualisation of the SCADA system can be viewed in Figure 15.

The user specification, installation scope and interface diagram were developed by EQUANS and H2SITE.The package was competitively tendered. Working with the package suppliers and the EQUANS design & operations teams, IES subsequently developed, delivered, installed and commissioned the system.

Each of the packages are controlled by a Programmable Logic Controller (PLC) unit. The SCADA system marshals alarms and status information from both PLC's and displays this information on the head end computer at the site office. It also relays alarms through an operational control centre to remote / on-call operations team members. The operators can dial into the system remotely to view the plant's operational and alarm status.

Input/Output (I/O) lists are available from the PLCs and integrated into the SCADA system. The operations team have rationalised the I/O lists and alarms into critical information only. Critical alarms are relayed to the operations teams. Non-critical and information is available to be viewed from the head end terminal directly or remotely. More detailed schematics and control panels are provided after the "Main Overview" page for engineers and operators to monitor each key component in the system for the cracker and vaporiser unit.

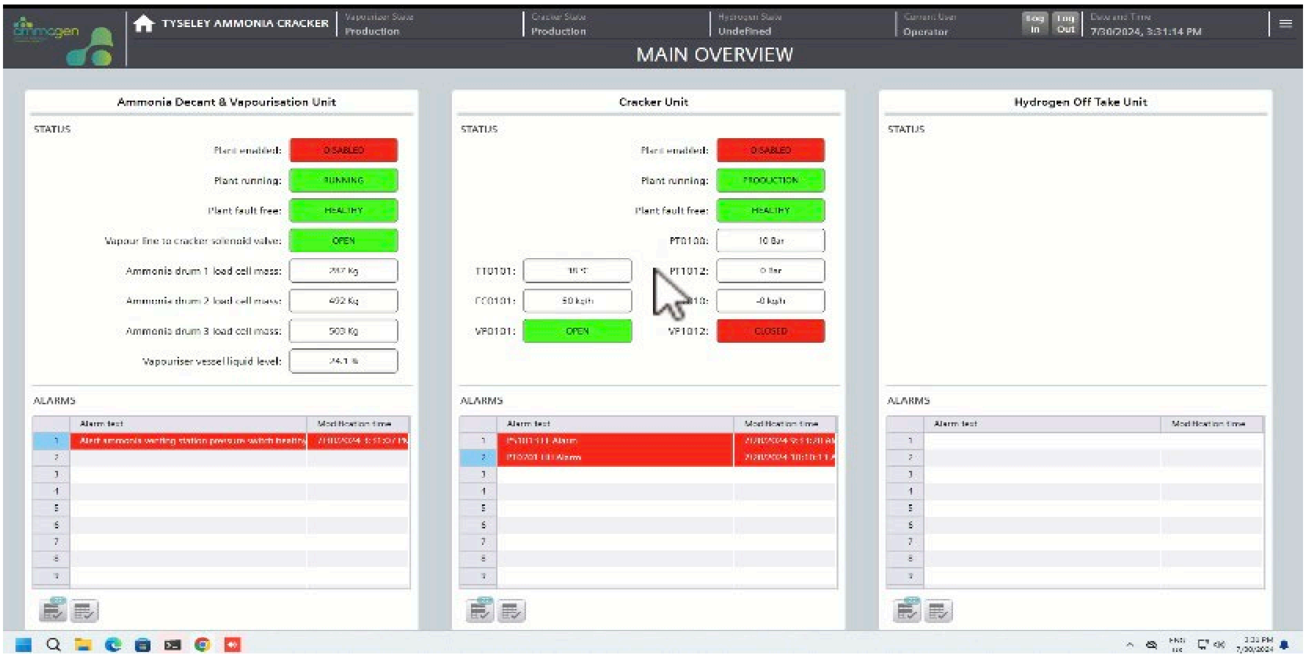

Figure 15: Screenshot of the SCADA terminal

3.8 Technical & Operational Challenges

Project challenges arose during the design, procurement, installation and commissioning. To ensure the project was delivered with a suitable mitigation plan, Change Requests and discussions with DESNZ were conducted to re-baseline the project sequencing of deliverables. A few examples of the main challenges that occurred and the required interventions are as follows:

- Unforeseen ammonia feedstock price volatility and price spikes of gas and energy due to the Ukraine crisis impacted the budget established at the start of the project.

- Procurement supply chain challenges for key components such as the hydrogen compressor and speciality materials for the cracker components and catalysts. Resulting delays impacted the ammonia cracker design process and mechanical assembly. As such, structuring of key timelines for procurement, assembly, and commissioning was required. Other components that had delays due to supply chain issues were some additional sensors advised by the FRA study, this was mitigated by having an operational staff trained to oversee the plant operations 24/7 whilst the delivery and installation of additional sensors could take place.

- Change in plan from providing hydrogen to a local off-taker due to change in ownership of the chosen local off-taker's facilities, which showed no interest in joining the project. This required the design and procurement of a back-up hydrogen flare system to ensure the operation and validation of the AMMOGEN plant could continue without the need of a hydrogen off-taker in place.

- Development of an NH3 gas burner with reduced NOx formation to supply energy for the cracking reaction and facilitate the scale up the technology. As consequence of time and costs constraints, the scope was reduced to engineering efforts and construction and offsite testing of the NH3 burner, but not its integration with the membrane reactor and long-term operation within AMMOGEN project. Instead, the ammonia cracker validation was carried out utilizing electrical heating.

- Meeting regulatory acceptance for the use of ammonia and production of hydrogen using a highly novel technology. This required extensive discussions with external experts to ensure compliance with the health and safety requirements such as the DSEAR and Fire Risk Assessment (FRA). This also increased commissioning and system design modifications to ensure compliance. The extra time needed to complete these studies were to ensure that the required sensors and control procedures as well as updated dispersion modelling could be undertaken to take into account design changes such as the additional hydrogen flare.

- During operations, several shutdowns occurred due to issues relating to stable supply of ammonia to the plant due to ambient temperature changes causing ammonia condensation in lines. Trips and alarms due to sensitivity of gas sensors and cross contamination readings from other operations on site. These were resolved with upgraded heat tracing and new gas sensors.

- Sub-optimal performance of ammonia scrubber resulted in small concentrations of ammonia having to be flared alongside the hydrogen in the flare stack for safety reasons and analysis suggested that in the worst-case scenario, the maximum concentration of NOx at the flare outlet would be 20 ppm. A review of the safety case i.e., HAZOP, DSEAR and FRA was undertaken to ensure safe operations on site and site personnel.

- The ammonia cracker had to operate at suboptimal working conditions (Temperature and Pressure) due to limitations in the original design. This meant that the 200 kg hydrogen per day production rate KPI was not achieved, whilst the rest of the main KPIs were. However, the lessons learnt during the operation of the AMMOGEN system provided H2Site with the required knowledge to overcome this issue in coming projects.

4 Demonstration Study

H2SITE successfully commissioned and tested the AMMOGEN ammonia cracker in its premises in Bilbao (Spain). All its performance parameters in the different operating modes (leak test, heating up, transient, nominal operation) were successfully validated before its transportation to Tyseley Energy Park (Birmingham) for full operations.

Commissioning in this location was performed by the end of Q1 2024, replicating the data obtained in H2SITE. After the installation of a hydrogen flare and an additional modification for feeding the retentate stream into this equipment, the cracker began its 24/7 operation on the 27th of June 2024. The test plan included the following validation and operational conditions to optimise the best process conditions:

- NH3 mass flow rate. To understand the turndown ratio and impact on system efficiency.
- Inlet pressure. To understand the impact of this variable on the system performance.
- Reaction temperature. To investigate the impact of this parameter on the process and on economics. Upgrading separation temperature. To investigate the effect of the temperature on the recovery and purity obtained from a polluted H2 stream.
- Optimising and durability testing. Membrane lifetime and catalyst deactivation analysis.

In summary:

- In total 2068 test and operational hours were achieved.
- The average hydrogen quality surpassed the target of 99.97%, achieving fuel-grade hydrogen, indicating that the technology can be used for various offtakes which is a key KPI.
- 5289 kilograms hydrogen was produced during the test and operations.
- Zero safety incidents on site. Demonstrating the strong process safety in the design of all modules.
- Although 200 kg hydrogen per day rate was not achieved, the lessons learnt during the operation provided H2Site the knowledge to overcome this issue in coming projects.
- When green ammonia is available, the GHG mitigation is -87.9% vs the natural gas energy equivalent (397.0 ton_{CO2eq}/year avoided for a small-scale system). Green or electrolytic ammonia is considered to have ~0 gCO2/MJ. Emissions come from the use of electricity in the grid. When blue ammonia is available, the GHG mitigation is -55.8% vs a natural gas energy equivalent (251.9 ton_{CO2eq}/year avoided for a small-scale system). Blue ammonia is considered to have ~20 g_{CO2}/MJ. In addition, emissions from the use of electricity from the grid contribute to the total process emissions.

4.1 Project Metrics

TRL8 is achieved when the hydrogen is used by a commercial offtaker. As this did not happen during the AMMOGEN project, the TRL progress has been limited from an initial TRL 6 to a final TRL 7.

A key metric that would allow commercialisation of the hydrogen is to demonstrate ISO-Grade D purity levels (99.97% vol. H_2). That has been achieved during system operations with consistent values along the testing campaign, thus hydrogen that can be utilized in sectors like mobility or industry.

The NH_3 conversion in the membrane reactor stayed always above 99.5% during the operational phase, all registered in a dedicated online mass spectrometer, indicating that the reactor design was optimal to convert the NH_3 inlet into hydrogen.

Nevertheless, the target of 200 kg/d recovery rate from the released hydrogen from the reaction has not been achieved during AMMOGEN project because of increased pressure drop and temperature losses in principal equipment as measured during the operation. The gathered feedback will be utilized by H2SITE for system optimization in scaled units.

The LCOH of the AMMOGEN project was also calculated. Considering the economy of scale and the need of optimization, the resulting value is higher than a fully optimized and commercial system. The expected LCOH of commercial scale NH_3 crackers utilizing the technology developed within the project will be in the range of 1 - 1.5 £/kg, excluding NH_3 consumption.

4.2 Secondary Project Benefits

Dissemination activities undertaken (including media coverage)

Following agreement of the Communications Strategy for the project, an initial stakeholder engagement list was agreed, and a suite of assets prepared.

This includes a website (https://AMMOGEN.co.uk/) which went live at the beginning of the project, a PowerPoint slide deck and a branded document template for externally facing project outputs.

The website included an animation video to promote the AMMOGEN project linked to the project website (Figure 16).

Figure 16: AMMOGEN project website homepage

Using analytics, continuous updates and monitoring of the webpage were undertaken. Most visitors were from the UK where the site is located, followed by the USA, France and the Netherlands.

Key outputs were developed over the course of the project, such as *Outreach to potential customers* and *Dissemination workshop(s)*. This was to enable the dissemination of project results and, especially, gain interest from future potential customers.

As part of the strategy, the University of Birmingham (UoB) regularly reached out to the public, including business-to-business communication. This was performed to spread information on project outcomes as well as utilise contacts from their interactions with other partners in projects such as the UK Hub for Research Challenges in Hydrogen and Alternative Liquid Fuels (Hy-RES) and Hydrogen Integration for Accelerated Energy Transitions (Hy-ACT), and stakeholders from the previous Supergen Hydrogen and Fuel cells (HFC) Hub.

This was complemented with e-mail distribution lists of the Birmingham Energy Institute at UoB, the Midlands Energy Research Accelerator (ERA), the HyDEX project and Gemserv.

As part of the dissemination Workshop series, a series of presentations were made with 20-minute talks from key project partners and stakeholders followed by 10 minutes for discussion with attendees. An example is shown below in Figure 17:

Figure 17: AMMOGEN workshop

Discussions with the audience and other key stakeholders were held on the energetic viability of ammonia as a means of transporting hydrogen, the economic feasibility and environmental concerns. Afterwards, a tour of the BEIC facilities offered the participants insight into the University of Birmingham work. Touring the outside of the building offered them a brief overview of the physical layout of the ammonia plant as it is planned to sit beside the existing ITM Motive hydrogen filling station.

The presentation slides from the sessions have been uploaded to the project website[7].

[7] Ammogen Website Home Page

Tyseley Energy Park and the University of Birmingham regularly have government and industry representatives visit the site or discuss the project at workshops and events. During these visits, guests are given a presentation about the key developments on-site before going on a tour of facilities. Also, during external events, presentation details of the AMMOGEN project are shared.

On the 12th of March 2024, the project hosted the AMMOGEN launch event (shown in Figure 18). The session took place at Tyseley Energy Park and gave delegates a deeper dive into the technology behind the project. Guests also had an opportunity to tour the facility.

Figure 18: AMMOGEN launch tour

22 delegates registered to attend the session; delegates comprised of businesses from varying sectors. These included: UoB, DESNZ, Algo Energy Trading, Gemserv, H2Site, Offshore Renewable Energy Catapult, Intelligent Energy, TEP, SLB New Energy, Equans, Yara, Commercial Fuel Solutions.

As some organisations could not attend, a separate workshop was held with ARCADIS for their clients and groups on the use of ammonia as a hydrogen carrier. Clients in attendance were from the UK, Brazil and the US. In total, 12 people attended this workshop. Presentations from the AMMOGEN launch event were uploaded to the AMMOGEN webpage resources[8].

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[8] AMMOGEN (2024) Event Resources | Ammogen

A number of articles referencing the AMMOGEN project were produced such as "*Foundations laid for ammonia to hydrogen facility*" in the Engineer publication and "*UK ammonia cracking plant takes first steps in push towards hydrogen economy*" in the Chemical Engineer publication. These were replicated in a number of national and international publications relating to hydrogen and energy publications.

The University of Birmingham presented the AMMOGEN project at a conference Regatec 2024 (10th International Conference on Renewable Energy Gas Technology in Lund, Sweden). The Conference was attended by 166 delegates from 21 countries including 125 from industry. A report was published in the conference proceedings *ISBN 978-91-981149-9-7 pages 97-98*.

4.3 Intellectual Property

H2SITE have patents in place for the development and implementation of a novel membrane-based ammonia cracker application. The learnings gained during the AMMOGEN project could develop further IP concerning the exploitation and export of technology for H2SITE and the gas burner developments proposed in AMMOGEN. It is expected that the project will result collaborations with project partners in future commercial developments resulting in further promotion of the R&D from the project and maximise the IP for AMMOGEN technology and application.

4.4 Skills and Jobs

A number of high-skilled jobs have been created and safeguarded within the consortium over the course of the project. This totalled 12.5 full-time equivalent (FTE), broken down as shown in Table 3:

Table 3: Project partner FTE breakdown

Project Partner	Full-Time Equivalent (FTE)
Gemserv	2
H2SITE	3.7
EQUANS	3
Yara	1.5
UoB	0.8
TEP	1.5

The potential for the replication and scalability of the AMMOGEN system in a commercial setting is expected to drive highly skilled jobs in the hydrogen sector. The UK/EU and the international community are committed to realise the benefits of a hydrogen-based economy. Given the development of this sector, significant economic benefits are expected to arise. Increased renewable hydrogen and green ammonia activity will lead to growth and investment from the entire hydrogen supply chain.

As the sector develops, there is a significant opportunity for the UK hydrogen production supply chain to build new skills, transition skilled workers and create new export markets. Sectoral growth will also drive demand for these highly skilled individuals as well as create jobs and supply chain benefits to the UK.

4.5 Business Relationships

A number of new business relationships have been created as part of the AMMOGEN project which relate to the supply chain for the production of green ammonia and transport/bunkering at ports as well as the conversion and transport of hydrogen through infrastructure stakeholders and end users of hydrogen in the industrial and transport sectors.

4.6 Hydrogen Offtake Discussions

Over the project, several organisations reached out to the AMMOGEN consortium to understand the capabilities and plans of the project and, more importantly, the plans after the project ended. Discussions with key stakeholders of the AMMOGEN project are still being held to develop scale-up plans linked to their needs. Typical discussion questions highlighted in Table 4:

Table 4: Typical questions from prospective offtakers

TYPICAL QUESTIONS
Can you share a plot plan of the site?
What is the total surface of the site?
What is the remaining available surface available for the compressor/filling station/truck parking?
What is the exact address of the site?
Are there infrastructures and buildings nearby?
What would be the route for truck traffic?
Can you share technical documentation on the H2Site cracking technology under NDA?
What is the outlet H2 flowrate in kg/h or m3/h?

Is the flowrate continuous?
What is the outlet temperature?
What is the outlet pressure?
What is the guaranteed H2 quality and level of impurities?
How do you monitor H2 purity and link this into your control systems?
Can you provide elemental analysis of samples of the ammonia feedstock supplied to the cracker to ensure acceptable quality and purity?
Can you share a block flow diagram/process flow diagram of the H2site technology?
What are the mechanical interfaces of the cracker (output)?
What is the soil type of the site (earth, concrete…)?
What is the max load acceptable for the soil and foundations?
What is the available electrical capacity on site?
Where can we connect ourselves for the electricity supply (existing substation, electric line close by…)?
Can you share the earthing plan of the site?
Have you done a lightning study?
Can you share your HAZOP or QRA study?
What constraints do you have in your HAZOP/QRA?
How do you manage site access?
Is there already a surveillance team on site?
Should there be a technician on site all the time, or can it be remotely operated?
What permits do you already have?
What additional permits should we ask for to install a fixed compressor and filling station?
What additional permits should we ask for to install a mobile compressor and filling station?
Can you share the command system specs of the cracker (hardware, bus…)?

5 Project Management

Gemserv was the overall Project Co-ordinator and carried out the project management activities, such as the interface to DESNZ and the consortium on the funded project.

Project management was carried out by the Senior Project Manager for hydrogen projects at Gemserv: Azhar Juna. He was supported by the centralised Project Management Office (PMO) through Shahzaib Arshad.

The role of Gemserv as the Lead Party was to ensure the full satisfaction of the Consortium Agreement according to the terms on which grant funds were made available from DESNZ. The Consortium Agreement included the SBRI Services Contract and, by extension, the conduct and activities of the Consortium.

In practice, this meant assigning the relevant roles and responsibilities among the Consortium who collectively delivered the project scope and outputs. Gemserv also managed, coordinated, and integrated deliverables and meetings at the project-level (as defined by Work Packages 1 & 8), whilst providing an escalation point for DESNZ and the Consortium.

5.1 The Project Plan

The Project Plan including a detailed Gantt diagram showing the key interdependencies across work package tasks and the key deliverables was developed at inception under the Consortium Agreement. The Project Plan was continuously maintained by the Project Manager who presented progress updates and any recommendations for amendment during Project Management meetings (and, consequently, Steering Committee meetings).

5.2 Work Packages

The outputs of the project were reflected across a number of work packages that included key deliverables, payment milestones and project milestones agreed with DESNZ. The high-level work package breakdown is given below (Table 5):

Table 5: Work package breakdown

Work Package ID	Work Package Name	Project Partner Lead	Description
1	Project management and integration	Gemserv	Project management, risk management, progress reports
2	Preliminary design, testing and procurement	H2Site	Design and fabrication of cracker
3	CDM implementation and site handover	Equans	Design and implementation of civils, integration and ammonia storage
4	Operations	Equans	Operation of cracker and system
5	Land and planning	Equans	Development of planning application
6	Project Exploitation	Gemserv	Delivery of exploitation plan, ammonia supply chain and techno-economics/commercial analysis
7	Dissemination and knowledge transfer	University of Birmingham	Site visits, workshops and teaching material development
8	Fuel supply	Yara	Ammonia supply

5.3 Weekly Consortium Project Management Meetings

Project Management meetings were held every week *via* MS Teams, chaired by the Project Manager. If the Project Manager was unavailable, the PMO or any other party chaired the meeting with the agreement of those in attendance.

The Project Management meeting standing agenda used the following format:

1. Health and Safety
2. Site Operations Update (between site preparation and decommissioning stages)
3. Project Schedule Discussion (with agreed progress presented to the Steering Committee)
4. Design Discussion (including outstanding information exchanges and issues)
5. Project Change Management Discussion (with agreed changes presented to the Steering Committee)
6. Agree deadlines to share upcoming milestone deliverables between the consortium (suitably in advance of the Steering Committee)
7. Any Other Business

All parties of the Consortium were invited to attend. Parties who wished to provide a material update or those who were required for input/attention were encouraged to attend the relevant meeting and notified at least a week in advance.

Meeting notes were recorded with the following format (Figure 19):

Service Provider	Lead Name	Status Summary	Date of the report	RAG Status	
				Current	Previous
GEMSERV					
H2SITE					
Equans					
Yara					
University of Birmingham					
Tyseley Energy Park					

Figure 19: Example of internal project update sheet

5.4 Steering Committee

The Steering Committee, as defined in the Consortium Agreement, met on a monthly basis *via* MS Teams for the duration of the project unless agreed otherwise. Azhar Juna of Gemserv chaired the Steering Committee Chair, supported by Shahzaib Arshad from the PMO.

The nominated members of the Steering Committee from the consortium were invited to these sessions which, in some cases, differed from the weekly project meetings.

The Steering Committee standing agenda was as follows:

1. Health and Safety.
2. Project Schedule Update, including milestones and deliverables.
3. Project Finance Update.
4. Project Change Management Update.
5. Stakeholder Communications.
6. Any Other Business.

The Steering Committee meetings discussed progress against milestone deliverables, ascribed by an assessment of percentage complete and background commentary. Any risks to the schedule or proposed mitigations were presented during Project Management meetings for endorsement and to the Steering Committee for approval.

5.5 DESNZ Monitoring Officer Meetings

As part of the project management activities, a monthly meeting with the designated DESNZ Monitoring Officer was held providing feedback of key activities, progress, challenges and summarised information developed during the weekly project meetings and monthly steering committee.

5.6 DESNZ Site Visit and Meetings

DESNZ site visit and meetings took place every year to highlight progress and challenges. This was held face-to-face or, where necessary due to project updates and amendments, carried out *via* MS Teams before the yearly schedule.

5.7 Financial Management

The format of the Financial Plan was developed in alignment with the reporting requirements of DESNZ and was maintained by the Project Manager. Each month, every consortium member provided the Project Manager with statements of project spend against budget, excluding VAT. Then, consolidated financial updates were presented during the Steering Committee meetings as a standing agenda item. This included invoicing status and cash position against the agreed budget. Other topics discussed during Project Management meetings included potential risks to the project's financial delivery and mitigation measures.

Invoicing and payments to each Consortium Member was done in arrears from the submission and approval of the associated invoice and Work Package Deliverables. Payments were made in accordance with the agreed Project Plan or actual expenditure, whichever was lower.

5.8 Work Package & Deliverable Document Repository

Gemserv utilised SharePoint and MS Teams as the primary means of coordinating the project. A document repository was set up and Gemserv provided access to the assigned Consortium Members. Access was granted on an invite-only basis, using multi-factor authentication as part of the registration process. Continued access was monitored according to the distribution list.

Quick links were available for key documents and WP Deliverables. They were located on the front-end of SharePoint, as shown in Figure 20:

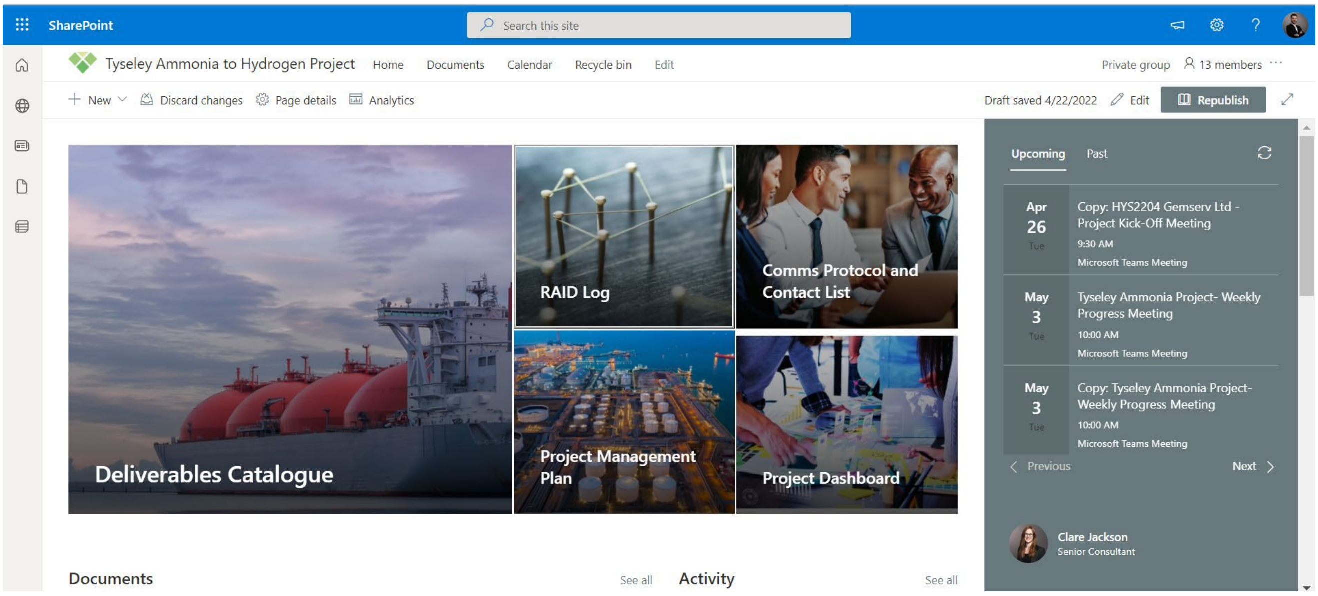

Figure 20: AMMOGEN project consortium SharePoint

5.9 Change & Risk Control Management

Due to the ever-changing technical, commercial and political environment in which the project operated, most of the documents went through multiple iterations and a formal project-wide control process was necessary to retain the level of oversight granted to the Steering Committee. Changes were only made possible by agreement of all Consortium Members.

It was also necessary to ensure risks to (or in connection with) the project were identified and considered, with subsequent mitigations offered and reflected through project documentation and activities. In particular, safety was of utmost importance to the Consortium.

A Risks, Assumptions, Issues and Dependencies (RAID) log was developed and used to capture the necessary information during progress meetings, Steering Committee meetings and dedicated risk workshops.

A record of all other approved version-controlled documents which were uploaded to the repository was reported and discussed during Steering Committee meetings.

Changes were also reflected within the RAID log, the Deliverables Catalogue and the weekly/monthly/quarterly reports. An example of the metrics used is shown below (Figure 21):

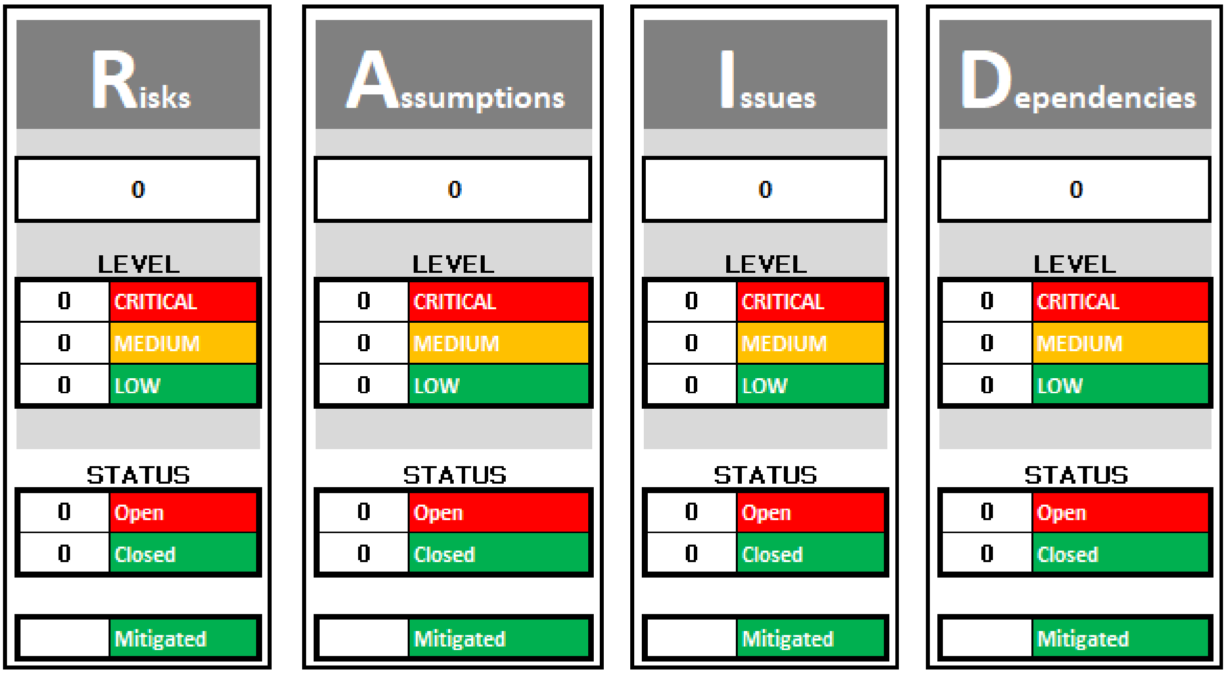

Figure 21: Overview of RAID metrics

5.10 Change Requests

When necessary, Change Requests were developed to ensure the continued viability of the project. These requests were discussed with the consortium and DESNZ. Any approved changes to the nature or sequencing of the Work Package Deliverables were reflected in a Deliverables Catalogue.

5.11 Key Risks, Mitigations and Issues

The project used risk registers that covered the pre-planning, technical work and later project execution/operation. These registers were reviewed quarterly by the entire consortium team.

The development and use of specific descriptors to what might prevent the work being successfully completed, and what might impact later execution and so could be mitigated were developed. Consortium-wide teams in the review process allowed the greatest cross-industry expertise to be used in assessing and planning the mitigation of identified risks.

Risks and issues were identified and developed as part of the RAID Log/Risk Register throughout the project. Risks, actions, assumptions, issues, decisions, and dependencies were documented as the project progressed with an updated RAG status.

Key risks were primarily concerned with completing the procurement; commissioning the snagging list; ensuring the safety and performance of equipment/systems; and keeping track of impacts to the operational test plan.

5.12 Project Management Lessons Learned

- The number of deliverables in the project plan was excessive and not effective in progressing payments to the project. Certain deliverables could have been incorporated into one. This amendment would have no impact on the payment schedule and would reduce delays in delivering the deliverables each month.

- The costs budgeted at the proposal stage changed at implementation due to inflation and other external factors. Necessary cost savings were required elsewhere to ensure the project remained viable. Where possible, more accurate forecasting as was needed for key CAPEX and OPEX components

- Procurement delays impacted project planning due to global supply chain issues for some critical components such as hydrogen compressors. Further analysis was required on procurement activities, alternative suppliers and to provide an estimation of when these tasks should have started.

- Various project insurance requirements required extra time and costs. The project engaged the services of specialist insurance broking and risk management to understand and identify the insurances required at the stages of the development, construction, and operation of this type of innovative system.

- DSEAR/Fire Risk Safety/ATEX Safety Compliance took more time than expected as external specialists had to be consulted to ensure that the innovative system could be signed off and compliant with regulations. Due to the technology's innovative nature, more time and analysis were required by all parties to complete this activity.

Due to some of the challenges stated above, a number of Change Requests were required to ensure the project kept on track. These were developed in conjunction with DESNZ.

6 Commercialisation Plans

Since hydrogen is seen as one of the key solutions to decarbonisation, the hydrogen market in the UK and the European Union is predicted to grow significantly over the next years.

Hydrogen demand will come from a range of sectors including the power sector, heavy industry and transportation. The role of ammonia as a hydrogen carrier within that market has gained significant traction and there is strong interest in the development of green ammonia to hydrogen infrastructure.

Countries that have access to low-cost renewable electricity have a comparative advantage in producing electrolytic hydrogen and have the opportunity to export this low carbon fuel to areas of higher demand. Transporting hydrogen in the form of ammonia is the most economical option for large distances and is, therefore, a viable option for hydrogen imports from further afield.

A considerable number of ammonia-related commercial projects are currently emerging across Europe, UK and in global regions such as the Middle East and North Africa. The European Commission's **REPowerEU** policy outlined the potential for ~4 MT of hydrogen imports in the form of renewable ammonia or other hydrogen derivatives by 2030 [9]. This figure is equivalent to 20 MT of ammonia - five times the amount of ammonia imported into the EU in 2020. The expected increase in ammonia imports stresses the need to scale up existing ammonia infrastructure.

Ammonia crackers will play a vital role in this market as they are needed to convert ammonia back into hydrogen. However, this must be done in a cost effective and efficient manner.

The AMMOGEN project aimed to deliver the highest efficiency ammonia cracking technology for hydrogen suppliers and end users. This is achieved through reduced OPEX costs; the cracker is operated at a significantly lower temperature (i.e., 450°C) than state-of-the-art industry standard ammonia crackers which operate at 600-950°C used in current technology on the market. Another cost-effective benefit of the AMMOGEN technology is that its membrane process module purifies the produced hydrogen in a one-step process that negates the need for further CAPEX downstream for purification. The development of innovative reactors that decompose and separate fuel cell purity hydrogen within the same vessel increases the hydrogen recovery factor and its energy efficiency at a lower temperature compared to conventional systems.

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[9] RePowerEU: supporting the full switch of existing hydrogen production to renewables - Ammonia Energy Association

6.1 Route to Market Assessment

Scalability and replicability will be defined by the requirements of different commercial partners.

H2SITE, who developed the proprietary technology for AMMOGEN, has developed different specifications for their technology including centralised, decentralised, and on-the-move ammonia crackers.

In terms of technology readiness, H2SITE has progressed to achieve Technology Readiness Level 8 for medium-sized crackers and is currently working to achieve Technology Readiness Level 9 for medium-sized crackers – the final level on the maturity assessment scale. While the membranes have already reached commercial readiness, the integrated catalyst units require further testing and development. In addition to testing large-scale crackers during the AMMOGEN project, H2SITE will set up a replica of an on-board ammonia cracker unit. This will enable maritime vessels to test the performance of the auxiliary power unit. The cracker could support the decarbonisation of the maritime sector.

The business model includes targeting the following applications:

- Hydrogen Refuelling Stations for urban and extra-urban locations.
- Hydrogen for industry.
- Hydrogen for centralised infrastructure.
- Onboard solutions for maritime power.
  Off grid sites for power production substitution.

6.2 Route to Market Strategy

The market is giving clear indications about the relevance and economic advantages of ammonia as a hydrogen carrier for long distance transport. An increase in hydrogen demand, that is unlikely to be met by domestic production, underpins the assumption that hydrogen will be imported into the UK and Europe. Thereby, cost-efficient ammonia cracking solutions will be needed. To meet these demands, key targets have been defined based on internal commercialisation plans.

6.3 Scalability and Applicability to Other Sites

Scalability is another factor to meet future demand in this growing sector. H2SITE's plans for scalability are highlighted below and show the need to scale to x100 tons/d based on market demand (Figure 22).

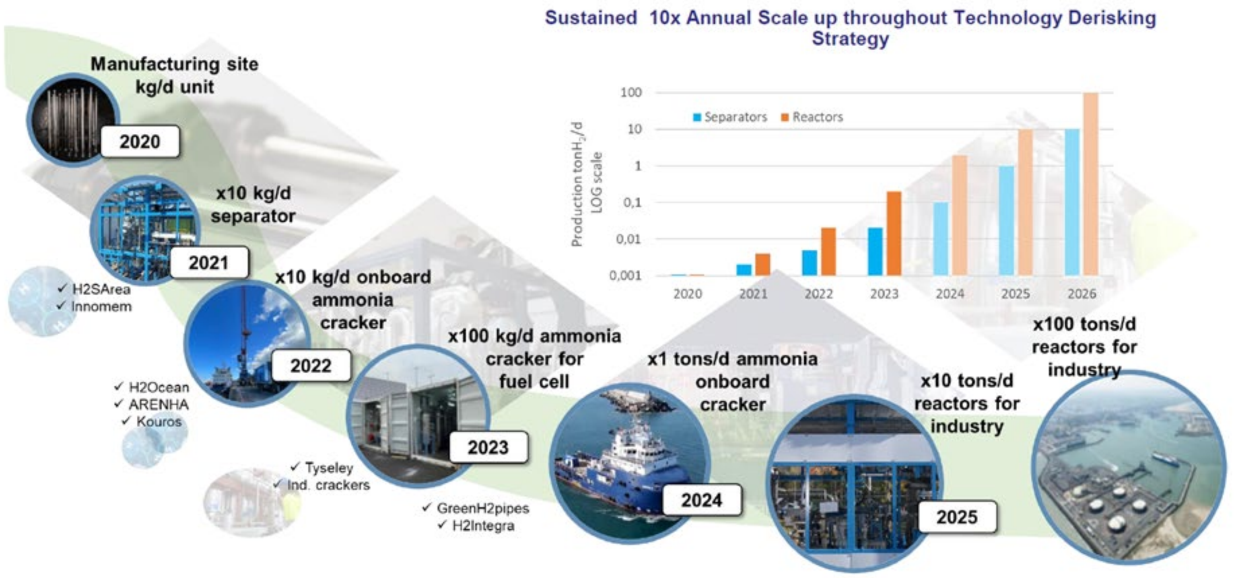

Figure 22: Scalability overview

H2SITE manufactures the membrane units for different business models looking to provide their customers with hydrogen. The business model includes mass production of certain units, but also custom-made products for larger projects requiring bespoke solutions and certification programmes. This could be relevant for large infrastructures for centralised ammonia distribution. H2SITE's sales strategy consists of an initial phase of demos with business model pioneers to convince potential buyers of the technology's functionality. The initial phase will be followed by a commercialisation phase in which H2SITE supplies these products so they can install it for their end users.

6.4 Considerations around access to revenue support mechanisms

To secure the successful penetration of the market segments outlined above, the H2SITE requires policies that offer the necessary financial support; incentivise the consumption of hydrogen; and introduce ammonia certification schemes. To accelerate the hydrogen economy, an extensive framework is needed to provide security to investors.

To decarbonise the sectors discussed, funding schemes that complement industry investments are needed. A mix of CAPEX and OPEX funding would support the implementation of large-scale projects, thereby aiding the growth of relevant hydrogen ecosystems through off-takers. Future EU and UK funding mechanisms will be explored to support the commercialisation and implementation of this technology in the marketplace.

6.5 Off-Take Discussions

Over the course of the project, several organisations reached out to the AMMOGEN consortium. They sought to understand the project capabilities and plans and, more importantly, the plans after the project ended.

7 Conclusions and Next Steps

The AMMOGEN project achieved several KPIs and validated the technology based on operational data and key results. Nevertheless, some KPIs were not fully achieved based on learnings and optimisation and system upgrades. Therefore, a strategy to meet these challenging KPIs can be implemented after the project end date.

In terms of system improvements, key learnings on the system design have been identified and will be implemented in the next generation system development.

Other lessons learned from AMMOGEN include the following:

- The importance of an experienced integrator in the safety and operation of a first of a kind system. Technology integrator must provide safety functions external to technology packages to contain ammonia e.g., through bunds and strong integration of control systems. Material selection learnings are paramount. Seasonality to be considered – pre-heating of ammonia required in winter months.

- Immaturity of Supply Chain. Off the shelf equipment must be prioritised to prevent long delays and high lead times. All partners and suppliers must understand and meet UK regulatory requirements. Instrumentation specifications must be modified for use in ammonia and hydrogen, and supply chain must understand the importance of this.

- Automation is key to scale up. More automation is required to scale due to the costs involved in manning sites.

- Further interaction with engineering insurers is required to develop policies for innovative technologies. A more detailed underwriting approach for this segment would help capture the risks associated with new hydrogen production, storage and transport technologies.

- Discussions with the insurers regarding the process and chemicals property risk from ammonia and hydrogen; organisational risk of ensuring adequate maintenance; implementing inspection procedures, operating procedures and training for personnel. Given the nature of this technology compared to existing hydrogen generation systems such as electrolysis, more time was needed to ensure adequate insurance coverage and to conduct discussions with insurers.

To make ammonia cracking sustainable and economical, the process must use as little fossil-based energy as possible and be linked to renewable energy sources with a PPA. Other key areas that could be explored further include optimising catalysts further and reducing the reactor operating temperature. For the centralised, large-scale production of clean hydrogen *via* ammonia cracking, the use of the ammonia's own energy is the optimal solution. This is due to process engineering reasons and to avoid CO2 emissions, be that from re-use of waste heat or “burning” some ammonia/hydrogen to heat up the reactor.

There are several key technical optimisation and commercial steps which could develop the technology further:

- Optimising the cracking reactor design and system operating temperature. Mechanical and thermal design of the cracking reactor has a significant impact on the efficiency of large-scale ammonia cracking plants. Reactor redesign to increase pressure and temperature in membranes for hydrogen permeation and minimise pressure drop.

- Sufficient spare membrane modules and other components such as actuators and sensors on site available to reduce replacement downtime.

- Reduce any potential ammonia slip from scrubber with a more optimised system.

- Developing the catalyst for lower operating temperatures and considering the need to reduce rare earth and costly catalysts in the ammonia dehydrogenation reaction.

- Optimising the process conditions that impact cracking efficiency and its suitability for industrial scale. Ensure a complete reaction while avoiding negative effects on the catalyst material the pressure and temperature of the reaction.

- Refining the selection of process materials by considering novel coatings and lower cost materials for key reactor components. Removing the need for more exotic alloys for construction materials.

- Improving the economics of the ammonia dehydrogenation process.

- Developing new business models related to the use of hydrogen from ammonia or for various applications such as centralised and distributed power generation, shipping, heavy mobility, etc.

For ammonia cracking to gain significant traction for the hydrogen economy, key economic considerations need to be addressed in conjunction with technical developments. In this way, ammonia's potential as an effective zero emission energy carrier could be realised.

Business development plans with agreed ammonia feedstock and hydrogen offtake pricing models need to be developed. These models must be linked in with supply chain and infrastructure for the implementation of large-scale projects. Supporting financial incentives and mechanisms are needed to encourage investment and adoption. These mechanisms will play a crucial role in mitigating upfront costs and incentivising industries to adopt ammonia cracking technology.

A shift to green ammonia production is also needed for the downstream production of green hydrogen using the ammonia cracking technology proposed. This would benefit key industry sectors to decarbonise utilising green ammonia and therefore green hydrogen.

Hazards related to ammonia are attributed to its flammability and toxicity. These hazards are well understood within industry due to the large number of operating ammonia plants globally. However, additional safety precautions are required to mitigate toxicity and explosion risks for specific use-cases and applications.

Although the handling and use of ammonia is well-established, for any new application health and safety, regulatory and public acceptance considerations will need to be developed. Part of this exercise has been conducted through AMMOGEN. However, further work is needed especially once the technology has been scaled up and demonstrated in large industrial settings.

Regarding next steps for the AMMOGEN technology, H2Site is confident that with further refinement and optimisation the technology will be able to meet all the stated KPIs with 200 kg of hydrogen per day with 75% availability. Follow-on projects are in the process of development with key end users to demonstrate technological application at an industrial scale.

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