Low Carbon Hydrogen Supply 2 (Stream 1 Phase 2)

ASPIRE - Phase 2

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Acknowledgements

The ASPIRE project has been primarily funded by the Department for Energy Security & Net Zero (DESNZ) but also financially supported by STFC.



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Executive Summary

This report describes the ASPIRE (Ammonia Synthesis Plant using Intermittent Renewable Energy) project led by the Science and Technology Facilities Council (STFC), funded by the UK Department of Energy Security and Net Zero (DESNZ). The purpose of the ASPIRE project was to assess the technical and commercial feasibility of a novel flexible e-ammonia synthesis technology and has delivered a small-scale demonstration plant (ASPIRE MK0) at the Rutherford Appleton Laboratory in Oxfordshire, rated at 150kW peak power consumption and 300kg/day capacity of ammonia production. E-ammonia is ammonia made with water, air and electricity. The ASPIRE design included two key technical developments to facilitate e-ammonia production from a variable renewable power source:

- High turn-down, rapid-response synthesis loop.
- A control system that allows the production rate to track available renewable power.

The ASPIRE MK0 plant is now fully functional and has produced over 100kg of e-ammonia during initial testing. Through-life carbon emissions are predicted to be 0.2kgCO2/kgNH3, whereas those of grey ammonia are at least 2kgCO2/kgNH3. The plant demonstrated flexibility while maintaining near-optimum operating conditions, thus meeting the requirements of high-turndown and rapid-response. The preliminary results are very promising, showing 40% efficiency at 30% of maximum generation rate. The novel control strategy was proven and used to test the plant against a simulated renewable profile that changed load every 5 minutes. Initial results are presented in this report, but complete performance results will be published once further testing has been completed. A fully UK-compliant design at the 150kW scale with Environment Agency approval and planning permission has been achieved, which is a strong basis for scale up and commercial feasibility. Technoeconomic modelling of the ASPIRE technology at a 5MW scale provided a predicted levelised cost of ammonia of £855/tonneNH3, enabled by Hydrogen Allocation Round (HAR) subsidies.

Multiple end uses of ammonia from ASPIRE technology are discussed in the report; the following three markets are presented with commercialisation plans:

1. **Ammonia as a commodity** – The ASPIRE prediction is more expensive than current grey ammonia pricing in the UK but initiatives such as CBAM, or import taxation to incentivise domestic production, could make the ASPIRE product competitive.
2. **Ammonia for energy storage** – New market opportunities exist for providing long duration energy storage and curtailment mitigation, appearing first in remote locations or areas with low-resilience grid infrastructure. Above a certain storage duration of the order of two weeks, ammonia energy storage would immediately be competitive with alternative energy storage methods.
3. **Ammonia as a marine fuel -** Opportunities for marine fuel could appear at the small scale where customers are willing to pay a premium for decarbonisation (e.g. leisure marine sector), but e-fuel subsidies will be required to compete with diesel or heavy fuel oil to achieve market potential.

This report describes all aspects of the project, including background, design, safety & regulations, procurement, testing, commercialisation plans and next steps.

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Glossary/Abbreviations/Acronyms

ASPIRE	Ammonia Synthesis Plant from Intermittent Renewable Energy
BOP	Balance of Plant
Blue Ammonia	Ammonia produced from natural gas with carbon capture and storage
CAPEX	Capital Expenditure
CDT	Doctoral Training Centre
CFD	Computational Fluid Dynamics
CSO	Chief Scientific Officer
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DESNZ	Department for Energy Security & Net Zero
DIT	Department of International Trade
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
DSIT	Department for Science, Innovation and Technology
EA	Environment Agency
ERU	Energy Research Unit (at Harwell)
FNC	Frazer-Nash Consultancy
Green Ammonia	Ammonia produced from renewable energy
GARC	Green Ammonia Research Centre
Grey Ammonia	Ammonia produced from natural gas with no carbon capture and storage
GVA	Gross Value Add
HAR	Hydrogen Allocation Round
IRR	Internal Rate of Return
JM	Johnson Matthey
LCOA	Levelised Cost of Ammonia
LCOH	Levelised Cost of Hydrogen
LOPA	Layers of Protection Analysis
OPEX	Operating Expense
PDR	Project Scope, Definition and Requirements
PEM	Polymer Electrolyte Membrane
PE(S)R	Pressure Equipment (Safety) Regulation
P&ID	Piping and Instrumentation Diagram
PPA	Power Purchase Agreements
PPM	Parts Per Million
PSA	Pressure Swing Adsorption
PSSR	Pressure Systems Safety Regulations
RAL	Rutherford Appleton Laboratory
RFNBO	Renewable Fuel of Non-Biological Origin
SHE	Safety, Health and Environment Group
STFC	Science and Technology Facilities Council
UKERC	United Kingdom Energy Research Centre
UKRI	UK Research and Innovation
UoB	University of Bath

1. Background

1.1. Company/Consortium Information

The project was completed by a consortium that was led by the Science and Technology Facilities Council (STFC) and sponsored by the Department for Energy Security & Net Zero (DESNZ).

Launched in April 2018, UKRI (UK Research and Innovation) is a non-departmental public body sponsored by the Department for Science, Innovation and Technology (DSIT). UKRI brings together the seven disciplinary research councils (one of which is the Science and Technology Facilities Council (STFC)), Research England, which is responsible for supporting research and knowledge exchange at higher education institutions in England, and the UK's innovation agency, Innovate UK.

STFC's vision defines its overarching objective, and how it can make a major contribution to the success of UKRI, by developing and exploiting its areas of science and its critical large-scale research infrastructures that support industrial and academic researchers across the whole spectrum of science.

STFC's Strategic Context and Future Opportunities report [1] takes into account the key Government strategy documents such as the Integrated Review of Security, Defence, Development and Foreign Policy [2], the Innovation Strategy [3], the Levelling up White Paper [4] and the first National Space Strategy [5]. STFC also contributes to UKRI's ambitions.

STFC's current Strategic Delivery Plan (published in September 2022) [6] lists its 5–10-year vision. STFC seeks to address a number of objectives including working across disciplines as part of UKRI and with external partners. Using its expertise STFC aims to target national priorities and transformative technologies, such as Net Zero, Space, Defence and Security, and applications of quantum technologies.

The STFC's Rutherford Appleton Laboratory (RAL) located in Didcot, Oxfordshire, where the Demonstration plant has been built, is an important part of the UK's R&D infrastructure. It has dedicated resources to ensure that the results of research work carried out by the Laboratory's 1500 professional scientists and engineers is disseminated to industry, academia, policymakers, and to the general public.

STFC was the lead organisation for the ASPIRE Phase 2 project with support from the following key consortium partners:

1. Johnson Matthey (JM) is a leading multinational with around 14,000 employees in the UK with expertise of ammonia synthesis technologies and a mission statement to work towards net zero by 2040 and became a signatory to the Business Ambition for 1.5°C, making them a member of the UNFCCC's "Race to Zero" campaign ahead of COP26. The catalyst developer completed confirmed performance modelling over the ASPIRE operating range as well as manufacturing and testing catalysts before supply. JM collaborated closely with STFC on the modular reactor and synthesis loop design. As well as technical expertise, JM brought knowledge of future markets, and they are particularly interested in commercial technology opportunities with small flexible ammonia generation.

2. University of Bath (UoB) received their Royal Charter in 1966 and are now established as a top 10 UK university with a reputation for research and teaching excellence. The Operational Edge Case and Scale Up Modelling was led by the Chemical Engineering Department who offer undergraduate and postgraduate degrees that draw on their innovative research and links with industrial and commercial sectors. These resources support individual projects and consider problems relevant to industry and develop technical, professional and design skills.
3. Frazer-Nash Consultancy (FNC) help organisations deliver innovative systems, engineering and technology solutions to make lives safe, secure, sustainable, and affordable. As a contractor FNC responsibilities included project design and process governance, independent safety assessments, control system support and business case and commercialisation assessment.

The ASPIRE project team also shared their progress with the following stakeholders:

1. Utility providers including EDF Hynamics and Engie.
2. DNV who have a history of wind farm development but also development of new net zero technologies in the hydrogen space.
3. University of Birmingham who have established centres focused on sustainable and circular technologies and energy storage.
4. STFC teams: Stakeholder Engagement (who interact with policymakers), Safety, Health and Environment (consulted on plant requirements ensuring compliance with organisation's policies and procedures), Communications (who interacted with national and local media), Public Engagement (who worked to disseminate details of STFC's work to the general public and in particular to university students and schools), and the Business and Innovation Department (who have extensive contacts with UK industry, and specialise in protecting and exploiting STFC's IP).
5. The Harwell EnergyTec Cluster since its launch in 2018 has brought together more than 80 participating organisations on the Harwell campus and over 100 in the wider network. It offers support for incubation, acceleration, funding, technical partnerships, expertise and skills, and routes into investment opportunities.

STFC's Business and Innovation Department took part in the Energy Innovation Summit 2022 at the SEC Glasgow and outlined the work that had been carried out in Phase 1 of this project. There was considerable interest from the participating companies (which included National Grid, Electricity and Gas supply companies) and organisations (including Ofgem, UKRI, Innovate UK, the Catapults). Subsequently future "Energy Innovation Summits", were attended as this is a very effective method of interacting with key staff in the energy supply industry. STFC is a long-term member of RenewableUK (the trade body for the UK wind and offshore industry) – indeed, the organisation can trace its origins back to an initial meeting held at the Rutherford Appleton Laboratory in 1978. Potential users of the technology being created in this project include onshore and offshore windfarms. It is therefore planned to disseminate information about the project via RenewableUK. Energy Research Unit (ERU) at Harwell is also now a member of the recently formed Green Ammonia Working Group and will present ASPIRE at one of their events.

STFC arranges a week of "Laboratory Open Days" every ten years – the Rutherford Appleton Laboratory's last such event was held in 2024. The week included dedicated days for interaction with policymakers, industry, academia, schools and colleges, and on the concluding weekend, the general public (during which the ASPIRE project was showcased).

Additionally, the STFC's ERU has many linkages into the UK academic energy community and has used these to promote capacity building particularly amongst students, postgraduates, and technical staff.

ERU is a founder member of the EPSRC/ESRC funded UK Energy Research Centre (UKERC) and since 2004 has run the UKERC Energy Data Centre which holds and disseminates information about UK energy R&D activities, and also curates data for use by academic and industrial researchers in a secure national data archive. Non-commercial operational data from the Demonstration Plant is being lodged in the UKERC Energy Data Centre for use by researchers.

The ERU was also the Principal Investigator for an EPSRC grant which had the aim of supporting academic research into green ammonia being carried out in four established Doctoral Training Centres (CDT's) - the ASPIRE Plant has been featured in consortium events.

In September 2022 the ERU hosted a post-conference visit by 45 delegates attending the "1st International Symposium on Ammonia Energy". It was clear that the delegates (who were drawn from both the UK and overseas) were very interested to hear that STFC had been funded to carry out the Phase 1 design study. The project team have attended subsequent international symposia and published their work through this channel. It is believed that this is an excellent way to keep the UK at the forefront of Green Ammonia R&D activities and so prepare the way for potential exports of UK Green Ammonia technology. The ERU has hosted a number of high-profile visits over the last three years including from the Government Chief Scientist, the Chairman and Chief Executive of Network Rail, senior delegations from Electricity Supply Companies, Siemens Energy, and regional bus companies. Visits of this nature will continue to provide an opportunity to show the Demonstration Plant to opinion-formers and policymakers.

1.2. Project Background

[What is ASPIRE and what does it produce?] ASPIRE stands for Ammonia Synthesis Plant using Intermittent Renewable Energy. Phase 2 of the ASPIRE project has delivered a small-scale demonstration plant (ASPIRE MK0) in Oxfordshire which has proved a novel (patent pending) flexible e-ammonia synthesis technology which enables green ammonia (NH_3). "E-ammonia" is ammonia made with hydrogen derived from electrolysis of water. Green ammonia is a term used to describe e-ammonia when the production process is powered by renewable energy. Green ammonia is considered an important net-zero compatible hydrogen-based energy vector that can be cracked to supply hydrogen, used directly as a carbon-free fuel or act as a sustainable chemical feedstock (for fertilisers, explosives etc.). There are no process carbon emissions associated with green ammonia from ASPIRE and therefore it falls into the zero-carbon hydrogen production category. The EU classifies green ammonia as a Renewable Fuel of Non-Biological Origin (RFNBO).

[What is the current industrial method for ammonia production?] The vast majority of ammonia that is currently traded is known as grey ammonia. It is produced in large-scale, steady-state Haber-Bosch plants where hydrogen is obtained from natural gas through Steam-Methane-Reforming. Grey ammonia production is responsible for 2% of global CO_2 emissions, traditionally running from plentiful natural gas supplies, these plants are optimised for steady-state operation; their catalysts and thermal management are designed to achieve maximum efficiency at a large scale in a narrow range of operation. In Puertollano, such a plant was coupled with 20MW green hydrogen from solar power so that, when possible, a portion of the input hydrogen is green and otherwise from natural gas. However, commercial plants like this can only be viably turned down to 70% or 80% of

maximum generation rate. Other industrial innovations developed elsewhere include implementing carbon capture and storage with the grey process (blue production). Green ammonia brings the technical advantages of having much lower carbon emissions than both grey (<10% of grey) and blue production (<30% of blue) and it is suitable for a wider variety of scales. Its commercial advantages are that it can make use of cheap electricity, avoid emissions penalties and is decoupled from the volatile price of natural gas.

[What are the technology gaps that ASPIRE addresses?] The production of RFNBOs, "e-fuels" and "green chemicals" is a rapidly expanding field of engineering with a common requirement for flexibility. A new generation of synthesis plants is required which must obtain calorific content from a source other than fossil fuels (e.g. electrolysis) and secondly must flex depending on the availability of renewable power. These plants may be powered in an islanded microgrid with local renewables or from national grids via renewable power-purchase agreements (PPAs) designed to ensure temporal and spatial correlation. In both cases the available power fluctuates frequently, and so the ability to ramp generation rate up and down, or turn off for a period, is essential to guarantee the green credentials of the product. The development of PPA regulations for RFNBO production is underway in the EU, with the stringency of temporal correlation increasing from monthly to hourly matching in 2030 [7]. The regulations are being set and the ASPIRE project proposes a new way to address the flexibility technology gap for green ammonia, but the innovations may find application in the production of other RFNBOs, such as sustainable aviation fuel. A further development need investigated by Phase 2 of ASPIRE is the higher degree of automation required by RFNBO plants in comparison to traditional plants if they are to be commercially viable at smaller scales, where paying for teams of operators is too expensive [8].

[What are the early opportunities for green ammonia?] Markets for localised agricultural supplies of green ammonia are emerging, with early-stage companies introducing pilot plants on farms in recent years [9,10]. Here, business cases that emphasise sustainability, the supply security of localised green ammonia, and the opportunity to simplify logistics and avoid import costs are developing. The agricultural sector offers the opportunity to realise the value of the ammonia with no follow-on processing in countries where direct anhydrous ammonia fertilisation is common practice. However, follow-on technologies (such as ammonia crackers and ammonia combustion systems), which are currently under development, may soon enable the hydrogen supply, energy storage and marine fuel markets.

[What are the longer-term opportunities for green ammonia?] There is strong emissions-saving potential to be realised by demonstrating cost-effective flexible green ammonia production; 2% of global CO_2 emissions would be saved if grey ammonia used for fertiliser were substituted by green ammonia. ASPIRE supports the development of decentralised, dedicated green ammonia plants enabling countries and regions to generate their own ammonia from local renewable power supplies rather than importing it. In addition, green ammonia production is predicted to expand significantly over the next 10-20 years as it is adopted as a carbon-free fuel in hard-to-decarbonise sectors such as shipping, peaking power plants and in the supply of hydrogen fuelling stations [11]. These new uses could unlock global CO_2 savings of 10%-15%. The benefit of generating green ammonia locally is that ammonia price will not be affected by volatile gas prices thus bringing energy security as well as food security.

[What was the state of ASPIRE at the start of Phase 2?] Key outcomes of Phase 1 of the ASPIRE project (ASPIRE Phase 1 Report) were the concept design of the plant, and the hypothesis that the optimal method for achieving flexibility of power demand was to make the synthesis process flexible, rather than relying on large hydrogen stores or batteries. Phase 1 ended with a high-level design of all major subsystems: an energy island to provide off-grid local renewable power (removed from Phase 2 in a descope), a pressure swing adsorption system which extracts nitrogen from air, an electrolyser which splits hydrogen from water, an agile ammonia synthesis loop (novel twist on a classic Haber-Bosch synthesis design) and a thermal store.

[How was Phase 2 to develop the ASPIRE concept?] Phase 2 provided an opportunity to build a demonstrator to turn the design into a feasible technology whilst revisiting the technoeconomic modelling with this mature design, capturing the learning of having built a real plant. The 150kW scale was chosen for the demonstrator and the 5MW scale was chosen for the technoeconomic studies. When referring to an ASPIRE plant capacity, a plant is given a power rating that corresponds to the maximum capacity of the renewable supply to the plant. Table 1 gives the annual ammonia production capacity of plants referred to throughout the report.

Table 1: ASPIRE Plant Renewable Supply Capacity and Corresponding Total Generation Capacity

Plant Power Capacity	Ammonia Generation Capacity (tPA)	Comments
150kW (ASPIRE MK0)	120	This is the size of the demonstrator that has been built at RAL during Phase 2 of ASPIRE (ASPIRE MK0).
500kW	400	The smaller of the two proposed sizes for future ASPIRE "modules".
1MW	800	Sizing provided for reference.
5MW	4000	The larger of the two proposed sizes for future ASPIRE "modules". This scale was studied in the techno-economic modelling components of Phase 2.

2. Project Overview

2.1. Aims and Objectives

Project ASPIRE focuses on achieving the lowest cost generation of green ammonia from intermittent renewable power. The project mission statement was as follows:

To determine if it is technically and commercially feasible to develop a green ammonia plant that can run on intermittent renewable power.

To guide the system design and provide criteria for assessing its commercial feasibility, a series of requirements were developed at the outset of the project, as follows.

No.	Description
1	Plant is able to run on an intermittent source of electricity from an onshore wind farm of output 10 – 200MW.
2	Technology exists to develop an operational plant within the next 3 years.
3	There is a market for green ammonia produced from renewables at this scale.
4	Through-life cost of the green ammonia produced from intermittent renewable power is competitive with other green ammonia technologies.
5	Ammonia produced is low carbon and has through-life carbon emissions <0.42 kgCO2/kg NH3.
6	Technology meets all safety and regulatory requirements.

A corresponding set of technical feasibility objectives were introduced to guide the demonstration and techno-economic modelling activity.

1. **Demonstrate a novel level of flexibility for a green ammonia plant.** Success would be the demonstration that ASPIRE can run between 10% - 100% capacity and move between these points of operation while maintaining a power to ammonia generation efficiency of at least 50%.

2. **Demonstrate the rapid response provided by the thermally managed modular reactor system.** Success would be to change production rate from one setpoint to another, including from off to on, in 30 minutes. This demonstration would prove that ASPIRE's technology can adjust its production rate and consequent power consumption within the 30-minute period used to price electricity in the UK. The proven ASPIRE technology could make exclusive use of cheap energy during periods of overgeneration, even if they occur without much warning. This accelerates hydrogen supply by being a new type of rapid response grid infrastructure which mutually benefits hydrogen supply and grid balancing.

3. **Demonstrate the running of an ammonia plant autonomously from an intermittent power supply with very low curtailment.** New wind farms which are seen to exhibit high curtailment could drive negative public opinions for renewable energy, especially if they have caused disruption to landscapes and communities. A successful demonstration of ASPIRE would achieve 99% utilisation of renewable energy over 1 month of operation. Should ASPIRE meet this target, it would prove ASPIRE's potential to reduce the curtailment of renewable energy whilst producing a useful commodity.

4. **Demonstrate that the Levelised Cost of Ammonia (LCOA) from the ASPIRE design is significantly cheaper than if the demonstrator of this scale was to be made flexible via batteries and/or hydrogen storage.** A successful demonstration would be achieving a real LCOA that is at most 60% of the LCOAs predicted for plant configurations where batteries or hydrogen storage are used in place of the flexible reactor. This will accelerate the development of hydrogen supply because it will support the economic case for flexibility over storage in green ammonia production, answering one of the questions that could stall deployment on a large scale.

Both the commercial feasibility and technical objectives are revisited in Section 9 and assessed against the design to determine if the ASPIRE mission statement has been achieved.

2.2. Schedule

The contract for the ASPIRE project was awarded on 17th March 2023 and was scheduled to be completed by 1st February 2025. There were delays in the project commissioning and testing – consequently the project was completed on 30th January 2026. The high-level schedule activities for the ASPIRE project included:

Phase	Description	Schedule
1	Project Scope, Definition & Requirements (PDR)	March to April 2023
2	Demonstration Plant Design and Development	March 2023 to June 2024
3	Procurement	January 2024 to March 2025
4	Demonstration Plant Build	March 2024 to October 2025
5	Plant Commissioning	May to December 2025
6	Plant Testing	December 2025 to January 2026

2.3. Deliverables

The deliverables successfully realised for the ASPIRE project are summarised in Appendix 1.

2.4. Financial Information

Total contract price awarded for the ASPIRE project was £4,283,445.42. At the outset STFC also agreed to support funding of up to £280,000.00 towards capital expenditure and payroll, though its financial contribution has subsequently increased.

3. Design Considerations and Challenges

3.1. System Design

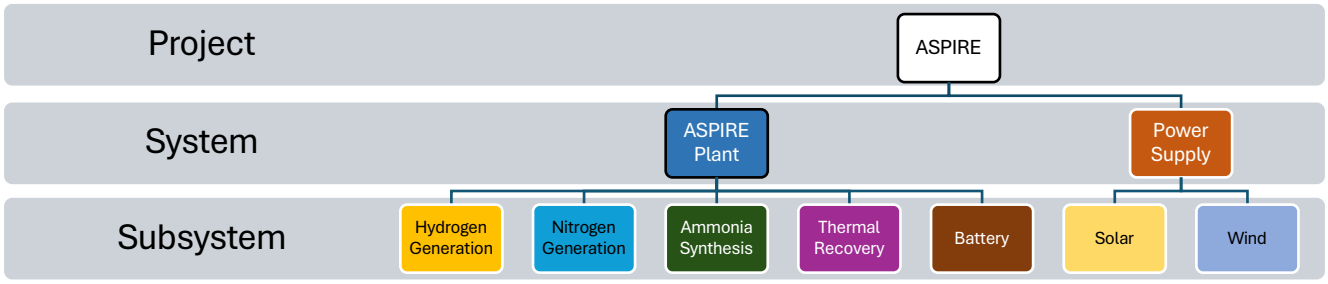


Figure 1: Product Breakdown Structure at the Start of the Project

The initial islanded design for the ASPIRE project included two systems, the ASPIRE Plant and the Power Supply. The power supply system was to provide islanded renewable energy for the ASPIRE plant. This was to have a wind and solar subsystem, with a capacity of around 150kW. The *Battery* subsystem within ASPIRE Plant was to play a balancing role between available power and the power demand of the plant. The ASPIRE plant consisted of four other subsystems, which are nitrogen generation, hydrogen generation, ammonia synthesis and thermal recovery. The nitrogen generation is achieved using a Pressure Swing Adsorption System (PSA) to separate nitrogen from ambient air. This is a commercially available unit that can deliver pure nitrogen with very low levels of oxygen, which is required if it is to be used for synthesising ammonia. The unit delivers and stores the pure nitrogen at up to 115 bar. The hydrogen generation is achieved by splitting water with a 100kW PEM electrolyser that was purchased by the project team from Oort Energy Ltd. Hydrogen is delivered at around 15 bar and then compressed via an inverter-driven reciprocating hydrogen compressor up to 110 bar and stored in a hydrogen buffer vessel. The hydrogen and nitrogen are mixed using control valves to assure the correct ratio of the two gases for making ammonia and then passed through a deoxidation dryer to ensure any remaining oxygen or water vapour is removed from the gas mixture prior to ammonia synthesis. The ammonia synthesis subsystem brings the nitrogen and hydrogen together to form ammonia using a miniaturised version of a traditional ammonia synthesis loop. The thermal recovery system was to store waste heat.

The ASPIRE synthesis loop was designed with the following key features to improve flexibility:

- Reactor enabling synthesis at optimum catalyst temperature for generation rates between 10% and 100% of maximum.
- Cyclonic directly cooled separator for compact effective ammonia separation across the range of generation rates.
- High and Low temperature recuperative heat exchangers for improving thermal efficiency across the range of generation rates.
- Direct Joule heated preheater for synthesis loop start-up.
- Low-pressure-drop synthesis loop with flow speed controllable by inverter-driven circulator to provide close control on synthesis rate.
- Storage of heat from the exothermic synthesis process in the form of hot water which could be used for reducing the PEM electrolyser's start up time.

The ammonia synthesis (Figure 2) loop is fairly compact fitting into a volume of $3m^3$.



Ammonia is condensed from the synthesis loop as a liquid and stored in an ammonia store at ambient temperature and corresponding saturation pressure. The store is capable of holding 1 metric ton of liquid ammonia.

The master document for the plant design is the Piping and Instrumentation Document (P&ID) and shows how all subsystems are connected.

ASPIRE also has two control systems that are designed to facilitate safe flexible operation of the plant. The basic process controller changes the hydrogen, nitrogen and ammonia generation rates up and down depending on the available power to run the plant. The safety controller performs safety critical control tasks such as isolating subsystems and stopping any production if parameters go out of tolerance.

Figure 2: Ammonia Synthesis Loop

The maximum power consumption of the whole plant is around 150kW and at full power is designed to generate 300kg of ammonia in a day. The whole plant sits in a space of 400 square metres and is surrounded by air rods to provide protection against lightning strikes. The plant is sited within a controlled compound and is designed to be operated remotely from a control room situated outside the plant compound. Figure 3 shows a layout of the plant with the location of the key subsystems as well as the classification of hazardous areas as a result of the presence of hydrogen and ammonia.

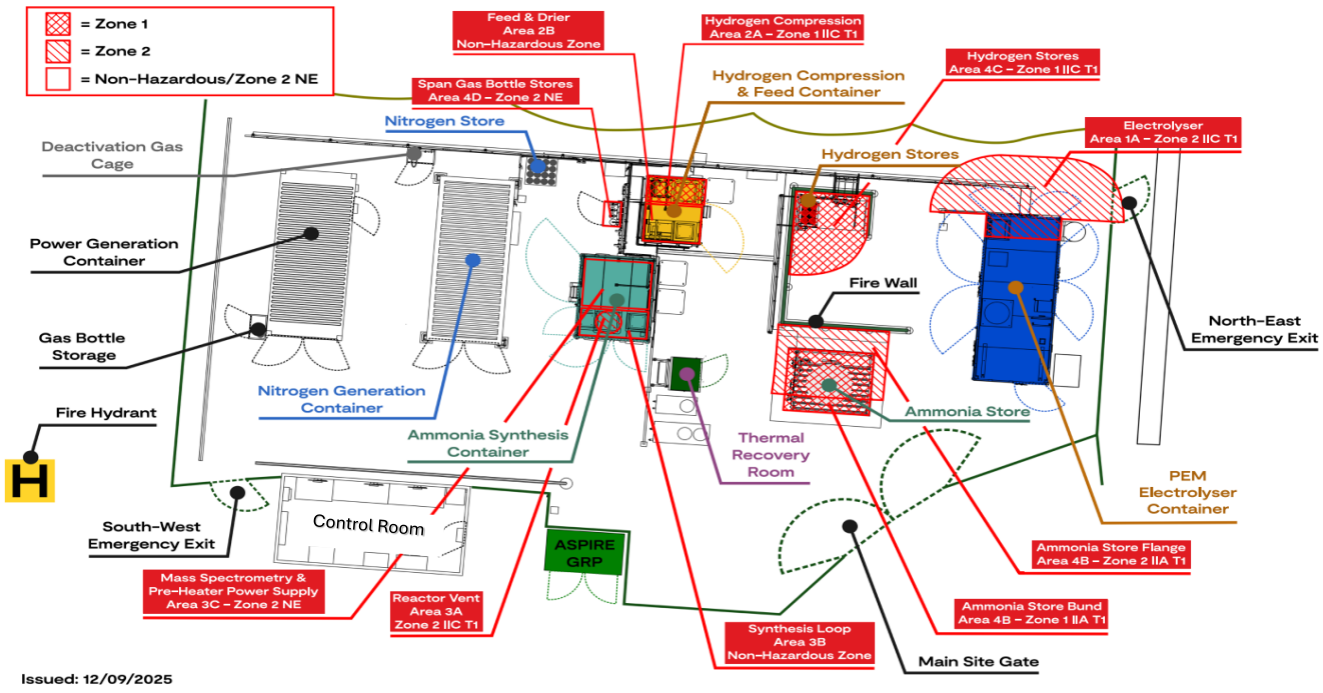


Figure 3: ASPIRE Site Map and Floor Level Hazardous Area Classification

3.2. Challenges and Verification Activities

The main challenges faced with the ASPIRE design are discussed below:

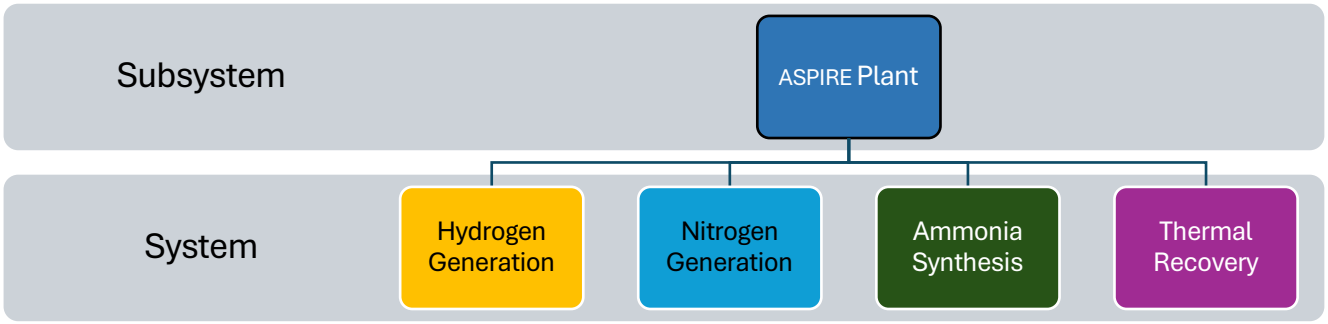


Figure 4: Product Breakdown Structure After 2024 Descope

Renewable Plant and Microgrid Challenges

The islanded operation and the battery were removed from the scope following cost escalation, meaning the final plant that was built ran from the national grid with a simplified breakdown structure shown in Figure 4. Reasons for this include errors in procurement strategy causing delays and cost escalation, and the technical challenge of a bespoke battery system with the necessary grid forming capabilities. Further reasons for the descope are given in the lessons learned sections (7.4 & 9.2) and in the TRL at start and end section (6.1). Though this was disappointing, the project team had a growing understanding that the off-grid power supply system was a significant technical challenge in its own right with the potential to derail the main technical deliverable of the ASPIRE project: the engineering and demonstration of flexible electrolytic ammonia synthesis. Furthermore, the mutual benefits of operating using PPAs with the grid were becoming more apparent; the plant would benefit from the resilience of the grid, and the plant offers an end-use to renewable power that may be curtailed from the grid. Finally, it was realised that not knowing the load characteristics had complicated the energy island design process and that gathering power consumption data of the now grid-connected ASPIRE plant could underpin a future micro-grid design, if a suitable reason for an off-grid iteration of the technology were to arise.

Nitrogen Generation Challenges

Pressure Swing Adsorption has been shown to be a flexible and reliable approach to deliver nitrogen with very low water vapour and oxygen content. However, argon is not separated by the PSA. These systems are generally provided to customers who want an inert gas in the form of nitrogen but are not concerned if the nitrogen contains some argon because that is also an inert gas. While argon is not involved with the ammonia synthesis reaction it builds up in the synthesis loop as it is not extracted with the ammonia. This reduces the effectiveness of the loop and so a continuous vent has been required to vent a small amount of synthesis gas from the loop post ammonia separation to control the build-up of argon. This is an efficiency penalty of the order of a couple of percent. An alternative way to obtain nitrogen is an air separator that generates nitrogen by cryogenic distillation, however, research and market analysis has indicated these systems would not be viable at the small scale of the demonstrator. Cryogenic distillation systems do not offer any flexibility of operation as it is only possible to turn them down to 90% of full generation rate and these systems can take several days to reach their operating temperature. The release of synthesis gas will mean a small amount of ammonia vapour is also released but this is at a level below that

where an environmental permit would be required. In any future plant developments that employ PSA there may be an opportunity to engineer an extra separation step to remove argon from the nitrogen or add a scrubber to remove and process ammonia from the continuous vent.

Reactor Design Challenges

The design of the reactor to minimise thermal stress during operational transients was a significant challenge. Designing the reactor to maintain catalyst operating temperature irrespective of generation rate was a significant design challenge. During the feasibility study we had worked on a multiple reactor design. A series of *Reactor Design* meetings were held between STFC, JM and UoB, which allowed the design to be revised according to the industrial catalysis experience of a range of engineers.

Initial results have shown that reactor temperatures are close to those predicted in the design phase and that they are maintained within fairly narrow operating ranges despite significant changes in synthesis rates.

Minimising pressure drops in the reactor, whilst also ensuring good distribution of flow at low generation rates is an optimisation problem. We believe we have found the optimum ratio of dimensions by using 3D CFD of the reactor geometry and our design has mitigated this challenge very well. In fact, the reactor itself offers only around 15% of the pressure drop of the whole synthesis loop.

Heat Exchanger Design and Thermal Storage Challenge

The project team attempted to devise a system during the design phase to extract and store high-grade heat (>300°C) from the exothermic synthesis reaction. However, despite several designs being considered, including a packed bed of gravel as a thermal store, no workable design was found. This was mainly because of the difficulty of transferring heat via the medium of a gaseous heat transfer fluid with minimal available temperature difference. This tends to necessitate a higher-pressure gas as the heat transfer fluid, but this then requires a pressurised thermal store or an additional heat exchanger loop both of which add cost or affect efficiency and level of high-grade achieved. The final design has a water-based thermal recovery system which can store heat at up to 70°C. This has proven to be much easier from a design perspective and also has been shown to work effectively. It has generated water during the tests which would be useful for maintaining electrolyser temperature when running at low load in cold weather. It also has the additional benefit of reducing the power consumption of the chillers as heat is dumped from the synthesis loop into the water storage tank rather than needing to be removed by the chiller.

Preheater Challenges

For rapid heat up the design has minimal thermal mass by using a direct joule heating approach where a low voltage high current power supply is used to pass current along the tube wall with the heating rate being directly proportional to the square of current. The principle of operation is that the pre-heating is only required for initial warm up and to recover from some transients and once the reactor is generating enough heat from exothermic synthesis, the preheater electrical power can be turned off and then it just acts as a recuperative heat exchanger. This design has proved to be effective, however, the electrical terminals where the power leads interface with the heat

exchanger proved to overheat during initial commissioning, primarily because not enough analysis effort was available during the highly compressed design phase of the project. These terminals were then redesigned with a full thermo-physical model which considered Joule heating and all modes of heat transfer, and the result enabled us to pass up to 700A DC without exceeding terminal operating temperatures of 60°C. This enabled us to apply 3kW of Joule heating directly to the stainless-steel preheater tube. During start-up of the synthesis loop from cold the integrated preheater and heat exchanger did not achieve system warm up as quickly as we had planned, it took around 8 hours for the reactor to reach a temperature of around 300°C where small amounts of exothermic synthesis started and then beyond that the heat up to operational temperature was much quicker. This slower than desired heat up rate was due to two reasons; we had initially planned an AC power source which would have enabled 5kW of Joule heating but due to procurement delays and strict project stage gate receipting deadlines we had to abandon that and go for a lower power DC power supply that could only apply 3kW. Secondly, in hindsight we discovered it would be better to keep the preheater and recuperative heat exchanger as separate units in series. It is a relatively subtle design change, but it could halve the warm up time, as with the current configuration a significant amount of the heat being applied by the preheater is lost in the outlet gas rather than being delivered to the reactor, sometimes up to 50% which means that we are only applying 1.5kW directly towards heating the reactor. While the startup time from cold could be improved, the preheater design has proved very effective at reducing the required input power when the exothermic heat from synthesis increases and at recovering reactor temperatures quickly following a trip. The fact that it is lower power than we had initially planned also means it is quite gentle at steadily heating the reactor vessel which is good in terms of thermal cycling of the reactor vessel. Also, it should be noted that once at operational temperature the preheater has proved very efficient and effective at applying a small amount of heat just to keep the reactor at operational temperature during a period of standby.

Feed Gas Purity Challenges

A significant technical challenge that was not really realised until commissioning was the need to vent off-specification gas during start-up. The plant has two deoxidation dryers; these units remove oxygen and water vapour from the hydrogen generated in the electrolyser and from the mixed hydrogen and nitrogen feed gas entering the synthesis loop. While the stringent specification on dryness and purity required by the synthesis loop has been achieved (<10 ppm oxygen content, <-35°C dew point) by both deoxidation dryers, the plant commissioning process showed that it can take time for the purification and drying systems to heat up from a cold start, complete a full cycle of batch operation and become fully effective. During this period the gas being produced is not necessarily of adequate purity to feed the ammonia synthesis process and so must be vented. As we had not foreseen this issue during start-up, we had to vent gas manually until adequate purity was achieved. The deoxidation dryers allow continuous flow through them due to a batch process where one desiccant tower is being filled with water vapour while the other is being emptied. This process was effective except that during the switch over from one tower to the other a short period of poor-quality gas has been observed, and this has caused multiple plant trips and enforced pauses in ammonia synthesis. We believe there is scope for some tuning of bypass flow parameters and heater hysteresis temperatures within the deoxidation dryers to improve continuity of performance. A small control change could also enable us to automatically vent feed gas in a controlled way if it is not of adequate purity rather than causing a plant trip.

Electrolysis Challenges

The maturity and reliability of PEM electrolyser membranes have proved to be a challenge for the operation of the ASPIRE plant. The membranes deployed in the electrolyser stack were advanced designs intended to maximise efficiency; however, during operation a gradual increase in hydrogen cross-over from the cathode to the anode was observed. In the short term, stable operation was restored by rebuilding the electrolyser stack with replacement membranes. A longer-term solution is expected to involve further optimisation of membrane designs to improve robustness at higher operating pressures, in line with ongoing industry developments. The electrolyser's deoxidation drier was designed for gas processing at 30 bar-g; consequently, its performance may have been affected when operating under the revised lower-pressure conditions. This behaviour highlights the importance of aligning balance-of-plant components with evolving operating envelopes as system optimisation progresses.

The PEM electrolyser starts to generate hydrogen once it reaches about 40°C. From a cold start on a cold winter night, it can take more than an hour to reach operational temperature. This time period is not driven by the PEM stack but rather the size of the water tank that feeds and circulates water through the electrolyser stack. The entire thermal mass of the water in the tank must also reach 40°C and is only heated by waste heat from the electrolyser stack which is at a relatively low-level during start-up. Heat loss from the large water tank has been found to limit turn-down of the flexible electrolyser because at high turn-down ratios where waste heat levels are low, stack temperature was not maintained above the design minimum of 40°C. The advantage of keeping the large water tank in the design is that a larger stack or even two stacks could be accommodated facilitating an easy upgrade of hydrogen generation capacity. Insulating the water tank or other simple thermal management control could also mitigate this problem.

Sampling and Purity Detection Challenges

The mass spectrometer sampling system posed the team several challenges during commissioning. The primary challenge was ingress of water condensate into the mass spectrometer blocking internal capillary tubes and resulting in no effective sampling. Initially the source of water vapour was thought to be from wet sample gas, however, it was confirmed that water condensate was back migrating into the mass spectrometer through the vent line assembly. These water ingress problems have been resolved by an installation of a cowling at the outlet of the vent lines. We also installed coalescing filters on all the sample streams to avoid any water vapour coming from the synthesis loop entering the mass spectrometer. This was found to be more of an issue during activation of the plant when significant water vapour is produced, however, once fully reduced the catalyst does not produce any water vapour.

Oxygen and moisture sensors have been employed to check the quality of feed gas being produced by the PSA and PEM electrolyser before it is injected into the synthesis loop. It is a safety requirement to ensure no significant breakthrough of oxygen into the synthesis reactor as this can cause a significant exothermic reaction with the potential to exceed vessel design temperatures and compromise the integrity. It is also important to keep molecular oxygen content very low to ensure longevity of the synthesis catalyst. When they have a consistent flow of sample gas flowing through them they have tended to work and give reliable results. However, when sample gas flow is stopped because the plant has gone into stand-by, oxygen levels and water vapour levels rise

quickly. This can only be due to oxygen and water vapour from the atmosphere migrating through the seals into the sensor. To avoid this problem, we have found it helps to ensure sensors have a consistent flow of sample gas and are constantly maintained at a pressure above atmospheric pressure. However, this is not always possible when the plant is in stand by and not generating any feed gas. If a sensor is left with no sample gas flowing through it for a few days then oxygen levels build up to the point where the sensor can become saturated with oxygen and then will either need recalibration or replacement depending how badly saturated it has been. We have introduced design changes and procedures to try to maintain a positive pressure of dry nitrogen sample gas across those sensors that we can try to ensure the sensors do not get saturated and are ready to operate next time the plant is operational. For a plant running from intermittent power there is good reason to design the housing of these sensors with a formal leak tightness specification thus avoiding having to waste dry nitrogen just to protect sensors during shutdown.

Flowmeter Challenges

We have had issues with the reliable operation of the hydrogen thermal mass flow meter and the synthesis loop thermal mass flow meter. During the preliminary test runs carried out so far this made our ability to measure the stoichiometry of the feed gas and loop flow rate difficult at times. The intermittent failure of the hydrogen flow meter is most likely to have been caused by water vapour condensing within the flow meters during periods when the deoxidation dryers are in fault or still in warm up and so not delivering fully dry gas. To solve this issue, we recommend introducing automatic venting when the water content is too high. The failure of the synthesis loop main flow meter is most likely to be due to condensation of ammonia within the device. To solve this, we would position this flow meter in a warmer section of the loop, give it a vertical mounting orientation and possibly introduce a gauze in the outlet of the separator to prevent the transmission of liquid droplets.

Separation Distance Challenge

Designing the plant to fit within the space available while also respecting the British Compressed Gas Association guidelines on separation distances between stored compressed hydrogen and other areas of the plant was a challenge. The main measure to achieve this was to build a 3m high fire wall around the hydrogen store, shown in green in the two example diagrams below where the fire wall is shown to increase the horizontal distance between the hydrogen store and any sources of ignition and between the hydrogen and ammonia stores. Figure 5 illustrates the design of the fire wall and placement of the hydrogen store and other components was really shaped by the space available within the compound and locations of existing utilities such as water and electricity substations. Given a blank canvas and with the experience of completing the ASPIRE design the team believe the separation distances and DSEAR regulations could be efficiently met in a more compact design.

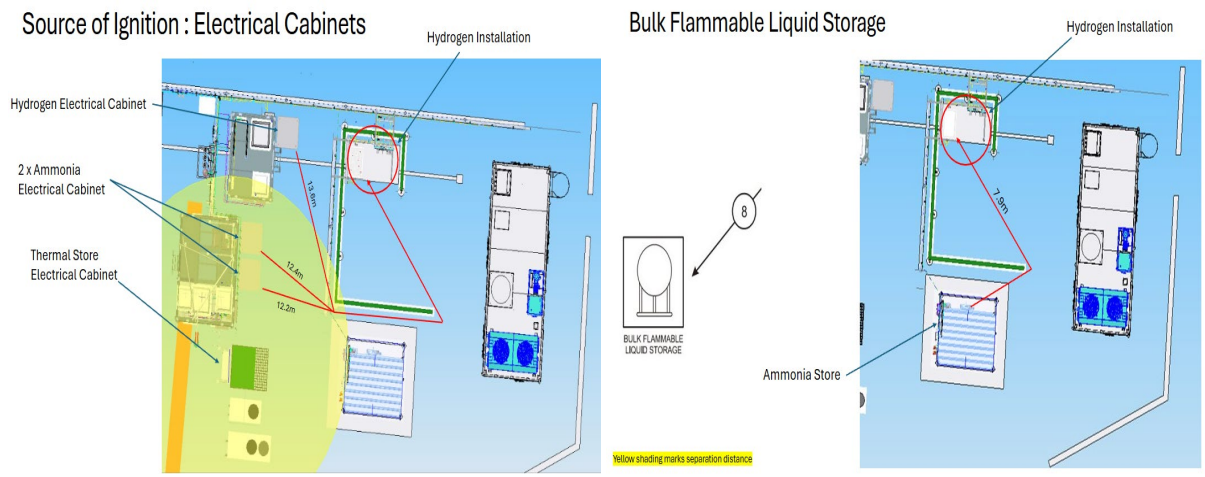


Figure 5: Fire Wall Specification

3.3. HAZOP(s) and Other Health/Safety Considerations

The independent safety assessments led by FNC involved a series of HAZOP and DSEAR assessments and was undertaken by the Clean Energy Safety group, a multidisciplinary team with a wealth of experience in high hazard and process safety across multiple sectors. To complement the wealth of experience brought by FNC, senior chemical engineers from the UoB and from JM played a major role as reviewers in the HAZOPs, drawing on experience from the Oil & Gas sector and the ammonia sector. The STFC team worked throughout the project to present design information to the HAZOP assessment panel and fulfil the actions identified in the HAZOP and DSEAR assessments. This formal safety process has resulted in a very carefully designed plant with safety as a top priority. It has also triggered STFC to perform a Layers of Protection Analysis (LOPA) based on the detailed HAZOP. This further resulted in a series of safety instrumented functions with appropriate safety integrity levels as derived from the hazard severity determined in the HAZOP. The DSEAR assessment led to the definition of hazardous areas where any electrical equipment had to conform to appropriate ATEX and intrinsic safety standards. The STFC electrical and controls group completed all electrical installations in accordance with the ATEX requirements.

As part of the ASPIRE development an application for planning permission was submitted and, following review by the Environment Agency (EA), was granted. In order to get acceptance from the EA, STFC had to demonstrate that they had minimised the risk of ammonia being spilled and then entering the underlying aquifers.

Pressure vessels and pressure systems have been designed and procured in accordance with the UK's Pressure Equipment (Safety) Regulations PE(S)R and Pressure Systems Safety Regulations (PSSR). A written scheme of examination has been obtained for all the pressure vessels and pressure equipment that make up the ASPIRE plant. The design and sizing of the pressure relief devices was completed following guidance from the IChemE approved course entitled "Pressure Relief: A Proven Approach". As the ASPIRE plant was being designed in the UK, BS EN ISO 4126 "Safety devices for protection against excessive pressure" was used to size relief devices. In addition to following the standard approach and using standard calculations to complete the pressure relief sizing, complementary compressible flow CFD analysis of each relief system was also carried out. This gave the ASPIRE engineering team extra confidence in the final pressure relief design.

Prior to operation of the ASPIRE plant the project team engaged with the STFC's Laboratory management, SHE team, and fire safety representatives with regard to the risks of having a full ammonia store on site. The most dangerous hazard considered was that the full ammonia store became engulfed in flames. Many layers of safety are in place to avoid this including administrative controls to avoid build-up of combustibles around the ammonia store and flame detection but in the event these systems did not stop a fire progressing, an evacuation plan was devised to clear the area in the event that a major fire caused the ammonia in the store to boil off and be released (through a pressure relief event). Staff and contractors working in the vicinity of the ASPIRE plant have all been briefed on the risk and the evacuation procedure.

3.4. Selection of Technical Components

Major components procured by the project that are integral to the plant design are listed below along with the reasons they were selected:

- The PEM electrolyser was selected from Oort Energy Ltd due to having good efficiency, plant scalability and high flexibility with the ability to modulate power across the operating range within 2 seconds. These features make it ideal for operation from an intermittent power source while also aiming to minimise the cost of green ammonia.

- The nitrogen generator was selected from Claind for its flexibility and ability to generate nitrogen with very low levels of oxygen, less than 10ppm.

- The hydrogen compressors are electrically driven reciprocating compressors from Hii. This selection was made as they are more efficient than pneumatically driven hydrogen compressors while still being designed for operation with hydrogen as a flammable gas. Their speed is also highly controllable with inverter drives.

- The ammonia synthesis circulator from EagleBurgmann was selected for smooth operation, efficiency and high turn-down capability.

- The deoxidation drier was selected from Aquagas because of its continuous operation without ever presenting a blocked transfer line to the plant and its effectiveness at achieving very high purity mixtures of hydrogen and nitrogen.

- The condenser chiller which is an ICS412LT was selected to achieve a condenser and separator temperature of -20°C to ensure effective condensation of ammonia from the gas stream. It also had a good coefficient of performance compared to other units on the market that can achieve this temperature.

3.5. Control Logic

The control logic required to run the plant was defined by STFC and iterated on throughout the project. During initial development it was scrutinised by UoB in two studies [12, 13] in addition to the scrutiny during the operational components of the HAZOP review by FNC, JM and UoB. The STFC team generated a Simulink model of the plant to test the control logic, and this was used as verification of the control logic. The initial stage of controller programming was undertaken by FNC's Modelling and Engineering Software team. They have implemented the controller on a PLC

and handed it over to STFC. Under the FNC contract, a first issue of the complete controller was provided to the STFC team. FNC gave an excellent handover which meant that the practical Siemens controller development skills were transferred to the STFC team. Due to the complexity of the controller and nature of this being an R&D project, STFC have made multiple controller changes during plant commissioning. Controller maturity has only really been achieved once the plant has been commissioned as it is impossible to simulate every integrated component accurately in a system of this complexity.

3.6. Procurement and Fabrication Activities

To handle the large volume of parts to be ordered for the plant, an equipment list and a structure was created. The procurement of bespoke items for the demonstration plant was initiated as early as possible. High value bought-in items, such as the electrolyser, were also ordered as soon as possible.

Where equipment was fabricated off-site, members of the project team visited suppliers regularly to monitor progress and verify design and factory acceptance tests. On-site commissioning from key suppliers was also encouraged to support the integration of the ancillary equipment on-site.

In brief, the hydrogen and nitrogen subsystems are bought in as complete operational units whereas the ammonia synthesis subsystem is designed from scratch although it is an assembly of multiple bought-in components.

STFC also carried out a large amount of site infrastructure works, including installing a comprehensive fire detection and alarm system, lightning protection, and upgraded connection to the Laboratory's electrical supply, installing civil engineering structures, and electrical and control system wiring within the plant's compound.

The capital expenditure for off-the-shelf components, along with materials and components to be manufactured totalled c. £1.9M. The total contracted budget was £4,283,445.42 and STFC initially agreed further funding up to £280,000.00.

3.7. Consents and Permitting Applications

A planning permission application was submitted to accommodate the ASPIRE Green Ammonia Research Centre (GARC). The Environment Agency (EA) engaged with the process and requested a risk assessment about the measures in place to avoid leaks of ammonia into the water table. STFC carried out this assessment and put forward mitigation measures that were subsequently accepted by the EA.

The Vale of the White Horse District Council granted planning permission on 9th October '24 subject to the following conditions:

1. Scheme of biodiversity enhancement.
2. Mitigation strategy for the landscape and visual impact.
3. Details of the external colours for existing and proposed plant.

Responses were submitted in accordance with the planning approval conditions on 8th January '25.

4. Secondary Project Benefits

4.1. Dissemination Activities Undertaken

Dissemination and engagement opportunities throughout the project have been extensive including plant visits from the Government's Chief Scientific Officer (CSO), attendance and dissemination at UK and international conferences and engagement with stakeholders who have interests in the ASPIRE technical and commercial opportunities. The following details the dissemination and engagement activities that have been achieved throughout the duration of the project.

- EPSRC Workshop at the University of Oxford – Presented on Green Chemicals, Hydrogen and Carbon Capture.
- ASPIRE Steering Working Group workshops to share and maximise new technology.
- Site visit by Chief Scientific Adviser to the Government, and the Chief Scientific Adviser to the Department for Education.
- Site visit by staff of the Department of International Trade (DIT).
- Attendance at the Green Ammonia International Symposium which attracts innovators from the energy sector from across the world.
- Ammonia Energy Symposium 2023 (Orleans, France) - ASPIRE participant.
- Energy Innovation Summit (Liverpool)- Engagement with Industry Experts.
- Presented ASPIRE project at NZIP Innovation Showcase: Hydrogen and Industrial Decarbonisation.
- IMechE Webinar; How Green Ammonia can help us reach net zero.
- Overview of ASPIRE 2 to Senior Representatives from the UK National Grid as part of a workshop on the digital spine and future electrical grid smart network.
- Presented at UK Energy Storage Conference (Nottingham).
- Attendance at European Green Ammonia Conference 2024 (Germany) engaging with potential business partners.
- Attendance at IETF event hosted by DESNZ in collaboration with Innovate UK Business Connect to understand potential for funding mechanisms for projects that have reached TRL 7 and above.
- Attendance at Innovation Zero, the UK's largest sustainability conference engaging with potential business partners.
- Harwell Open Week.

- Innovate UK Innovation Showcase engaging with future business partners and collaborators.
- CSIRO – Australia's National Science Agency to discuss and share technologies and opportunities for any synergies.
- Invited to present at Man0EUvRE a groundbreaking initiative aimed at supporting the transition towards renewable energy systems across Europe.
- Attended Ammonia Energy Symposium 2024 (China).
- DESNZ site visit 30+ members of the DESNZ Nuclear Infrastructure, Capabilities and International Team.
- Site Visit by members of the DESNZ Chief Scientific Adviser's Team.
- Attendance at the EU Hydrogen Week to promote ASPIRE technology and seek potential collaborators.
- Collaboration with Electricity Supply Board of Ireland 6-month project funded by Commercial Pump Priming Fund to look at design of a 5MW ASPIRE in collaboration with ESB.
- Visit by UK Ministry of Defence's Climate Change and Environment Department.
- Visits by various industrialists from the agriculture and transport sectors.

4.2. Media Coverage

A national press release UK green ammonia prototype plant tackles energy storage challenge following the successful ASPIRE plant operation and ammonia generation has been issued by UKRI.

An article has been prepared by a leading UK national newspaper journalist, after a visit to ASPIRE.

A journal paper will be published once all results have been consolidated.

The progress building ASPIRE has been regularly reported via posts on LinkedIn – for example #aspire | Tristan Davenne | over 10000 impressions, UK Scientists Develop Ammonia Storage Solution for Renewable Energy | STFC posted on the topic | LinkedIn and STFC's ASPIRE Facility Converts Wind Energy to Green Ammonia | STFC Business & Innovation posted on the topic | LinkedIn.

4.3. IP Generated

UKRI have a patent application for the ASPIRE Plant.

4.4. Number of New Jobs Created

The Phase 2 funding underpinned both direct and indirect jobs at STFC and our project partners - directly supporting 19 employees. Focus has been made to source components and skills from UK suppliers, and it is estimated that this supported another 20 indirect jobs.

It is estimated that this funding will have contributed to the upskilling of 30 engineers, 3 software engineers and a postdoctoral research officer directly involved in the project, 10 Chemical Engineering PhD Students at UoB, and more than 100 undergraduate students, will use ASPIRE as a case study when learning about green ammonia.

Additional support from each organisation's extensive network has been called upon with specialist skills and knowledge including plant consultation and construction management, safety and environmental, business development and communication, internal design and manufacturing, and administration project support, being deployed.

4.5. Improvements to Skills/Experience in Sector

Two engineering placement students working on the ASPIRE project secured graduate jobs at STFC following completion of their degrees.

An electrical engineering apprentice was trained on ATEX wiring and inspections.

A senior research engineer was trained on pressure relief.

Multiple STFC design engineers were given the highly valuable experience of having to assemble what they had designed.

Seven engineers were trained in tube bending and correct use of compression fittings to achieve enhanced tightness standards when working with hydrogen and ammonia.

4.6. New Partnerships Formed from the Project

In addition to the key project partners (JM, UoB and FNC) other new key partnerships resulting from the ASPIRE project have included:

1. Oort who is relatively new supplier for electrolyser technology and the ASPIRE project was one of the initial users of their technology.
2. DRAGONFLY Actuation Lab Engagement who is another DESNZ-funded project and their technology is being trialled within the ASPIRE demonstration plant.
3. Cardiff University as a potential user of ammonia generated from the ASPIRE project.
4. Commonwealth Scientific and Industrial Research Organisation (CSIRO) is an Australian Agency and is responsible for scientific research, commercial and industrial application to share technological synergies.

4.7. Supply Chain Development

The records and supplier relationships we have now would certainly be of benefit to a future ASPIRE build of a similar scale. Also considered here is the supply chain readiness with respect to a 500kW scale-up and a 1MW scale-up. There is now a parts list which records the supplier of all items purchased for the 150kW plant (ASPIRE MK0) so there is a proven supplier for all components. This means that a next iteration of the ASPIRE plant would start from an unoptimized, yet functional supply chain. The order quantities were not sufficiently high that suppliers have developed their own supply chains specifically for the ASPIRE design at this point.

For bespoke items, each supplier has a baseline design which could be re-manufactured or used as a starting point for scaled-up iteration. In each case, this may reduce the design workload, thus reducing cost and/or improving lead times. These items are generally the items of high value and longest lead time, and so savings here could be significant. The highlights of these cases are shown in the following table:

Equipment	Supplier	Comments on Future Potential
PEM Electrolyser	Oort Energy Ltd.	Containerised electrolysis product available with proven integration with the ASPIRE system up to 500kW with very little modification required; this could be delivered within the next 2 years. Scaling to beyond 500kW introduces a level of product development and is probably more towards the 5-year time scale.
Deoxy Drier	Aquagas Sweden AG	Custom drier with proven integration with the ASPIRE system made for the ASPIRE MK0 scale (150kW). We know that this product is available up to the MW scale and that our scale was abnormally small for Aquagas. A model suited up to the 1MW scale would be available from Aquagas.
Ammonia Store	MC Integ Ltd	A 2500L bunded and solar-shielded ammonia vessel was designed and built for the ASPIRE MK0 scale. By visiting their manufacturing facilities, we know that MC Integ can scale this up to a much larger vessel as per the requirements of a future build or application. As the scale of storage increases, it is recognised that pressurised storage could be switched for cooled storage. The question of ammonia storage capacity is somewhat decoupled from the size of the plant.
Separator	MC Integ Ltd	An actively cooled jacketed vortex separator was built for the ASPIRE project. This design could be reproduced or scaled up by MC Integ as per the requirements of a future build.
Syngas Circulator	EagleBurgmann	The syngas circulator operates towards the bottom of its capability in terms of flowrate in the MK0 design. Provided the pressure drop can be kept low by using a larger bore size at a larger scale, the same pump could deliver flow rates compatible with 1 MW.
Co-axial Heat Exchangers	Swagelok (Fabrications)	The heat exchangers for ASPIRE MK0 were made by Swagelok Edmonton, Canada. They have gained experience and have done the technical learning required to build these complex geometries. They successfully manufactured two batches over the course of the ASPIRE project. These designs were built towards the upper scale that is possible in helical geometry with the co-axial tube-in-tube Swagelok products, due to length and bore restrictions for tube bending. Both the length and the bore size could be enlarged if the geometry were changed to be straight rather than helical, with a maximum outer bore size of 2”. We believe that this change could support a design of 500kW scale, but that for 1MW scale we would have to transition to a bespoke welded solution.

Catalogue Items

There are many suppliers from whom we purchased off-the-shelf items. We have established a good relationship and have in-depth knowledge of their catalogue and procurement times. Some highlights and future comments follow.

Equipment	Supplier	Comments on Future Potential
Hydrogen Compressors	HII Pumps International	The 150kW ASPIRE scale required two of the largest electric hydrogen boosters in the HII Pumps catalogue in parallel. They have proven to be a good choice of compressor over commissioning and testing. Continuing to add these in parallel could conceivably be done up to the 500kW scale, which would require 6. After this point, another supplier would need to be found.
Process Lines	Swagelok	The 150kW scale ASPIRE (ASPIRE MK0) has a heavy dependence on fittings from the catalogue, having used Swagelok tubing and their twin ferrule compression fittings for almost all process connections. The ability to disassemble and re-tighten was valued greatly for the prototyping stage of ASPIRE MK0. By going larger in the catalogue, we believe the 500kW scale could be reached using the 2” bore compression fitting items. These tubes cannot be bent to the same extent as the sizes we worked with (up to 1”) and so the geometry would have to change. Moving to a bore size larger than 2” would be necessary for the 1MW scale synthesis loop and we anticipate changing supplier and opting for welded connections in this case. However, we could still use Swagelok for gas sampling, the feed system, the quench lines and transfer lines.
Shutoff Valves + Control Valves	Rotork (Hanbay)	The 150kW scale ASPIRE uses Rotork shutoff valves throughout for the safety case. The choice of these valves is linked to the process line design because the Rotork products use Swagelok valves and are directly compatible. Because there are no automated valves in the ammonia loop, other than the quench and sample lines which are smaller bore than the loop, the Rotork range could cover the 1MW scale.
Flow Meters	Bronkhorst	The flow meters for the 150kW would need to be scaled to measure flowrates up to around 6 times larger for the 1MW scale. This is not an issue for the flow meters inside the feed system, it could present a challenge for the quench lines. For the meter dedicated to the main loop flow, we would opt for another type of technology rather than a through-flow device as we were already at the upper end of the catalogue.
Chillers	ICS	The chiller models selected for the 150kW scale proved reliable and robust. ICS offer chiller systems up to the size we require for a 500kW and 1 MW iteration of ASPIRE so we would likely continue using this supplier.

5. Demonstration Study

5.1. Overview of Test Plan

The plan for commissioning and testing was prepared prior to commencement and contained five stages.

1. Commissioning Part 1 - Passive Safety Tests

2. Commissioning Part 2 - Control System Testing

3. Commissioning Part 3 - Preliminary Operations

4. Testing Part 1 - Performance Validation

5. Testing Part 2 - Flexible Operation

The aim of the testing performance validation process involved a 5-stage test plan led by STFC and supported by JM and UoB during the commissioning and testing phase:

Stage	Outline Process
1	All primary safety equipment was tested. This included pressure vessel inspection, testing and certification and a signed-off written scheme of examination for the plant. Correct operation of key safety equipment such as normally closed valves, ATEX ventilation equipment, interlocks and fire and gas detection systems.
2	Checked and confirmed that the basic process control system and safety controller are fully operational and able to trigger actuators as required. Checked that all sensors are providing sensible correctly encoded signals to the controller. Checked that control logic worked by isolating different controllers and checking their functionality. Operation of all Safety Instrumented Functions tested, which was supported by UoB.
3	Commissioning involved testing the operation of all the principal components. Initially the system was tested with nitrogen in the synthesis loop and then some initial steady runs where hydrogen was added. Once we had commissioned the feed system and knew we could generate hydrogen/nitrogen mixtures of adequate purity we were able to complete the commissioning by activating the reactor catalyst. JM actively supported STFC on-shift and engaged with their colleagues to propose alternative solutions when issues were experienced.
4	Set point performance testing was then carried out where the ammonia generation efficiency, (i.e. calorific value of ammonia produced / input energy) was measured across a range of steady state generation rates from 10 to 100% of full capacity. During these tests many other parameters were measured to characterise and understand the plant and by the end of it we had built up enough confidence to operate the plant following an intermittent signal.
5	Flexible operation following a transient power trace. During a period of 8 hrs the plant followed the transient power trace, and a full set of plant operating parameters was logged including actual plant power consumption and ammonia production rate.

5.2. Results of Demonstration Study

1. Commissioning

Once the passive safety tests were complete and as many components of the plant and controller had been commissioned in isolation, we were ready to start the activation of the reactor catalyst. This is the point where the ASPIRE plant would make its first ammonia. This process involved completing the reduction of the iron oxide-based catalyst by passing hydrogen over it at ever increasing temperature. The temperature ramp is controlled to limit the amount of water vapour produced in the reduction reaction as water vapour will damage the catalyst. The evolved water vapour is extracted through a vent and through the separator which is cooled to no lower than 5°C to avoid freezing. This avoids water passing back through the reactor. Quite a lot of hydrogen and nitrogen is also vented with the water vapour in the process and so the activation requires a significant amount of hydrogen gas. The figures below show the controlled temperature ramp of the reactor (coloured lines on the first graph are temperatures at different positions in the reactor) and the water vapour content measured at the outlet of the reactor which was generally kept below a target of 500ppm.

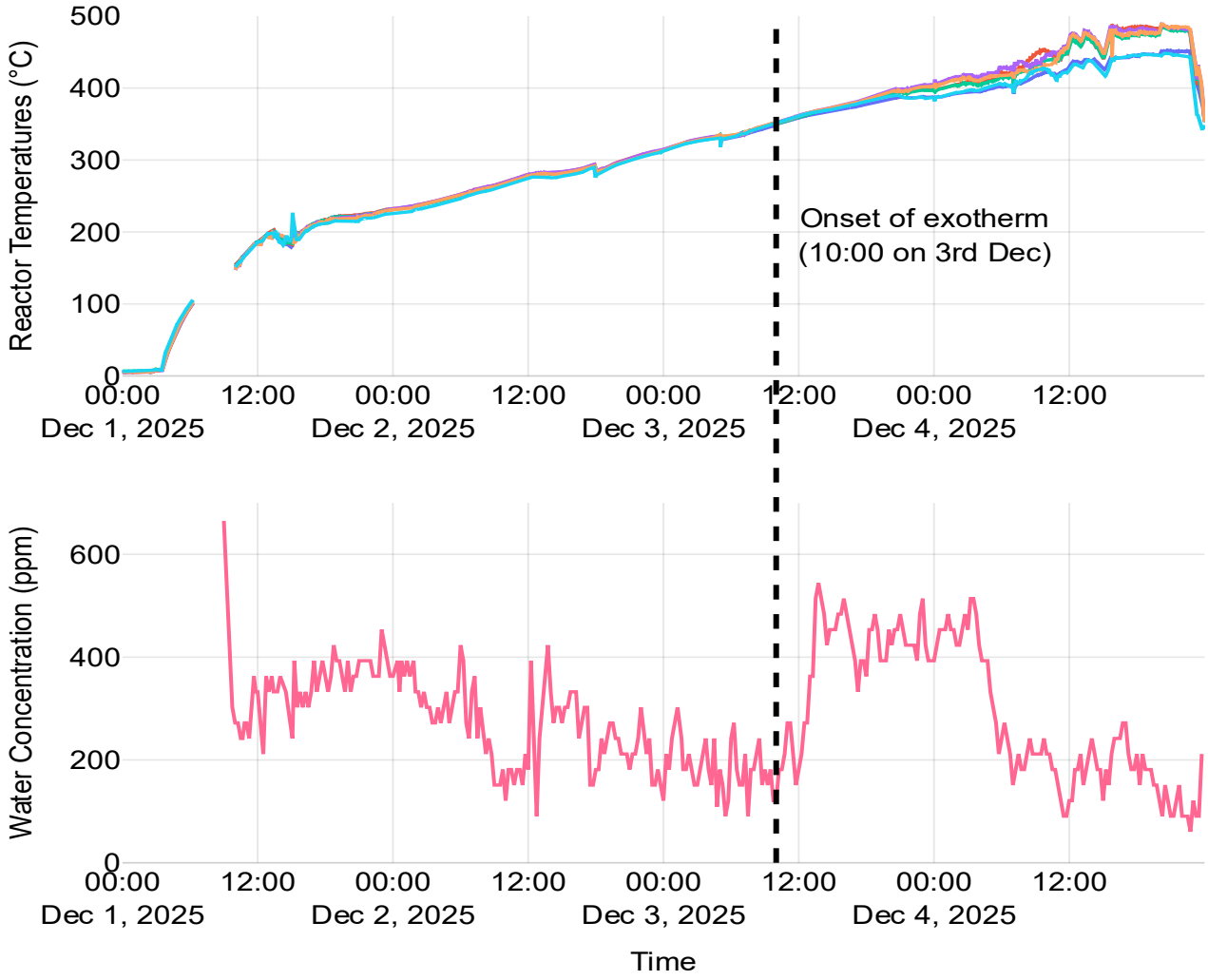


Figure 6: Controlled Temperature Ramp of the Reactor

During activation as the catalyst becomes reduced the amount of water produced reduces and ammonia formation commences. At a certain point there is enough ammonia being produced with the water vapour such that the freezing temperature of the liquid is below the condenser chiller temperature of -20°C and so the condenser chiller can be turned on. At this point there is a significant increase in ammonia separation and extraction from the synthesis loop. At the end of this activation process reactor temperatures were held high between 450°C and 490°C for 5 hrs and around 30kg of ammonia was made during this period as can be seen from the graphs below which integrated extracted liquid ammonia as measured with a Coriolis flow meter and ammonia store pressure.

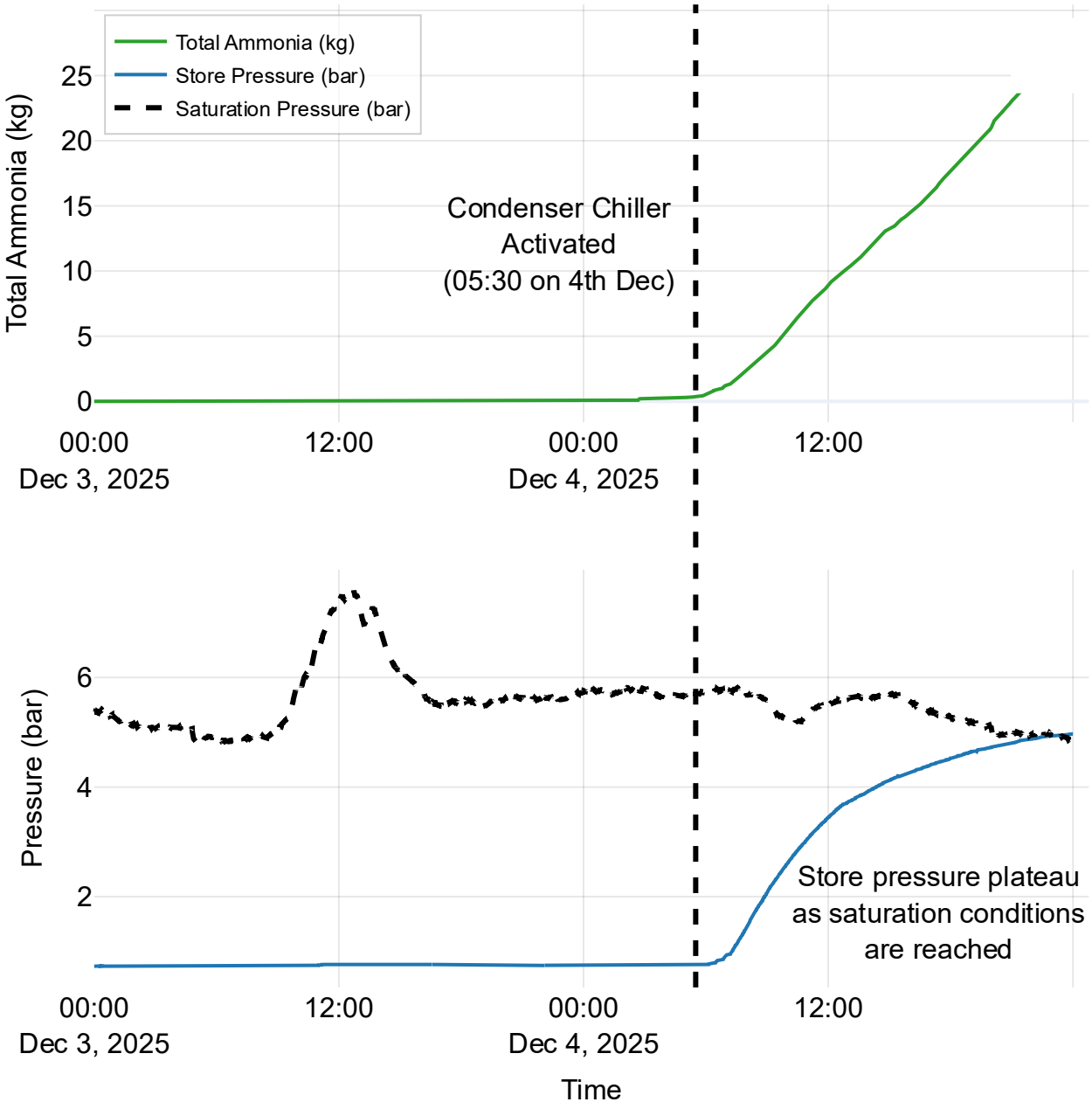


Figure 7: Separation and First Ammonia Extraction

2. Set Point Performance Testing

Once activated the plant was ready for some set point performance testing. To do this we ran the plant following a set of 40-minute-long steps, each with a different circulator speed and hence generation rate. The profile is shown in the Figure 8.

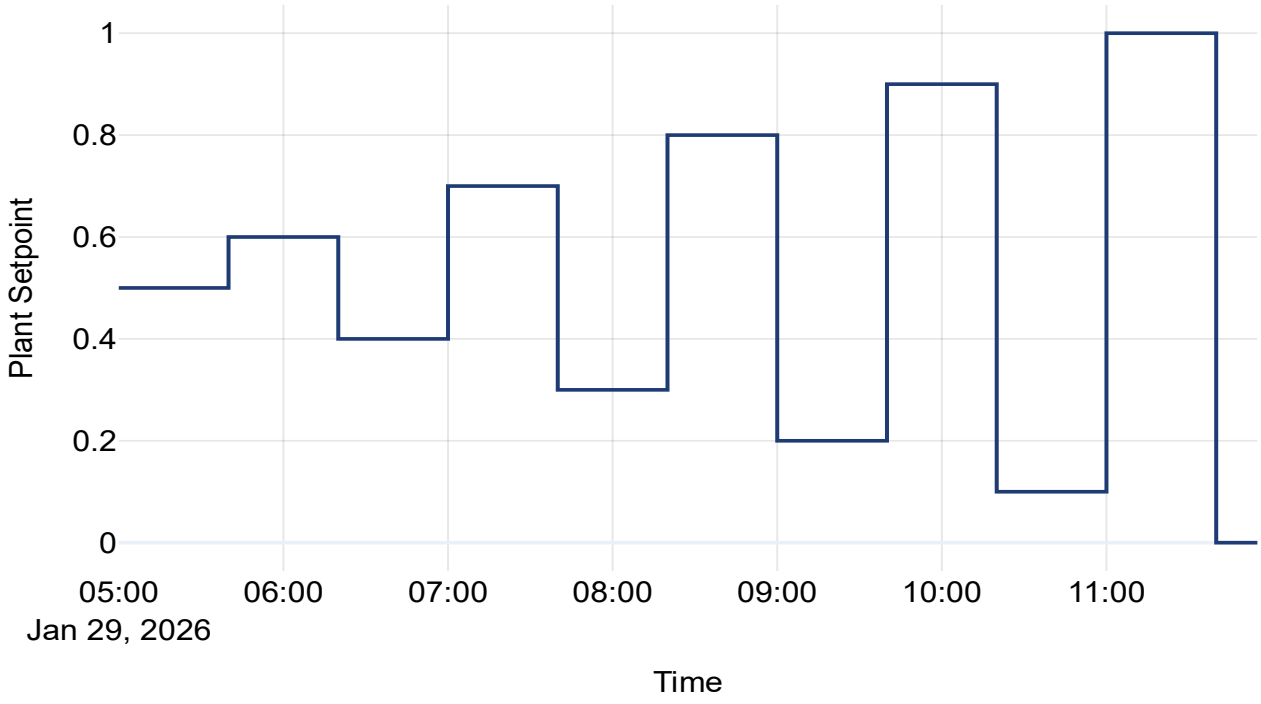


Figure 8: Set Point Performance Testing

The ammonia generation rate is roughly proportional to flow rate passing through the synthesis loop and a circulator speed of 45Hz was thought to correspond to 100% operation. Power consumption was measured at each step and a complete breakdown of where the energy is used is shown below. On some steps the PSA was not operational, and the plant was drawing from the nitrogen buffer tank storage, whereas on other steps the PSA was running evidenced by the power consumption of the PSA and air compressor that feeds it.

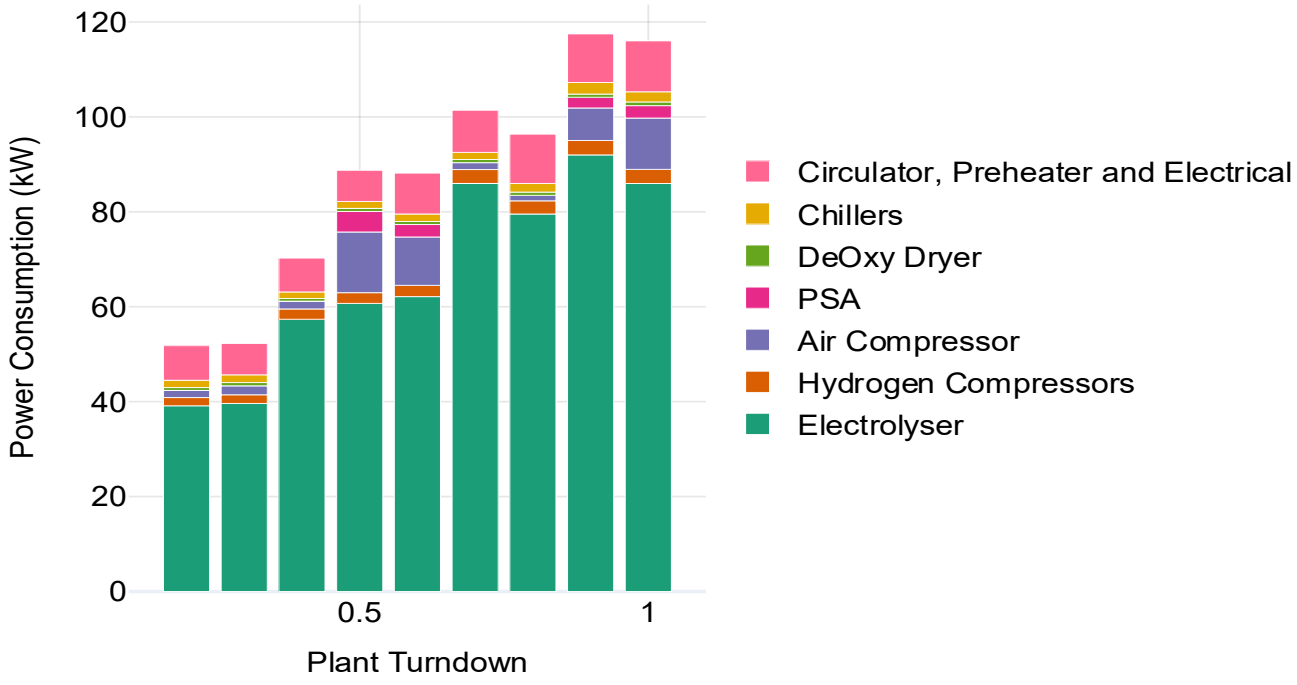


Figure 9: Power Consumption Breakdown

Time averaging over the set point tests has yielded the following pie chart showing the division of the power consumption within the three main subsystems.

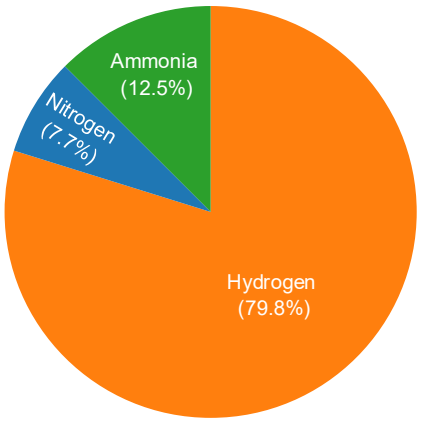


Figure 10: Division of Power Consumption

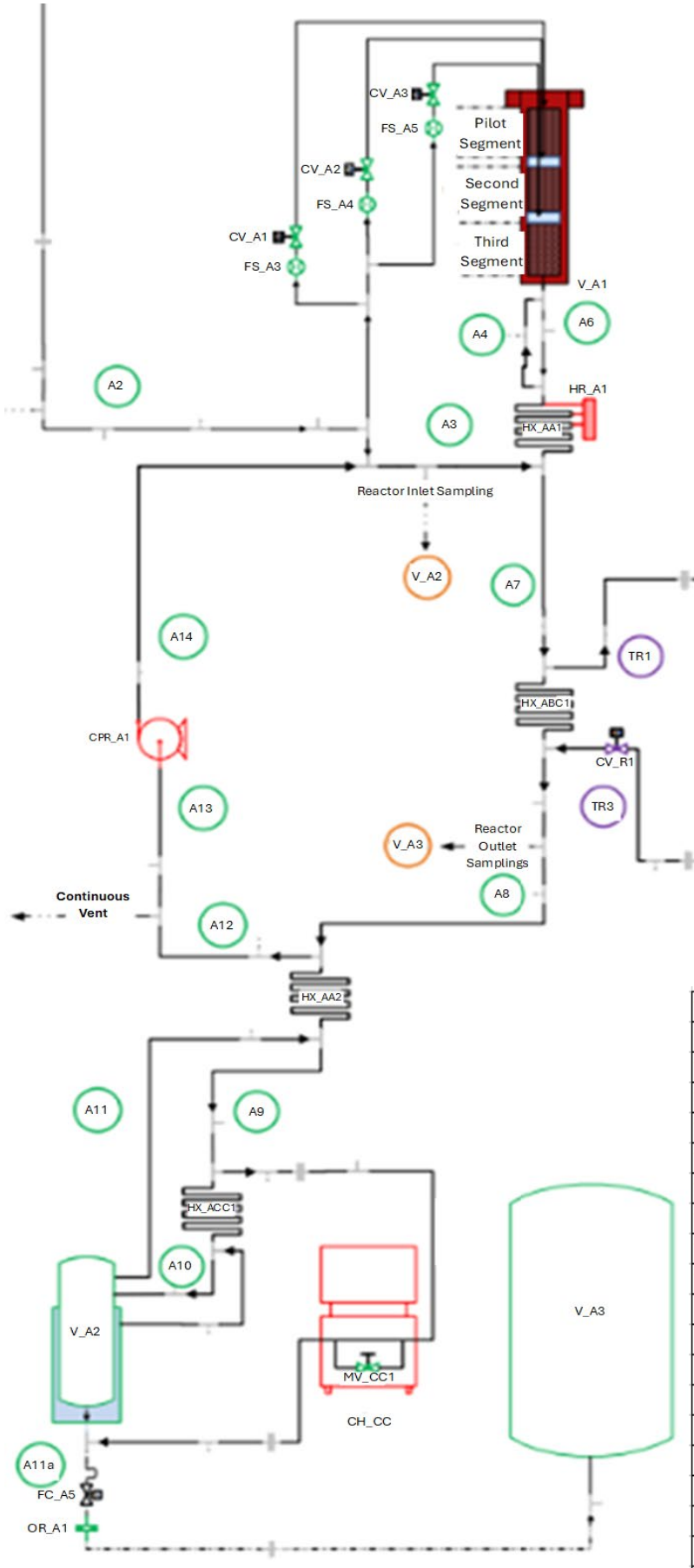
The overall efficiency of ammonia production is calculated as follows;

$$Efficiency = \frac{HHV\ of\ ammonia\ generated}{Electrical\ energy\ consumed}$$

Power meters are used to measure consumption during sustained operation at a given set point generation rate. The ammonia produced during the period is calculated by integrating the measured ammonia extraction rate during each set point test. Ammonia production was measured throughout the performance tests and when comparing this to the power consumption, an efficiency of 40% was achieved with the plant turned down to 30% of maximum generation rate. Figure 9 highlights that the synthesis loop is working in-line with predictions, given that at this high turn-down ratio the electrolyser was achieving an efficiency of 45%.

During the set point testing problems controlling the stoichiometry of the feed gas were experienced. This became more apparent during post processing of the data and was retrospectively identified as being due to an intermittent failure of our hydrogen thermal mass flow meter, which misled us on the quantity of hydrogen being introduced to the loop. Analysis of the test data has indicated that the synthesis reaction was often short of nitrogen during these set point tests which was limiting ammonia production. As such, at the point of writing this, we are only able to report efficiency for the case of the plant being turned down to 30% of maximum generation rate and we are as yet unable to accurately report efficiency across the other set points. However, we are confident that once we have resolved the flow meter issue and are able to confidently control stoichiometry, we will see efficiencies climbing greater than 40% as we move towards maximum power. This is primarily because plant operations so far have confirmed that the electrolyser efficiency increases towards full power.

The operating pressures and temperatures around the synthesis loop were found to agree well with the predictions presented in the process flow diagram in the detailed design phase. The process flow diagram Figure 11 in conjunction with the table provides some detailed information about the operational parameters in the ASPIRE synthesis loop during a steady set point test at 30% of maximum generation rate. It shows the effectiveness of the preheater/ high temperature recuperator, HXAA1, and the low temperature recuperator, HXAA2. It can be seen that these two heat exchangers successfully reduce the heating and cooling power requirements of the loop. Some heat is being extracted from the synthesis loop via HXABC1, which produces hot water while also reducing the power consumption of chiller CHB1. It can also be seen that the pressure drop around the loop is relatively small at 0.5 bar for this operating point. At maximum ammonia generation the pressure drop increases from this value but is still below 3 bar which when operating the synthesis loop at 90 bar means the circulator must deliver a pressure ratio of 1.033. The significant design efforts to minimise pressure drop in the synthesis loop have led to this low-pressure ratio requirement and a correspondingly low power consumption for the circulator.



T_A2	5.5	C	feedgas inlet temp
T_A4	395.6	C	reactor inlet temp
T_A6	398.3	C	outlet from reactor
T_A7	93.3	C	inlet to back up cooler
T_A8	25.6	C	inlet to cold recuperator
T_A9	6.7	C	inlet to condensor
T_A10	-15.4	C	inlet to seperator
T_A11	-15.3	C	outlet from seperator
T_A12	15.9	C	inlet to circulator
T_A14	19.7	C	outlet from circulator
P_A2	90.5	bar	feedgas inlet pressure
P_A8	90.2	bar	reactor outlet pressure
P_A11	90.2	bar	seperator pressure
P_A12	90.1	bar	circulator inlet pressure
A2	-41.8	C	feedgas dew point
A2	1.4	ppm	feedgas oxygen content
T_R1	47.3	C	thermal store inlet temp
T_R2	39.6	C	thermal store outlet temp

Figure 11: Process Flow Diagram

3. Flexibility Testing

The ability of the plant to follow a variable power trace was investigated by giving the plant an available power setpoint to follow and then measuring the actual power consumption of the plant. The renewable data was taken from open-source SCADA data for Kelmarsh Wind farm for May 2021[14], and the data frequency was artificially increased from 10 minutes to every 5 minutes. The data is scaled to simulate us having a 150kW renewable wind energy plant. Figure 12 shows a comparison of plant power set point with actual power consumed. The plant is seen to respond to the set point with the actual power consumption generally following the set point within minutes. There is however a fairly continuous offset where the plant power consumption is about 10-20kW over the set point. This offset is easily remedied by tuning the control parameters. We also believe that more accurate tracking of the setpoint will be possible once closer control over the stoichiometry of feed gas is obtained.

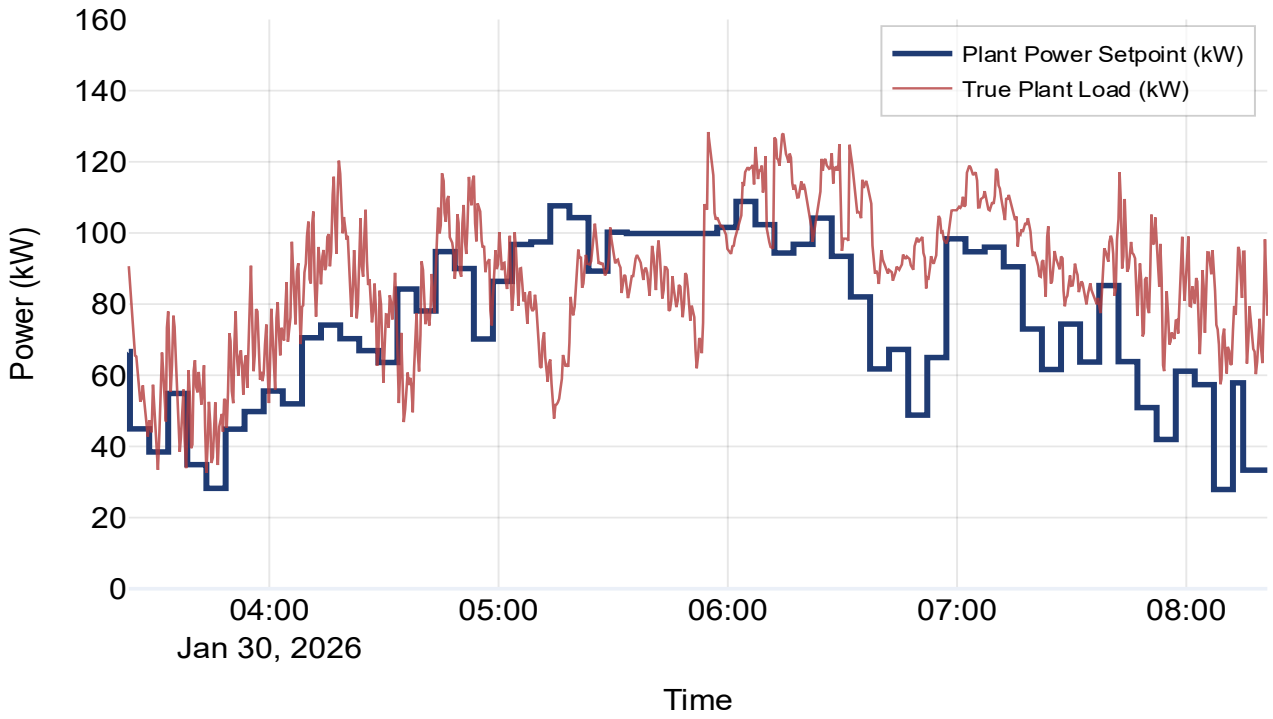


Figure 12: Comparison of Plant Power Set Point

During this period of transient operation, we recorded ammonia production as a function of time and also calculated the cumulative ammonia produced during the transient test period as shown in Figure 13. During the transient period the instantaneous ammonia production rate varies from 0.2g/s to 1.6g/s and a total of 14kg of ammonia was extracted from the synthesis loop.

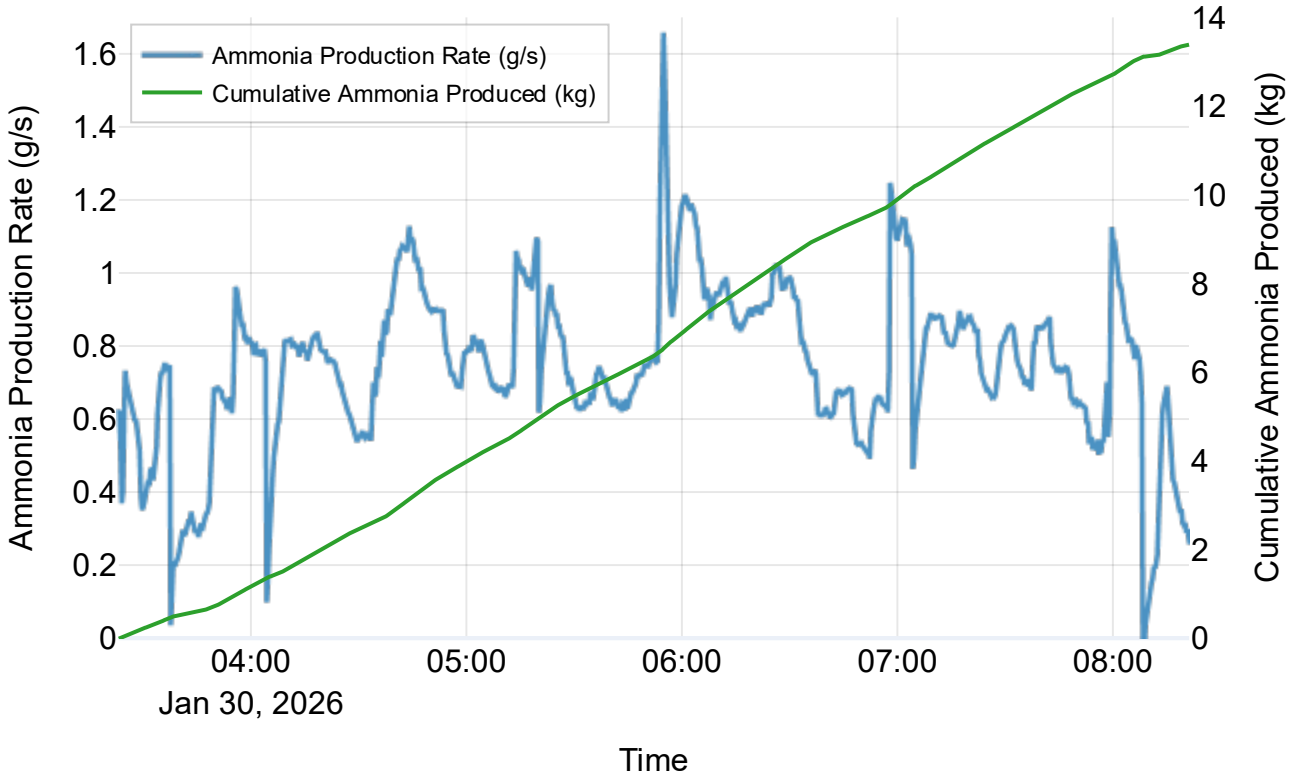


Figure 13: Flexible Ammonia Generation

An important metric for determining how flexible the ASPIRE plant is how effective the control system is at matching the actual plant power consumption to the available power. For example, perfect tracking of the available power trace would mean 100% utilisation over a defined period of operation. We calculate utilisation as follows;

$$\boldsymbol{Utilisation} = \frac{\boldsymbol{Plant\ Energy\ Consumption}}{\boldsymbol{Available\ Energy}} * \mathbf{100\%}$$

A value of utilisation below 100% indicates that the plant has not been able to draw as much power as is available. A value of utilisation above 100% indicates that the plant is demanding more power than would have been available from a renewable plant and this would cause resilience issues if it were to continue for long periods. In the case of an ASPIRE plant running off grid then a battery is required to accommodate excursions from the 100% utilisation. When running from the grid as we are, there is no resilience challenge of this nature as the grid will provide the actual plant power consumption even if it is above the available power trace. The utilisation has been calculated as 111% for the transient test period. Were the plant to be run using a PPA, there would be penalties associated with this as the plant would have consumed more energy than allocated. We believe this is a consequence of the initial run of the plant not having setpoints tuned for a specific power consumption. Future testing would enable the plant setpoint to be tuned to draw an average power which would enable better load following of the renewable supply and better overall utilisation.

Figure 14 shows the instantaneous difference between available power set point and actual power consumed throughout the transient test period. It also shows the cumulative difference to reach 60kWh of over-demand. This implies that a battery buffer with a rated power of the order 60kW and a storage capacity of 60kWh would be adequate to facilitate operation off grid. The storage capacity required can be reduced by better tuning of the plant to remove the general positive difference between plant power and available power. We also believe that more accurate tracking of the setpoint is possible once closer control over the stoichiometry of feed gas is obtained and this can lead to reduction in the instantaneous peak power requirements of a battery buffer.

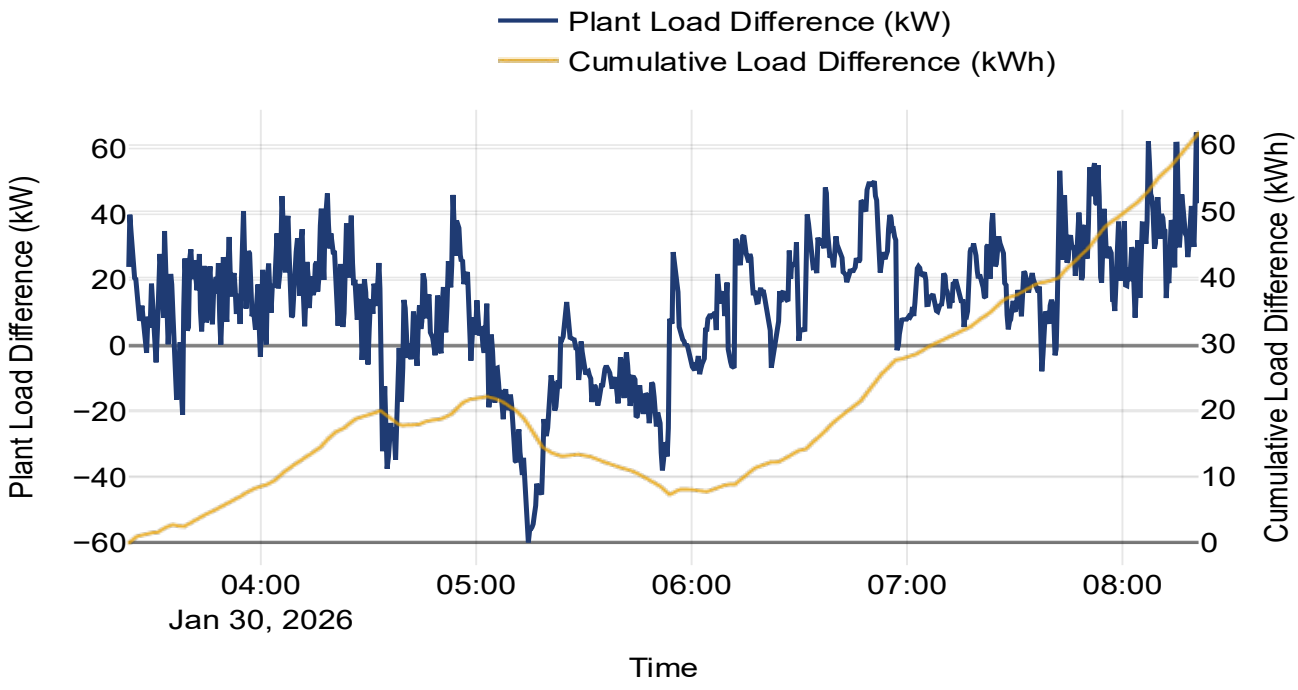


Figure 14: Power Trace – Set Point and Actual Power Used

Throughout the transient operation period the reactor temperature was successfully maintained within the operating range. Our target reactor inlet temperature was between 375°C and 400°C.

The ASPIRE thermal store was successfully deployed during the transient run with heat being extracted from the synthesis process and stored at 50°C. Figure 15 below shows the temperature of heat transfer fluid entering the thermal store at 50°C while the exit temperature was approaching the storage temperature of 50°C as the store filled up.

The graph shows thermal input and output temperatures: the inlet temperature is the orange line, the outlet temperature is the blue line, and heat transfer occurred at **50°C** as the store filled.

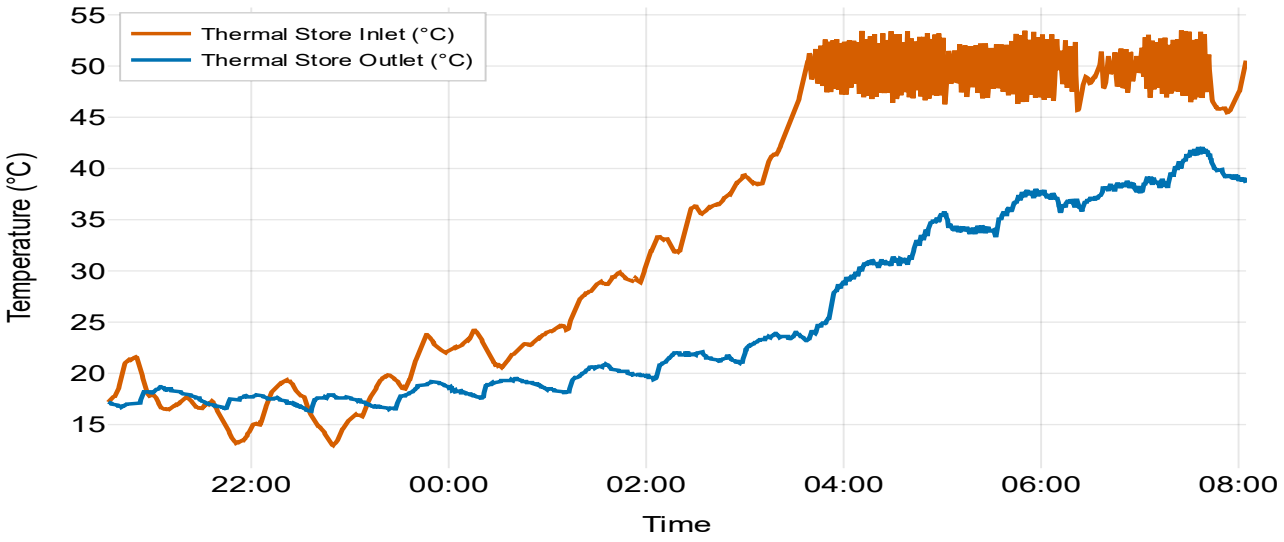


Figure 15: Power Trace – Thermal Store Through the Transient Test

6. Project Metrics

6.1. TRL at Start and End of Project

1. <u>At Project Start</u>

The ASPIRE design was at TRL 4 before the Phase 2 demonstration project. The TRLs of the subsystems of ASPIRE are 9 for hydrogen generation and nitrogen generation but were about 4 for the ammonia synthesis loop, thermal management and control system. Sensor and actuator components were available off the shelf, but synthesis loop components such as reactor, separator and heat exchangers needed to be designed in house and then manufactured. The thermal storage subsystem is based on an off the shelf hot water storage system that has been integrated into the plant. The operating and control strategy for the flexible synthesis loop was on paper as an engineered strategy but undemonstrated at the start of the demonstration project. Initially the project team considered that the power supply subsystem was at TRL 9 and commercially available.

2. <u>At Project End</u>

At the end of the project, we believe the ASPIRE plant subsystem has achieved a TRL of 7 in line with the project aim. While the timescale available for testing proved to be very short, the electrolytic synthesis plant has been successfully commissioned and operated and has generated ammonia over a period of a couple of weeks. The synthesis loop has been shown to be flexible with reactor temperatures and separator extraction efficiency being maintained near optimum levels irrespective of flow rates. The low pressure drop synthesis loop has proven to be reasonably efficient achieving a generating efficiency of 40% with the plant turned down to 30% of maximum generation rate. The synthesis process (including all plant electrical auxiliaries such as control cabinets and ATEX systems whose power would not scale with plant size) was absorbing only 12.5% of the total power consumption needed to make the electrolytic ammonia. An initial demonstration of the power tracking capability of the plant has also been completed. The control system has been well tested and has worked very well showing potential for the plant being run autonomously or with minimal surveillance requirements.

As described earlier the power supply subsystem was dropped due to escalating costs. Part of the reason for escalating cost was due to some design uncertainty on how to provide a grid forming micro grid to power the plant purely from renewable energy. The following technical challenges were proving difficult to resolve within procurement and project constraints:

- Issues with selection of a battery that could work as an energy buffer making up the difference between plant load and available grid power.
- Fire safety challenges around Lithium-Ion batteries.
- Being able to start the microgrid and maintain 50Hz frequency.
- Dealing with short term peak currents induced by the plant when for example a large motor starts up.
- Selecting compatible and capable solar inverters able to interface with the proposed solar array and the microgrid.
- Combining a solar array and a wind turbine as energy sources for the proposed microgrid.

Some of these components, in particular the grid forming capabilities and battery buffering requirements appeared to require quite specialist design effort not available from large renewable energy systems companies that are generally contracted to connect renewable plant to the grid. As such we would suggest that some elements of a large-scale microgrid are bespoke and so we don't have evidence that they have reached TRL 9. This finding has been verified by discussions we have had with two contacts made during the course of the project who have both attempted to run a significant hydrogen plant off-grid and both faced significant technical challenges with load matching and inverter failures.

6.2. Levelised Cost of Ammonia

The levelised cost of ammonia produced by the demonstrator was assessed using the CAPEX costs during the construction of the project and from the assumed OPEX throughout the demonstrator's lifetime. Total project expenditure for the demonstrator was spent during the first 3 years of the project and this approximately cost £5million (including engineering effort) with £2million being spent in each of the first 2 years and £1million being spent in the third year. It was then assumed the project's test life would be 5 years and in each of these years approximately £100k would be spent on operational costs. The plant was modelled to run on solar energy throughout the test life with an expected plant availability of 70% (due to the plant being a research facility).

$$\boldsymbol{LCOA = 124\ £/kgNH_3 = 24\ £/kWh}$$

The cost of ammonia is very high (£124,000/tNH3) due to the plant being a small-scale demonstration.

6.3. Levelised Cost of Ammonia (LCOA) for Minimum Commercial Scale Product

To assess the commercial cost of green ammonia, a minimum commercial scale plant was modelled. The scale of this plant was assessed as the minimum size required where any increase in scale would result in a minimum of changes in design parameters and this was chosen as a 5MW ASPIRE plant supplied by a wind farm with 5MW peak capacity. The plant model was developed assuming ASPIRE could respond instantaneously to a change in renewable supply, and for a given renewable supply, ASPIRE has a corresponding production rate. Then, for a given year of wind data, the model assumes a constant total generation each year for the rest of the plant's lifetime.

A wind farm profile was used to determine the annual ammonia production for the minimum commercial scale ASPIRE plant. An hourly time series was generated using MERRA-2 data [15] to assess the theoretical load factor of a wind farm for a given year, this load factor was then scaled to match the renewable supply to the plant. Hourly cost data for the UK day ahead market price [16] was then mapped to the renewable supply over the same period. Then, the model evaluates curtailment at the end of each quarter [17], and the generation from this is added to the total ammonia generated at the end of the year. Ammonia generated from curtailment is assumed to use "free electricity" as no direct cost is incurred by using the electricity although, this generation could be considered a cost saving to consumers because their bills may be reduced if they are not paying for network operators to settle curtailment payments.

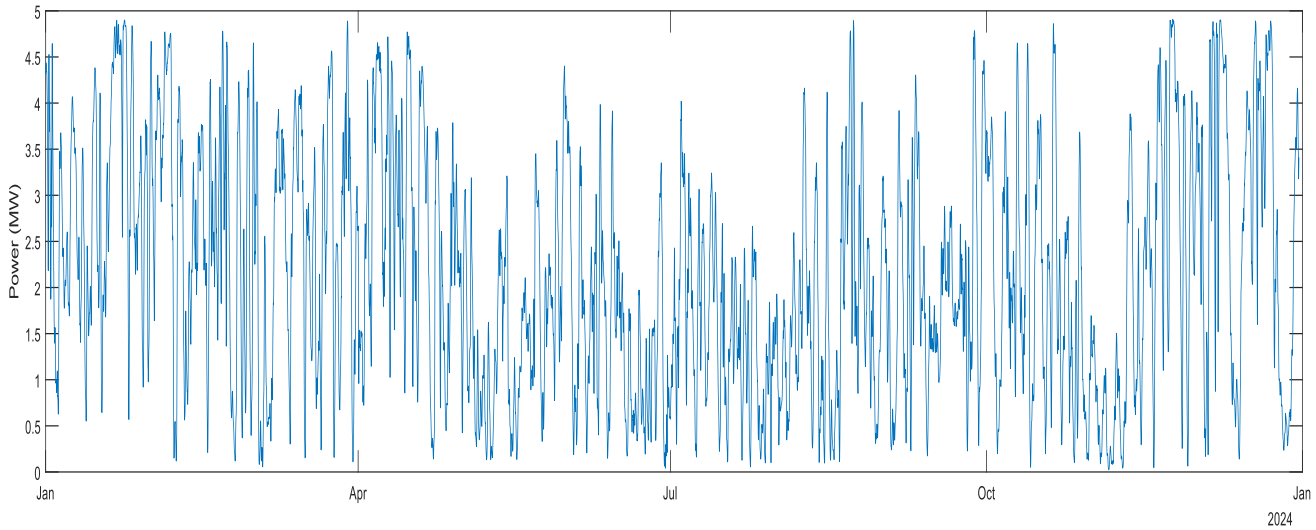


Figure 16: Modelled 5MW Wind Farm Output in UK NUTS2 Region UKH1 for 2024

The cost of a 5MW ASPIRE was informed by the costs of building the demonstrator technology and performance assumptions were validated through demonstrator testing (Appendix 2). These costs were scaled accordingly based on volume or area where appropriate. Other large items are costed based on budget prices provided by suppliers who provided specific equipment for the ASPIRE demonstrator. These costs were assigned to the year in which they would be spent and were discounted accordingly.

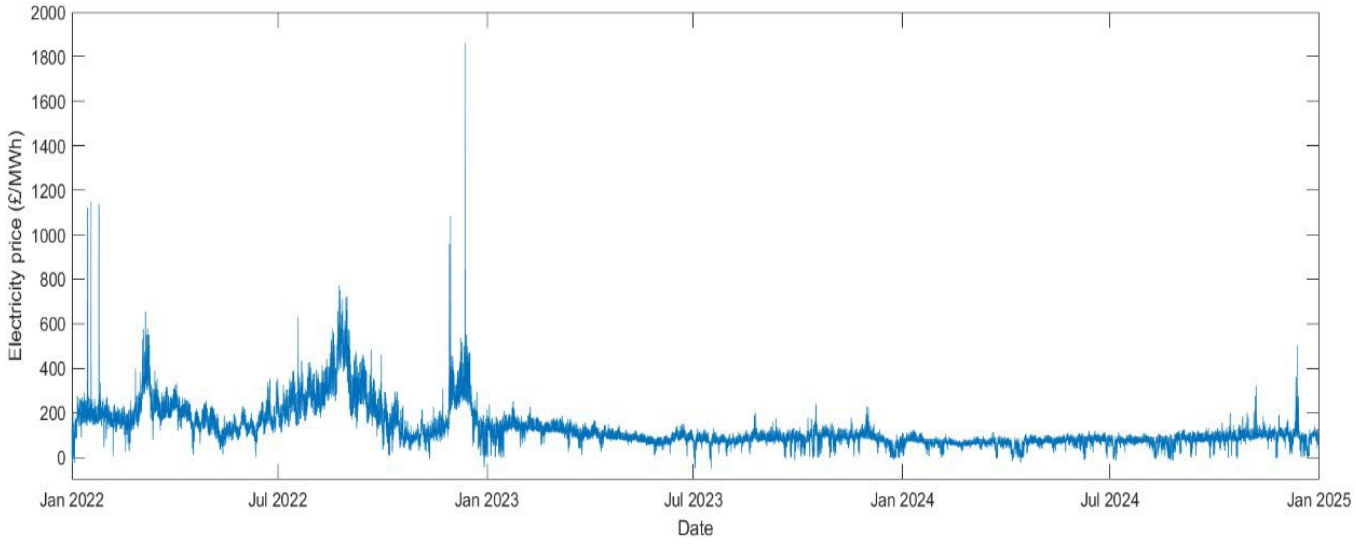


Figure 17: Modelled 5MW Wind Farm Output in UK NUTS2 Region UKH1 for 2024

The model was run considering 3 years of wind data to assess the lifetime generation of the plant and in each of these years, 3 different cases for operation were considered.

Case 1: Wholesale Market Price
The first case assumed the plant operates the same as the ASPIRE demonstrator, where the plant is grid connected but maps a specific renewable energy supply profile therefore, the plant buys electricity at the wholesale market price.

Case 2: Dedicated Wind Farm
The second model assumed that a wind farm is dedicated to generating electricity for ASPIRE hence, the plant still maps the renewable profile however, the cost of electricity is fixed and assumed to be the same as the typical levelised cost of electricity from a modern wind farm (£40/MWh) [17].

Case 3: Dedicated Wind Farm with HAR Subsidy
The final model considered a hydrogen subsidy to be in place enabling ASPIRE to buy hydrogen at a fixed price. This subsidy assumed an equivalent energy of hydrogen could be bought at 1.2 x the price of natural gas. The plant then operated with a simulated dedicated wind farm, but it was assumed that the plant only required 20% of the total electricity because the cost of using electricity to make hydrogen is covered by buying the hydrogen at the subsidy price.

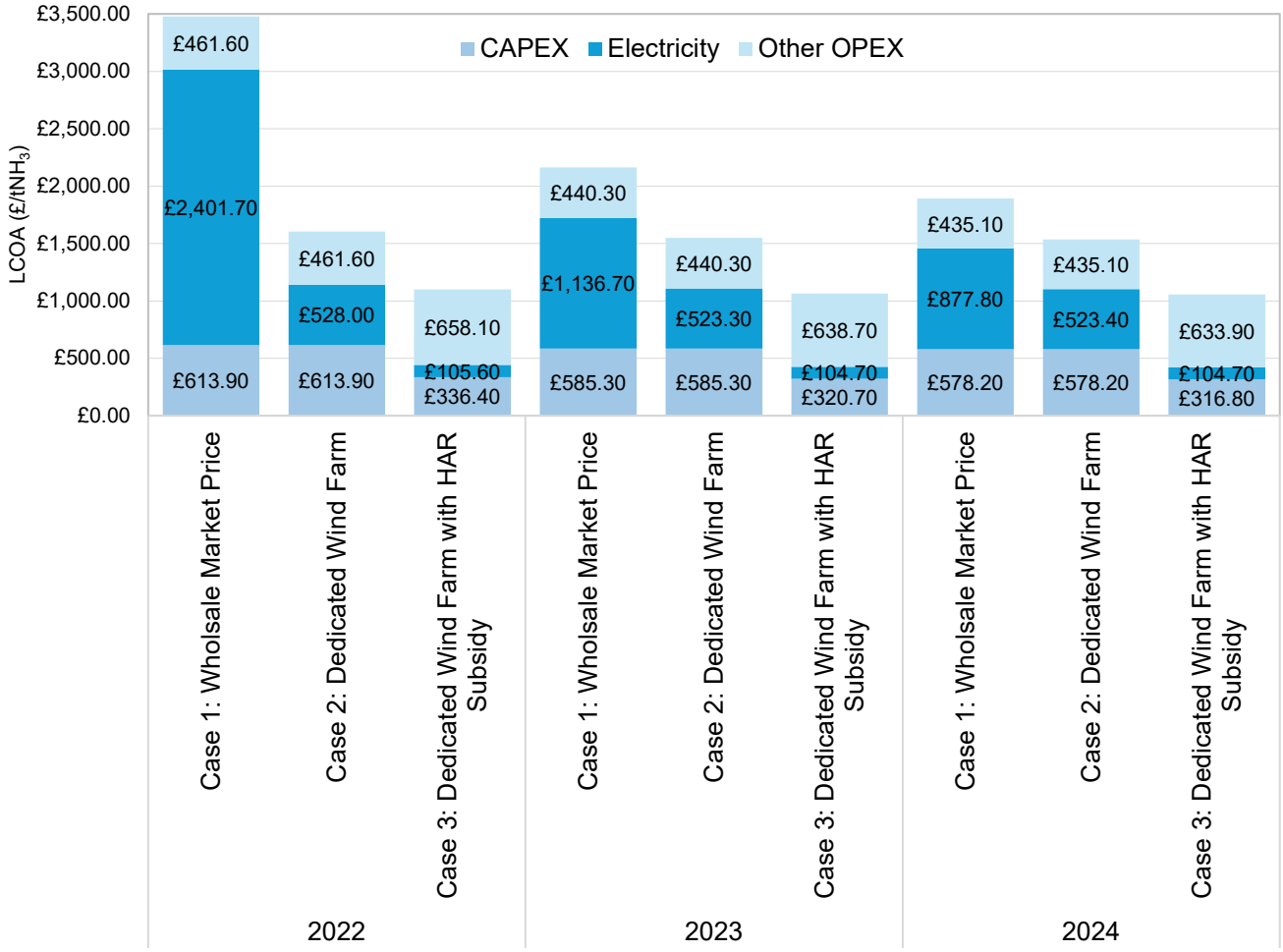


Figure 18: Levelised Cost of Ammonia for a 5MW Scaled ASPIRE Directly Mapping Renewable Energy Profile

Using electricity at market price was found to be the most expensive method of producing green ammonia. This is because buying electricity at market price is more expensive due to market pricing being dependent on various factors including renewable energy penetration and energy imports. Running ASPIRE using a dedicated wind farm therefore has multiple benefits as the ammonia produced is cheaper and the cost is less volatile to external factors thus, improving security of the ammonia produced.

6.4. Comparison of the Levelised Costs with Alternatives and Existing Technology

The flexible ammonia synthesis approach used in ASPIRE was compared to other approaches where the synthesis generator could remain inflexible. To enable continuous operation, these approaches required either large battery storage or large hydrogen storage. Alternatively, a plant could be inflexible but capable of rapidly responding to shutdowns, such a plant would then have a compromise of battery and hydrogen storage (Appendix 3.1). These plants were modelled for the same scenarios as the flexible plant and, as Hydrogen Allocation Round subsidies were the cheapest approach, this is what was used to compare.

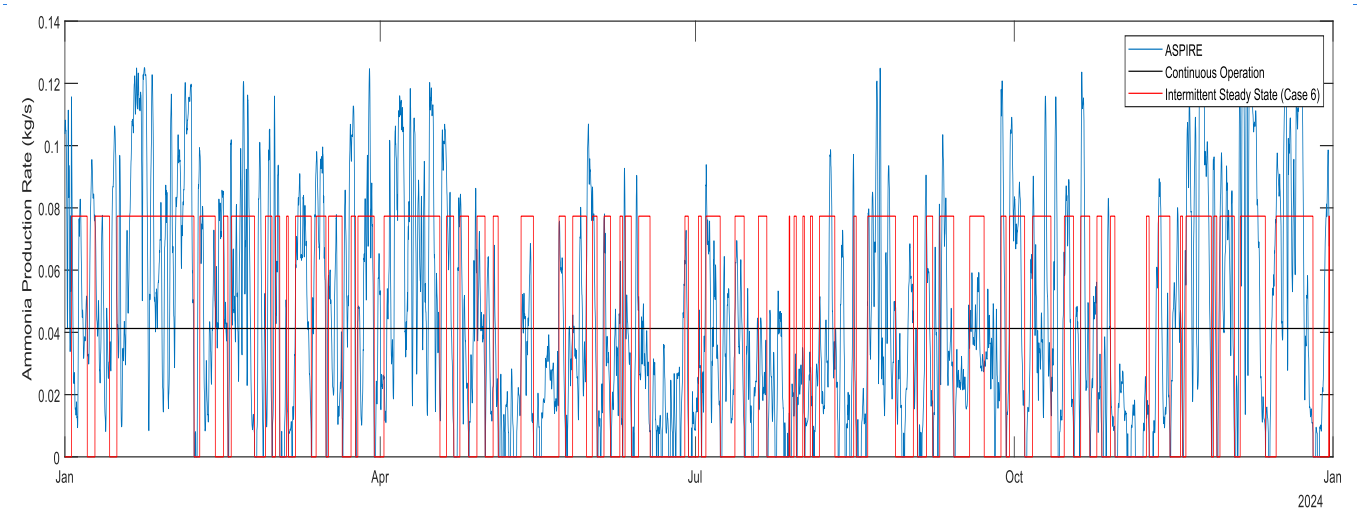


Figure 19: Comparison of Modelled Green Ammonia Production Profiles for 2024

The comparison of levelised cost results demonstrates that a flexible ammonia plant is cheaper than alternative inflexible approaches. The inflexible approaches generally result in an increase in cost because they slightly reduce the cost of the synthesis component of the plant but require a large quantity of hydrogen storage which causes a large increase in CAPEX. Furthermore, if the plant is inflexible with small hydrogen storage, this results in the plant spending a large period in shutdown. From modelling various rapid response inflexible plants, the cheapest approach to an inflexible plant was the plant with the quickest response to a change in renewable supply that could maximise capacity factor. A steady state plant with large storage is expensive due to the plant capacity being lower than the maximum capacity of the renewable supply, this results in a lower utilisation of the renewable supply. Whilst a flexible plant reduces in efficiency at lower power, this still results in maximising energy utilisation when compared to other approaches. Ultimately, the total ammonia generation in a year of all plants considered is similar because they all use the same renewable energy profile and are mapping that profile to an ammonia generation rate. Therefore, the plant that will achieve the best levelised cost is the plant that minimises capital and operational costs and maximises utilisation of the renewable energy profile.

A large battery storage approach was also considered; however, this resulted in a levelised cost 100 times greater than other cases (Appendix 3.2). This was due to the large CAPEX and OPEX associated with long-term energy storage in the form of batteries and the entire installed capacity not being used most of the time resulting in wasted CAPEX and OPEX. This is highlighted notably by large storage plants as they only briefly use their entire installed capacity to ensure the plant can continue operating during low renewable supply periods. A flexible green plant must be designed to operate at peaks of renewable supply, however, most operation occurs at around 40% of this rated capacity. The result is wasted CAPEX and OPEX spent on oversizing a plant that rarely runs at full capacity.

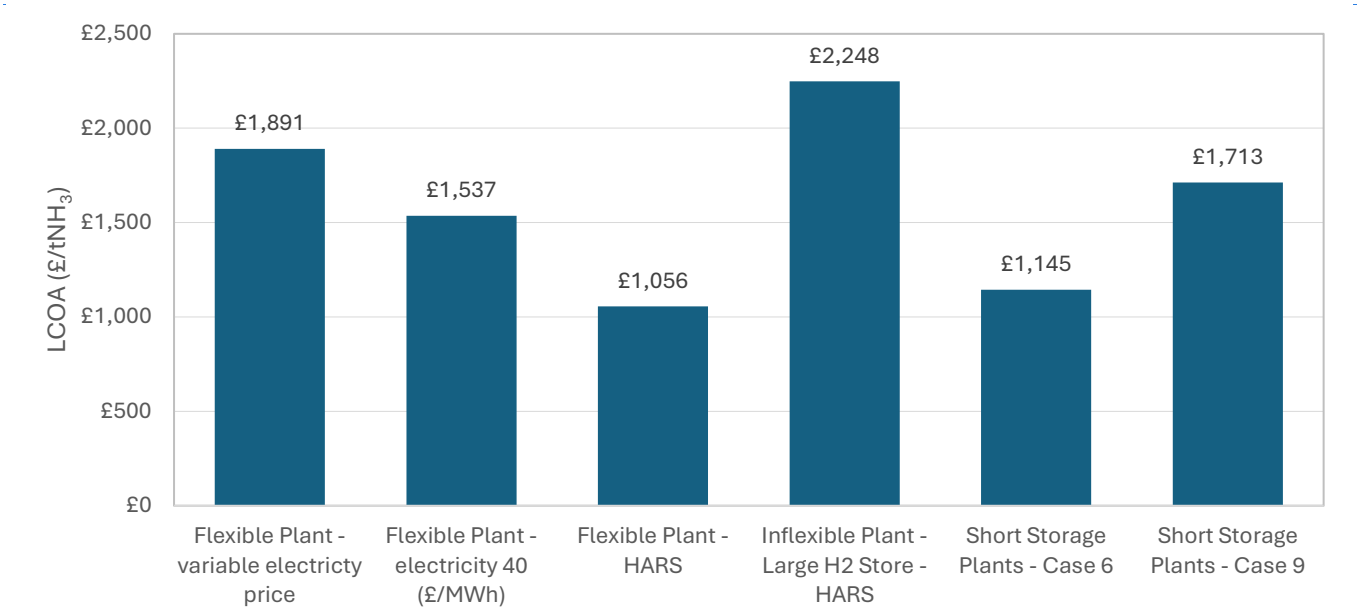


Figure 20: Levelised Cost Comparison Between Inflexible and Flexible Green Ammonia Plants

Alternative scenarios have been proposed for operation of ASPIRE to help reduce wasted CAPEX and OPEX by increasing the capacity factor. These include future wind farms which expect a higher capacity factor of >60% [18], high renewable penetration PPAs (80%) and oversizing renewable supply to be significantly greater than the ammonia plant. All these approaches result in reduced levelised cost of green ammonia. We believe the case of operating from a higher capacity factor new wind farm with hydrogen sourced through the Hydrogen Allocation Round subsidy is the most likely scenario for producing green ammonia in the near term and hence why we have used the figure of £855/tNH3 as a representative cost for producing green ammonia. Figure 21 contains current ammonia prices for grey, blue and green and it can be seen that the best case of running ASPIRE from an oversized wind farm achieves a LCOA at a similar level to current ammonia prices. The current prices also include predicted costs of importing ammonia once carbon taxes on imports such as the proposed CBAM (Carbon Border Adjustment Mechanism's) are put into place (2026) and these are estimated at £67.2 per tonne of greenhouse gas equivalent. Additional costs are also applied on top of the market price index including predicted shipping costs to the UK at £44/tonne ammonia [19] and UK import tax at 4% anticipating that ammonia is supplied from a third-party country [20].

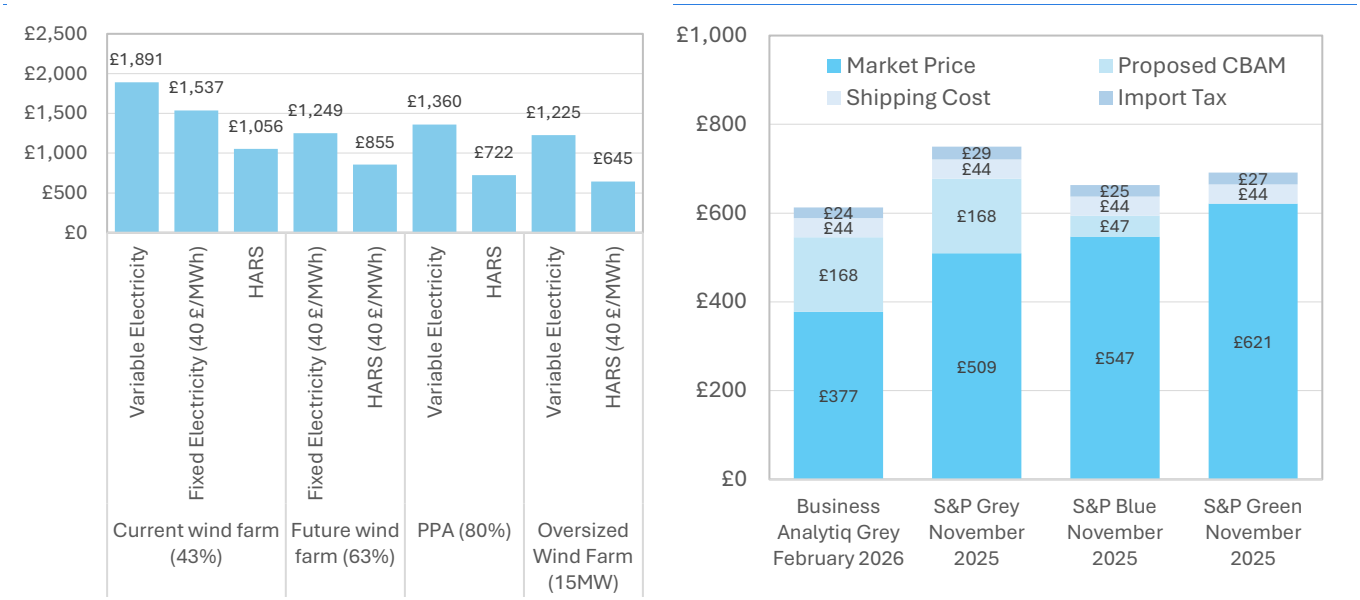


Figure 21: ASPIRE Future Business Case Models Compared to Current Ammonia Market Prices for Grey, Blue and Green Including Approximations for proposed CBAM Costs on Imports

As the minimum commercial case, the cost of green ammonia should benefit from economies of scale for larger plants capable of a greater output of green ammonia. Furthermore, technical learning with deployment of flexible green ammonia plants will help reduce costs as less design effort and R&D will be required as the technology becomes more established. Further benefits of green ammonia production may still be realised in the form of curtailment mitigation as it is currently difficult to quantify the cost saving benefit of mitigating curtailment. This benefit will improve as the proportion of the grid supplied by renewable energy continues to increase and the cost of curtailment increases proportionally. Despite this, for green ammonia to be competitive within the UK, it will require some form of subsidy to reduce the cost of green hydrogen which remains the main driver behind the high price of green ammonia when compared to grey. Furthermore, subsidies to encourage storage of energy to mitigate curtailment would encourage renewable plant operators to avoid curtailing their plant. Other cost drivers which may help green ammonia to be more competitive include fluctuations in natural gas price due to international markets, cost of importing and transporting other types of ammonia from abroad and carbon taxes on conventional ammonia production methods.

An advantage of locally produced green ammonia is that it can be directly used as an energy storage vector to accommodate the intermittency challenge of renewables. Of the production approaches considered, the most likely case for future green ammonia production in the UK is the future wind farm case as this can be co-located with high output future renewables or to a temporally matched PPA. By purely considering the energy stored within the ammonia, the levelised cost of stored energy is 136.8 £/MWh. However, to deploy this energy for grid resilience there are additional costs to convert green ammonia into electricity. Deeper analysis of this is beyond the scope of the ASPIRE project, but an approximation for this using simplistic assumptions and the determined cost of green ammonia give a levelised cost of electricity of 461 £/MWh.

6.5. % Purity of Hydrogen Produced

The hydrogen generated for the ammonia synthesis process is delivered with a purity of 99.999%. This is guaranteed by the post electrolyser stack deoxidation dryer which oxidises any remaining oxygen in a platinum catalyst and then absorbs the resultant water vapour in a reusable desiccant.

6.6. Efficiency of Production Technology

Power meters are used to measure consumption during sustained operation at a given set point generation rate. The total energy consumed during the set point period is used for the calculation of efficiency. The ammonia produced during the period is calculated by integrating the measured ammonia extraction rate during each set point test.

Only one setpoint test was identified as having a feed composition near to the stoichiometric molar ratio of 3 (see discussion of stoichiometry issues in section 5.2). During this period, we had a molar ratio of 4 and were running the plant at 30% of maximum generation rate. The calculated efficiency at this point was 40%.

6.7. Energy Associated with Production (kWh/kg H2)

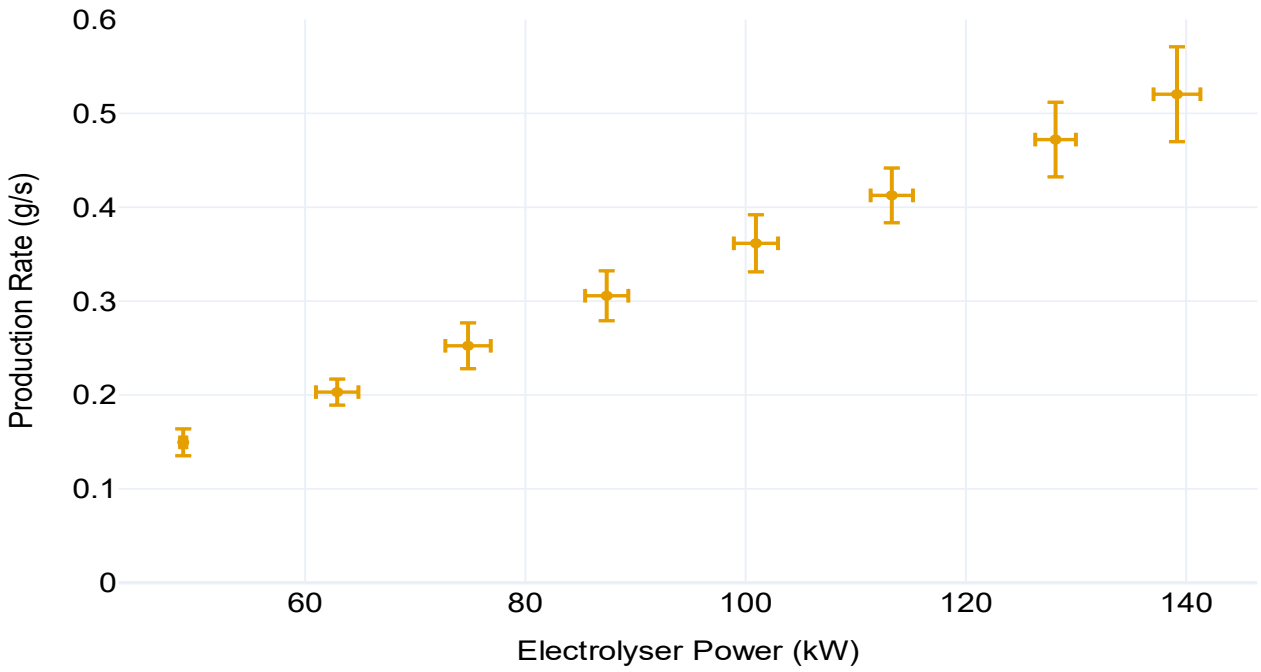


Figure 22: Plot of Hydrogen Production Rate Against Electrolyser Power

To assess the production capabilities of the electrolyser, a test was setup where the electrolyser was run at increments of 10% of nominal capacity, and both the power and generation rate were measured to develop a performance map. At full capacity, the Oort PEM electrolyser can generate hydrogen with an energy consumption of 74.3kWh/kgH_2. Whilst at a low generation rate of 30% of nominal capacity, the energy consumption increases to 90.9 kWh/kgH_2. This is due to the balance of plant for the electrolysis system, as it remains near constant irrespective of generation rate.

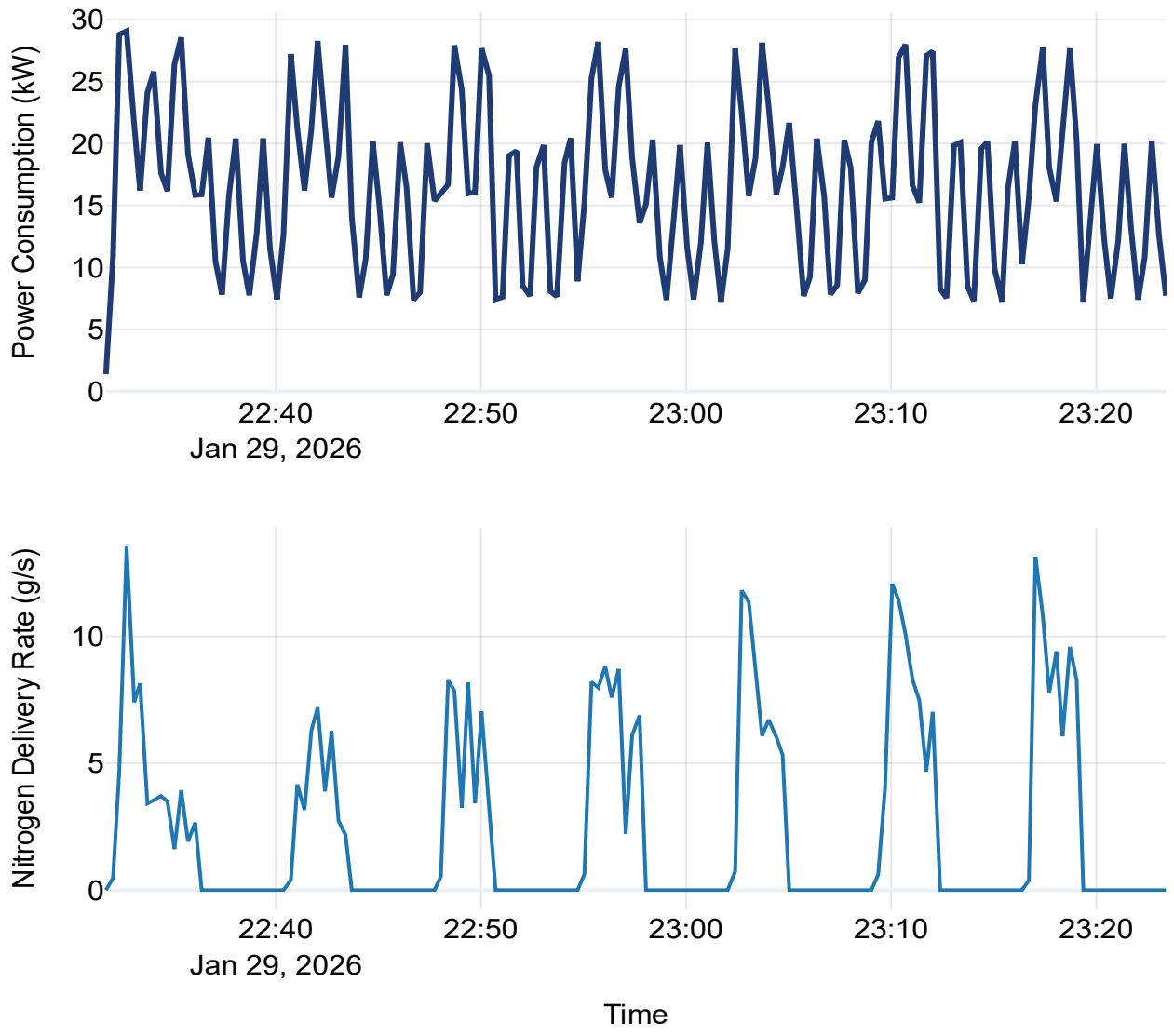


Figure 23: Plot of Nitrogen Subsystem Power Consumption (Top) and Nitrogen Generation Rate (Bottom)

A similar test was conducted to evaluate the energy required to generate nitrogen from the PSA. Throughout the test, the power draw of the PSA was monitored alongside the nitrogen generation rate. As the PSA operates as a batch process, the total energy and total nitrogen generation was averaged across seven batches. It was determined that the PSA produces nitrogen with an energy consumption of 1.94kWh/kgN_2. When the PSA is not in the process of producing nitrogen, it has a balance of plant steady power consumption of 1.2kW.

Process	Specific Energy Consumption (MWh/tnNH3)
Hydrogen Generation	12.6
Nitrogen Generation	1.0
Ammonia Synthesis	2.0
Total	15.6

To summarise the energy associated with the production of ammonia in industrially accepted units, the table above was prepared from the 40% efficient performance point. Here, the ammonia synthesis specific consumption includes all auxiliaries on ASPIRE MK0 and we believe that if ASPIRE were to be built at the MW scale, the ammonia synthesis specific consumption would be <1 MWh/tnNH3. This is because the power consumption of the auxiliaries would account for a much smaller proportion of the overall power consumption than they do at the 150kW scale (ATEX fans, control cabinets, operator cabin, mass spectrometer with vacuum pump are all included).

6.8. Durability/Lifetime of Production Technology (hrs)

1. Catalyst Durability

JM have carried out lab-based accelerated thermal cycling of the synthesis catalyst that they provided for the ASPIRE reactor. The aim of this was to find out if the catalyst would be adversely affected by thermal cycling as many in service catalysts don't currently see regular cycling. The catalyst was ramped from 400°C to 520°C and then cooled back down again 360°C times all completed within a 15hr test. A reduction in activity of 15% was observed when comparing catalyst that had undergone the accelerated ageing as opposed to a fresh catalyst. However, some drop-in activity is expected as the catalyst achieves complete reduction, and it was noted that the fresh catalyst was not completely reduced. It has also been noted that the primary cause of loss in catalyst activity is due to sintering, and this is most pronounced initially and then the rate of reduction in activity decreases at longer lifetimes (for instance when catalyst charges have been installed for 10 years plus you don't tend to see much further deactivation at this point).

2. Hardware Failures

Within timescales of the DESNZ contract, no durability or lifetime testing has been completed. However, examples of the following products suffered failures during the several weeks of commissioning and testing completed during the contract:

- Actuated Shutoff Valves
  - Failure to complete spring return to closed position when close signal received.
- Oxygen Sensors
  - Air diffusing into oxygen sensors causing saturation.
- Moisture Transmitter
  - Failing to provide readings probably due to short term saturation with gas mixture containing high water content.
- Flow Controllers
  - Failure due to operating with ammonia at –16°C which caused water vapour from the air to freeze on the outside of the unit.
- Flow Sensors
  - Failure to read a correct value due to liquid phase buildup in sensors.
- Mass spectrometer
  - Filament failures.
- Electrolyser
  - Internal leak across stack membrane.

6.9. % Purity Operating Range

The ASPIRE plant is designed to generate anhydrous ammonia, which is greater than 99.5% pure, however, once reaching mature operation we expect 99.9% purity will be possible. This is because any residual water vapour and inert gas from the commissioning process expected to be present in the first batch of ammonia produced will be removed from the ammonia store and then subsequent production will not be subject to further introduction of water vapour or inert gas. An important point regarding purity is that e-ammonia (using electrolysis-derived hydrogen) is inherently pure as compared to grey ammonia where the hydrogen is derived from steam methane reforming and may contain carbon-based impurities or unwanted components of natural gas.

6.10. Operating Conditions

Here we describe the headline operating conditions achieved during the initial plant tests. The Electrolyser stack operated between 40°C and 50°C and delivered hydrogen at 15/bar and ambient temperature.

The hydrogen compressors compressed the hydrogen from the electrolyser delivery pressure up to a maximum of 110/bar where it was stored within the hydrogen store.

Nitrogen was generated by the pressure swing adsorber and stored in the nitrogen store at up to a maximum of 110/bar with an oxygen content of around 30 ppm.

Hydrogen and nitrogen were mixed and passed through the plant deoxidation dryer after which the mixture of compressed gas had an oxygen content of <10ppm and a water content of -35°C dew point. The pressure in the deoxidation dryer was typically around 92/bar.

Ammonia was generated as the hydrogen/nitrogen mixture pass through the synthesis reactor with temperatures varying between 375°C and 475°C. The synthesis loop pressure was maintained at 90/bar. Ammonia was condensed from the synthesis loop at -16°C. It was then separated from the loop and stored at ambient temperature and the corresponding saturation pressure. During the tests, the ambient temperature was below 10°C, and the storage pressure was between 5/bar and 6/bar.

6.11. Flow Rates (Nm^3/hr)

The design figures for plant flow rate are:

1. Hydrogen generation rate at 0.05 g/s to 0.5 g/s (2 – 20 Nm^3/h)
2. Nitrogen generation rate at 0.25 g/s to 3.5 g/s (0.72 – 10 Nm^3/h)
3. Ammonia generation rate at 0.3 g/s to 3.5 g/s

The plant flow rates were recorded throughout the testing plan, and they have been plotted for the renewable profile part of the testing. Issues with composition are discussed in section 5.2.

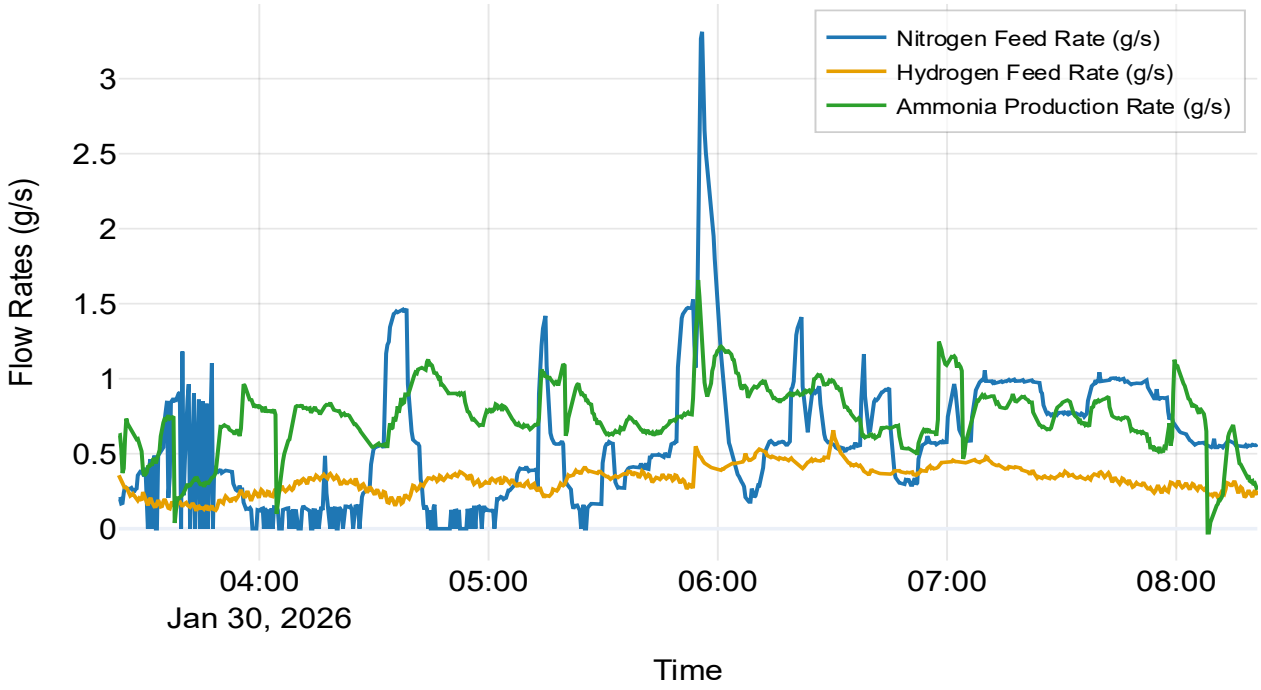


Figure 24: Plot of Feed Mass Flow Rates into Synthesis Loop and Ammonia Extraction Rate Throughout Renewable Profile Performance Testing

6.12. Total Volume of Ammonia Used During the Demonstration Study

Although no ammonia was used as part of the demonstration study, ammonia was produced across four separate test periods. The first two test periods focussed on catalyst activation; hence, ammonia production was limited during these test windows because the catalyst was in a deactivated state. The second two test windows aimed to map the performance data of the plant and most of the total ammonia produced was made during the final performance mapping test. Across all these tests, a total of 130.3kg of ammonia was produced and this is approximately 200L liquid volume. ASPIRE has the capability to store up to 1 tonne of liquid ammonia which can be decanted in a single operation. A licensed off taker (Polar Pumps Ltd) has been identified for the decant procedure, however, the limited time of the demonstration phase meant there was not enough time to perform a decant.

6.13. Total Volume of Hydrogen Used During the Demonstration Study

Throughout the four test procedures mentioned above, hydrogen and nitrogen were used to reduce the catalyst and then to make ammonia once the catalyst had been fully reduced. This resulted in a total of 261.6kg of hydrogen and 731.2kg of nitrogen being used to complete these tests. Under normal conditions, this equates to a volume of 2907m^3 of hydrogen and 585m^3 of nitrogen.

6.14. A Brief Description of How Any Outputs of the Demonstration Study (Hydrogen, Ammonia and By-Products) Were Used (Offtaken) or Disposed Of

There are several options for using the ammonia produced by ASPIRE.

- Supplying research projects that use ammonia across the Rutherford Appleton Laboratory.
- Supplying research projects that use ammonia in the UK such as Amburn. These projects currently use grey ammonia generally supplied by BOC or Air Products.

- Supply refrigeration systems that use ammonia – these users currently pay a premium for pure ammonia that could be more easily produced by the ASPIRE e-ammonia plant as compared to grey ammonia.
- Ammonia could be removed in a safe way by Polar Pumps Ltd who are a licensed disposer of ammonia. This is not our preference but is a back-up solution.

The electrolytic hydrogen we have produced has sometimes been too wet to use for ammonia production and so has been vented to atmosphere.

6.15. GHGs Mitigated in MtCO2e/year for the Demonstration Study

We do not expect that the demonstration plant itself will result in any mitigation of greenhouse gas emissions. The build of the plant has a carbon footprint associated with it and for the demonstration study we only had time to generate a small amount of e-ammonia. The carbon benefits assessment carried out in the feasibility phase included the embedded carbon associated with the ASPIRE demonstrator and showed that the potential carbon benefits are only seen once a large-scale plant comes into operation.

6.16. GHGs Mitigated in MtCO2e/year for the Commercial Product if Rolled Out as Expected

If the ASPIRE technology is rolled out on a wide scale it has the potential for a significant carbon benefit. Design calculations suggest that it is possible to generate ammonia from a scaled up ASPIRE plant for a carbon output roughly 10% of that being emitted from grey ammonia production. If we assume a gradual adoption of dedicated green ammonia plants powered by renewable energy between 2030 and 2050 with the first plant coming online in 2030 and by 2050 all current UK ammonia usage (i.e. 1million tonnes per year) transitions to green, then the carbon saving per year will increase from 0.1MtCO$_2$ in 2030 to 1.9MtCO$_2$ in 2050. The cumulative saving over the period would be over 20MtCO$_2$.

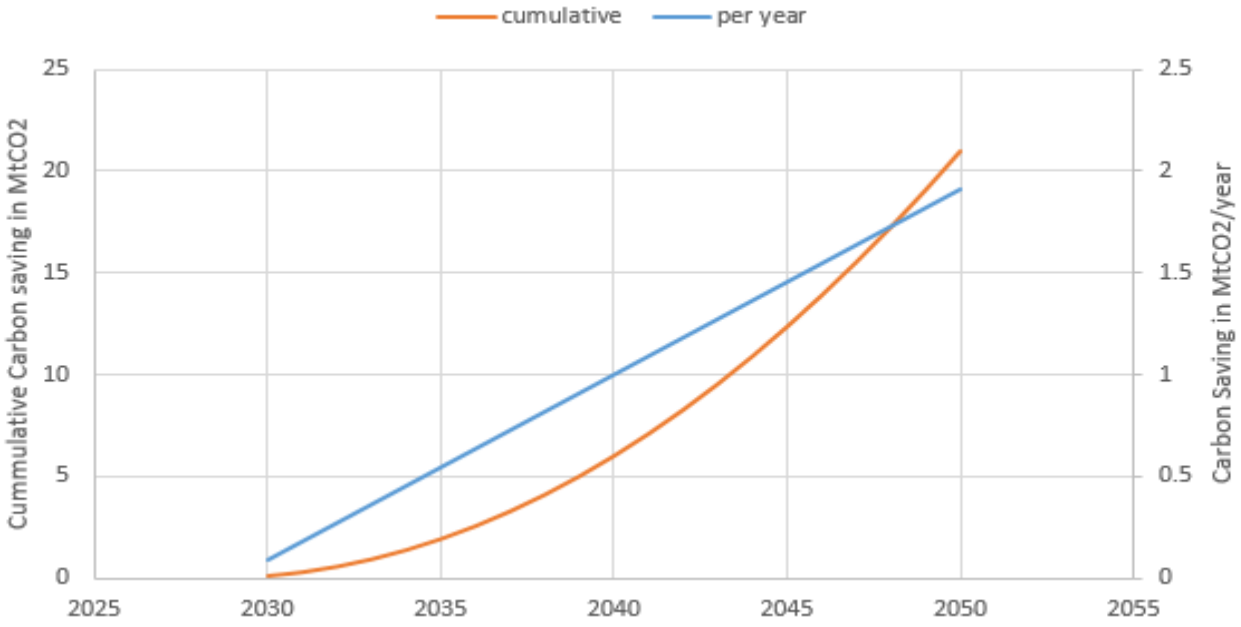


Figure 25: Carbon Emissions Up to Point of Production in gCO2e/MJLHV in Accordance with Low Carbon Hydrogen Standard Version 3

The ASPIRE team completed a carbon assessment for a 5MW plant and derived a number for carbon emissions of 0.18kgCO2eq/kgNH3 when the plant is running entirely from renewable energy. This gives us a figure of 9.6 $gCO_2eq/MJLHV(NH3)$. For context grey ammonia produces 2-2.5kgCO2/kgNH3. As part of phase 2, we considered how operating a 5MW ASPIRE on the UK grid would affect the carbon intensity of the ammonia produced. For each of the green ammonia cases considered, they are assumed to operate with a fixed price of electricity of (£40/MWh). The cases considered are as follows:

1. **Deep Green –** An islanded plant entirely powered by a wind farm with an equivalent carbon intensity of $11gCO_2eq/kWh$ [21].
2. **Grid Balance of Plant (BOP) –** An on-grid plant coupled to a wind farm via a PPA that uses the wind farm to generate ammonia with a carbon intensity of $11gCO_2eq/kWh$ but uses the grid carbon intensity to maintain balance of plant when the plant operates below 15% of max generation rate.
3. **UK Optimised RFNBO -** An on-grid plant coupled to a wind farm via a PPA that uses the wind farm to generate ammonia with a carbon intensity of $11gCO_2eq/kWh$ but uses the grid carbon intensity to maintain balance of plant when the plant operates below 15% of max generation rate and also uses the grid when it is at minimum carbon intensity to produce ammonia up to the point where it has a carbon intensity of $376gCO_2eq/kgNH3$ [22].
4. **Constant Operation –** An electrolytic ammonia plant coupled to a wind farm via a PPA that uses the wind farm to generate ammonia with a carbon intensity of $11gCO_2eq/kWh$ but also uses the grid to ensure the plant is synthesising continuously and the carbon intensity of the energy provided by the grid is matched to a grid carbon intensity time series [23].

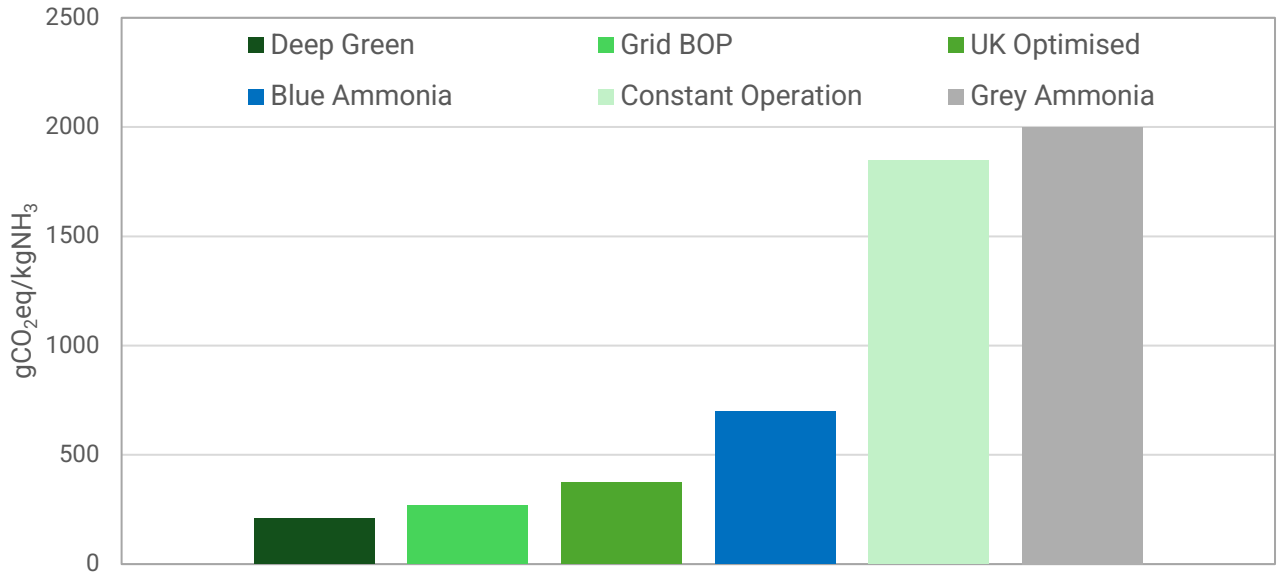


Figure 26: Plot of Carbon Intensity for Each Case of Ammonia Synthesis Considered

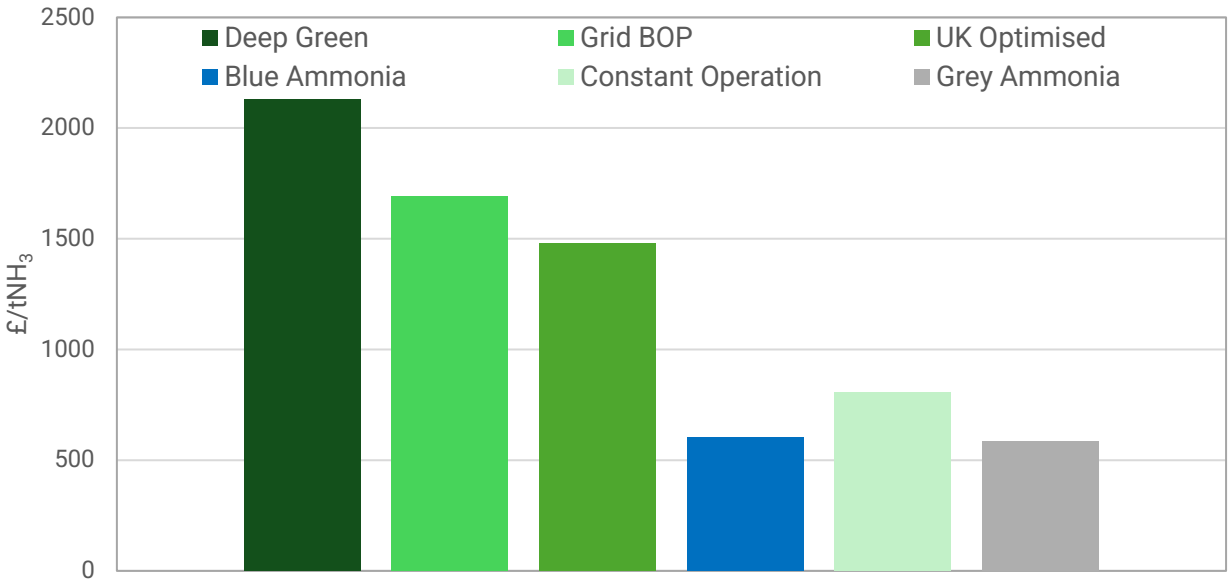


Figure 27: Plot of Levelised Cost for Each Carbon Intensity Case

Figures 26 and 27 show the trade-off between cost and embodied carbon emissions. A plant with a greater carbon intensity is likely to be cheaper as it runs independent of a renewable supply and therefore can output more ammonia. It is important to recognise that just because ammonia has been produced electrolytically, that does not mean that it is green. The constant operation plant has a similar carbon intensity to that of grey ammonia synthesis because it is running on the grid and using electricity from non-renewable sources. The costing in Figure 27 does not include HAR subsidies and assumes a low-capacity factor wind farm (~34%) meaning the green ammonia costs are not competitive when compared with conventional grey processes. To ensure electrolytic ammonia production is green, the power supply to the plant must also be green but to enable maximum cost competition, the ammonia producer must utilise as much energy as possible whilst remaining within the carbon intensity threshold.

Current grey ammonia production is mainly used for fertilisers and explosives and is often cited as being responsible for close to 2% of global carbon emissions. A transition to green production is required to seriously address the carbon emissions associated with current ammonia production. Green ammonia could be adopted as a carbon free fuel in several hard to decarbonise sectors with scope for significant further carbon savings.

- Worldwide shipping currently burns heavy fuel oil and is responsible for almost 3% of global carbon emissions. Ammonia and methanol are seen as leading options for replacing heavy fuel oil while ammonia is the leading carbon free solution.
- Globally over 50% of electrical power is still provided by fossil fuels. Increasing renewable energy penetration is reducing this but many open cycle or closed cycle gas turbines will still be required to provide resilient grid power. These plants could decarbonise by burning green ammonia to provide dispatchable power when available renewable power is low.
- Freight road transport is responsible for over 4% of global carbon emissions. There are multiple candidate decarbonisation technologies for this sector such as electrification via overhead cables, batteries and hydrogen fuelling. If hydrogen fuelling expands then green ammonia may play a major role in storing and delivering the hydrogen.

7. Project Management

7.1. Structure and Scheduling of Project

The Phase 2 project team, led by STFC, included JM and UoB, with FNC as a subcontractor. FNC was a key partner in Phase 1 and have a whole system working understanding of the project and strong working relationships with the wider team. As the subcontractor, they were responsible for four key packages of work, and undertook the following:

- Design and Process Governance
- Independent Safety Assessments
- Control System Design
- Business Case and Commercialisation Plan

The following is an outline of the project organisation structure, roles and responsibilities employed throughout the project.

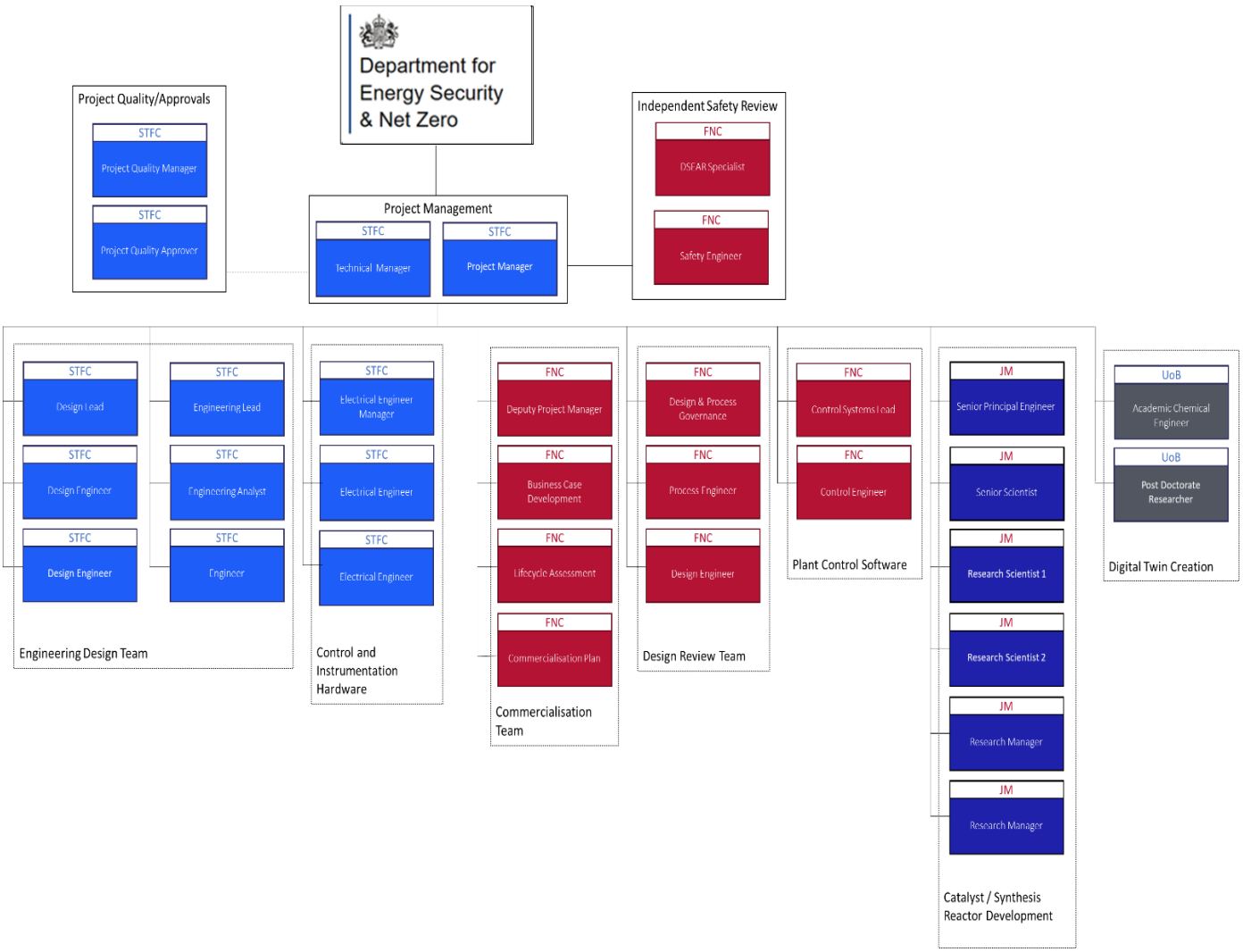


Figure 28: ASPIRE Project Organisation Structure

7.2. Recruitment Activities

During the first quarter of the project there was an initial delay in deploying the core project team members of STFC and JM due to existing work commitments and the notification to transfer once contract awarded. A significant benefit to the project was being able to utilise the extensive network across their organisations to supplement any delays or skill gaps to support the project and its evolving requirements.

7.3. Key Risks, Mitigations and Issues

There were two processes applied throughout the project to manage risks. A project register consisting of the potential project risk was frequently reviewed throughout the project that numbered 58 risks. Prior to commencement of the testing phase 37 risks were closed. The following were the top 5 risks to be managed throughout the testing project phase summarising each risk, planned mitigation and RAG rating post mitigation.

No.	Risk	Mitigation	RAG Rating
1	Catalyst exposed to high temperatures resulting in damaging reactor. Recovery if risk realised would extend testing schedule.	Modelling to verify catalyst operation and reflected into reactor design and operation process control.	AMBER
2	Release of chemicals via emergency vents leading to vapour cloud affecting local pedestrians.	Pressure relief valve proximity and dispersion rates calculated. Emergency procedure implemented.	AMBER
3	Challenging project schedule extending completion of commission and testing phase.	Regular reviews conducted internally and with customer. Change request submitted to formally approve project extensions.	AMBER
4	Fire or explosion within the plant.	Assessments undertaken throughout project phases to improve plant design and input from specialist fire and safety experts.	AMBER
5	Pressurised vessel registration for existing and new equipment.	Pressure vessel inspection and formal registration.	AMBER

The project team also employed a register to manage risk related to the plant design, which was frequently reviewed through project review meetings. The design risk register was also reviewed throughout the project including appropriate design and safety reviews.

There were five issues that were experienced during the project. Two were related to significant inflationary and project equipment cost increases and three were related to repeated extension requests to ensure project commissioning and testing could be completed, summarised below.

Issue	Detail	Reflection
1	By August 2024 it was apparent to STFC that the contract awarded to the supplier for the supply and installation of the photovoltaic array and associated electrical infrastructure schedule was slipping and that the costs of the ASPIRE project were increasing. A comprehensive review of options was undertaken with the funding body and STFC presented three options. It was agreed that additional funding and project extension would not generate additional benefits, above the scope the project originally set out to deliver, therefore, reducing the value for money to taxpayers. All stakeholders remained committed to supporting the ASPIRE project and successfully demonstrating flexible production of ammonia using grid electricity simulating renewable resources.	A change request was prepared to reduce the scope of the project and delay the commissioning and testing. A temporary extension to the project was approved whilst the detail of the change request was clarified. The change request was approved confirming the removal of the photovoltaic array from the scope of the project and approved the delay for the commissioning and testing from 1st February 2025 to 31st July 2025. A combination of original quotations for work to be undertaken from internal stakeholders were not fully scoped and above inflation price rises contributed to originally contract value being exceeded.
2	Risk number 44 was added to the register as capital equipment sourcing lead times taking longer than expected and the risk could impact installation, commissioning and testing schedule. It was confirmed December 2024 that there were a number of critical items (5) there were outstanding and would impact the completion of the plant build and delay the commissioning and testing.	
3	Risk No. 51 reflected further delays to the commissioning and testing schedule resulting from obtaining plant safety approval and commissioning verification of critical equipment.	Three further change requests were submitted detailing root cause to commissioning delays and recovery activities reported.
4		
5		

7.4. Project Management Lessons Learned

The following are examples of lessons learned related to project activities and the potential mitigation to prevent reoccurrence for future projects.

No.	Lessons Learned	Potential Mitigation
1	Revalidation and adjustment to schedule aligned to contract award. The formal approval of the contract was delayed but the project schedule was not adjusted.	Adjust and agree schedule changes to ensure deliverable milestones are achieved. If project start dates are delayed due to negotiations on contract price etc., then end date must also be adjusted back accordingly otherwise the project will start behind schedule and catch-up and unnecessary change request required.
2	Monthly detailed review with key partners.	Closer scrutiny of project partner activities measuring progress against timescale, deliverable and budgets to avoid unnecessary project impacts.
3	Inflationary prices significantly higher than forecasted (i.e. solar array, raw materials, pay inflation rate).	Future bids must state basis of quotes to capture and discuss inflationary cost outside of project scope.
4	Delayed approval for planning permission.	Earlier engagement with local planning authority to understand and address concerns.
5	Transition of customer project assignments and changing expectation on project requirements and deliverables including: • Changing requirements (Schedule 3). • Loss of consistent project knowledge (i.e. utilisation of budget to offset unplanned inflation awards). • Additional work scope (expectation for additional engagement for new project partners/conferences).	STFC need to maintain better detailed recording of discussions/meeting outcomes.

6	Maintain procurement control within the project team even for infrastructure projects.	Ensure contracts for renewable infrastructure projects such as installation of a solar array do not include any elements that require technical development meaning they cannot be fully specified accurately at the point of tender. Confirm specifications are clearly written and all costs are checked to be competitive before infrastructure contracts are signed and that the project expected to fund the infrastructure work can actually afford to do so before signing the contract.

8. Commercialisation Plans

Currently, fertiliser usage dominates both the UK and international (grey) ammonia markets, with the UK heavily reliant on imports. However, the composition of the market is undergoing a transformation, with notable emerging opportunities leveraging green ammonia, for purposes such as hydrogen supply, energy storage or marine fuel. New avenues for innovation and growth in the ammonia industry are appearing, which ASPIRE seeks to realise. FNC's Technology Management team produced a commercialisation report [24] during the build of ASPIRE MK0. Highlights from the FNC report include the following:

- A three-horizon model:
  - Horizon 1 - ASPIRE MK0 is demonstrated.
  - Horizon 2 - First commercial deployment; successful deployment to a satisfied first customer with a view to showcasing commercial viability to the wider market.
  - Horizon 3 - Major market opportunities; secure a supply of profitable deployment opportunities and flourish in a particular market segment.
- First commercial size recommended to be 1MW and to make use of surplus renewable energy,
- The first target customer is a local council or community energy group.
- ASPIRE should also seek out a local industrial customer seeking a small quantity of ammonia with an interest in innovation.

Taking some of these points on board, the STFC team have developed three commercialisation plans, each focussing on a different future use of green ammonia. They are based on real commercial interest ASPIRE has attracted from various organisations that have collaborated or met with the STFC team during Phase 2 of ASPIRE.

1. Ammonia as a sustainable commodity
2. Ammonia for marine propulsion
3. Ammonia for energy storage

Note that before starting each plan, there is a need to perform some minor upgrades on the ASPIRE MK0 system, conduct further tests and obtain a more mature performance map.

Commercialisation Plan 1 - Producing ammonia as a sustainable commodity

As discussed in section 6.3, breaking into the ammonia market with green ammonia is a question of price competitiveness against fossil-fuel ammonia. In our analysis, we looked in detail at the 5MW case study and showed that it is a challenge to reach cost competitiveness. However, green ammonia plants in Kenya and USA where the costs of importing grey ammonia make local green ammonia production competitive. They produce green ammonia for agricultural ammonia markets where little to no follow-on technology is required to realise the value of the ammonia. Business case emphasises the security of supply offered by the localised, small-scale production of green ammonia. Note that to be a small-scale system, which is around 30 times larger than the ASPIRE MK0 plant in terms of production, would require some product development to scale-up. We feel that the supply security argument is strong in countries where importing grey ammonia is theoretically the cheapest option, such as the UK. When considering import taxes, shipping costs and the soon to be introduced Carbon Border Adjustment Mechanism (CBAM), local green ammonia supply could soon become competitive in the UK.

Forming a strategic alliance would provide a route to market for the ASPIRE technology. What is exciting about this route is that the next iteration of the ASPIRE technology would be revenue generating. A rough plan is below.

1. **Licensing the design and engineering support of the STFC team to deliver a 5MW version of the ASPIRE technology.** In this scenario, the STFC team remain in their roles at the Rutherford Appleton Laboratory but work on the design, manufacture and control integration of a containerised 5MW iteration of the design. The licensing approach allows the STFC team to take ASPIRE to the next stage and gain experience without the risk and burden of manufacturing the entire system. The intended approach, to minimise risk and continue to develop the IP portfolio, is to license the feed and ammonia synthesis subsystem and its integration, leaving the hydrogen and nitrogen subsystems to be sourced.

2. **Licensee fulfils direct sales to customers.** Scale up of the production of ASPIRE plants is led by the licensee, following the delivery and successful deployment of an initial batch of containerised plants. This phase will require significant investment and a demand for direct sales from new customers. Note that this is appropriate only once the containerised design is validated.

3. **Acquisition by a larger organisation**. To reach very large production volumes, it may be appropriate for the licensee to accept acquisition offers from larger firms able to access mature industrial supply chains. This in scenario, the license arrangement would transfer as part of the acquisition.

Commercialisation Plan 2 – Producing green ammonia refuelling stations for maritime propulsion

Bespoke marine engine manufacturers have introduced the STFC team to the opportunities in a sector that is not necessarily cost-driven, in which customers have an appetite to pay a premium for novelty and sustainability. A strategic alliance would involve the development of ASPIRE into a coastal refuelling station and the maturing of a suitable engine design. Early adopters would be UK coastal marinas, and a prototype at the 500kW scale. This commercialisation option has several steps before there is revenue generation but could unlock major maritime markets.

1. **Access R&D funds to install an ammonia-to-power demonstration of a 150kW marine engine at the ASPIRE MK0 site.** Before or while building a pilot refuelling station at a small harbour, STFC could also help mature the ammonia Internal Combustion Engine (ICE) technology. A significant research grant (>£1M) would enable a container for ammonia-to-propulsion to be added to the existing ASPIRE MK0 facility and allow STFC to develop existing ammonia cracking IP into an injection system. However, if an existing modular ammonia engine is available, that does not require any R&D of the injection system and is ready to deploy, this step may be skipped in favour of accelerating the route to market.

2. **Establish a Spin Out or a Joint Venture. Direct sale of a pilot fuelling station at cost price.** The first installation on the route to market would be a 500kW pilot fuelling station at a UK boatyard with the goal of having at least one ammonia powered vessel fuelled locally and acting as a round-trip green ammonia marine propulsion demonstration. Establishing a spin out supported by STFC Business Innovations Ltd for this phase would provide a commercial entity to supply the system. The spin out could be a joint venture and an electrolyser supplier to ensure integration of the integral technologies. The stakeholders would use this facility for publicity and for attracting investment. Following this phase, we would have a 500kW containerised, deployable ASPIRE design and a novel marine engine, potentially with some injection technology from STFC.

3. **Future of the ammonia injection system.** If applicable, the fuel injection system would be patented and licensed to engine manufacturers, or it may become a parallel business unit within the spinout. Either way, its mention ceases here to keep this focussed on the ASPIRE technology.

4. **Direct sales of 500kW for profit to other UK harbours. Opportunity to franchise.** Using the pilot refuelling station for publicity is expected to attract the attention of other similar sites and gain traction in the leisure marine sector at a 500kW scale - simply repeating the pilot design. We do not anticipate a large market initially because diesel will remain cheaper. However, as the push to decarbonise continues, there are range limitations of electrifying boats, and we are aware of the imminent challenge with appropriately sized diesel engine supply chains dwindling. Together these changes will push the leisure marine sector and other small-scale marine towards new engines designed to run on sustainable fuels. If many harbours were to take an interest in the technology and ASPIRE were to gather a good reputation in the sector, franchising the design for many harbours may be appropriate. Serving leisure marine and small-scale marine sectors provides the chance for the ASPIRE technology to gain maturity without the commercial pressure and scaling requirements of industrial shipping.

5. **Scale up and roll out refuelling stations for industrial shipping through acquisition.** In step 4, small scale marine may be realised as a market in itself, but it could be a catalyst for large-scale marine to demand scaled-up versions of the 500kW refuelling station. In step 5, we explore the scenario that the plant has attracted the attention of industrial shipping and fuelling companies. Here, we would need to secure a large amount of investment to perform the necessary scale-up activity. The 5MW scale is estimated to be a good target here. Though speculative at this stage, it may be appropriate for the spin-out or joint venture to accept acquisition offers from large firms able to use their existing customer base, land and infrastructure. Alternatively, the licensee of the ASPIRE technology for the agriculture sector may be able to serve the large-scale industrial shipping market, whilst the spin-out or joint venture maintains the small-scale marine market.

Commercialisation Plan 3 – Producing ammonia for grid-scale ammonia storage

Another route to commercialisation is to develop an ASPIRE plant coupled to a turbine for use as a grid-scale energy storage facility (i.e. Long Duration Energy Storage). In this route, the round-trip cost of energy storage offered by ammonia becomes relevant rather than the levelised cost of ammonia. Though dependent on some R&D on the power-to-ammonia side, techno-economic estimates indicate that, when measured by its cost per unit energy stored, green ammonia is competitive with existing energy storage technologies particularly when long duration storage is required.

A commercial plan would need creating and driving to serve energy and utility company customers. A rough plan is as follows:

1. **Access R&D funds to develop the ASPIRE MK0 site to include ammonia-to-power demonstration in partnership with a turbine manufacturer.** The coupling of ASPIRE with a turbine has not yet been demonstrated and STFC has the capability to develop existing cracking technology into an injection system for turbines. Ideally, STFC would collaborate with a turbine manufacturer so that the interface would be at the injection system. To de-risk this R&D phase and allow good working relationships to be established, STFC would secure research funding and deliver this work under similar conditions as for ASPIRE Phase 2. It is conceivable that this first phase is skipped if private/industrial funding opportunities are better than those available with public funding. However, a utility company would most likely only want to invest in something that will work for phase 2 so having successfully completed phase 1 could be a key step. To do this step well we anticipate funding of the order >£1M.

2. **Establish a Spin Out or a Joint Venture with an energy supplier, or a turbine manufacturer & electrolyser supplier. Deliver a pilot 5MW storage facility as a direct sale at cost price for publicity and R&D.** To attract the industrial investment required to develop this technology at scale a spin out supported by STFC Business Innovations Ltd should be formed, with the mission to establish ASPIRE as an energy storage technology. As in phase 1, it would be prudent to partner with a turbine manufacturer to de-risk the turbine design. It would also be beneficial to focus on the ammonia synthesis technology and ensure the hydrogen delivery is the responsibility of a project partner. The aim of this phase is to build a pilot plant of around a 5MW scale for a utilities customer and in so doing, develop a containerised, deployable technology and have a facility to use for publicity.

3. **Continued development through strategic direct sales of the containerised design to step through the 10-100MW scale.** Following a successful pilot plant, the design must be scaled up to meet the requirements of major utilities companies. Opportunities to scale up to the 10's of MW will be sought, using the pilot plant in phase 2 to raise the profile of the technology. R&D is required to get to the 10's of MW scale and there will be a challenge to meet the stringent reliability requirements of a utilities contract with a nascent technology. It is anticipated that taking a modular approach to the design, for example reusing the design of the 5MW containerised modules, may de-risk and accelerate the scale up.

4. **Exceeding the 100MW scale through acquisition.** To reach very large scales (above 100MW), the containerised design will probably give way to a more traditional chemical plant design. For this scale, it may be appropriate for the spin-out or joint venture to accept acquisition offers from large firms to make use of their large-scale chemical industry knowledge and mature supply chains. The investment for each iteration of the plants at this scale also becomes very large, and it may be more feasible for a company with large amounts of capital to do this.

Common Themes & General Scale-Up Strategy

Generally, demonstration with public funding prior to spinout formation is favoured to demonstrate the foundation technology on which to raise investment. In the case of ammonia for energy storage and for a marine fuel, this means that some further public funding is expected. Other common themes:

- R&D towards containerised/repeatable design is required in all cases.
- Each route brings benefits to security of supply by not relying on imports/global supply chains.
- Differing scales required for each path:
  - Ammonia as a commodity:
    - No further demonstration required.
    - Development of 5MW ASPIRE container (module for the ammonia synthesis subsystem, feed system and master controller).
  - Energy storage:
    - Demonstration of ammonia-to-power systems at Rutherford Appleton Laboratory anticipated.
    - Development of 5MW ASPIRE module (module for the ammonia synthesis subsystem, feed system and master controller) + downstream 5MW ammonia-to-power unit.
    - Scale up to 100MW using 5MW modules.
  - Marine fuel:
    - Demonstration of an 150kW ammonia engine at Rutherford Appleton Laboratory anticipated.
    - Development of 500kW ASPIRE container (module for the ammonia synthesis subsystem, feed system and master controller).
    - Roll out at 500kW or scale up to 5MW.

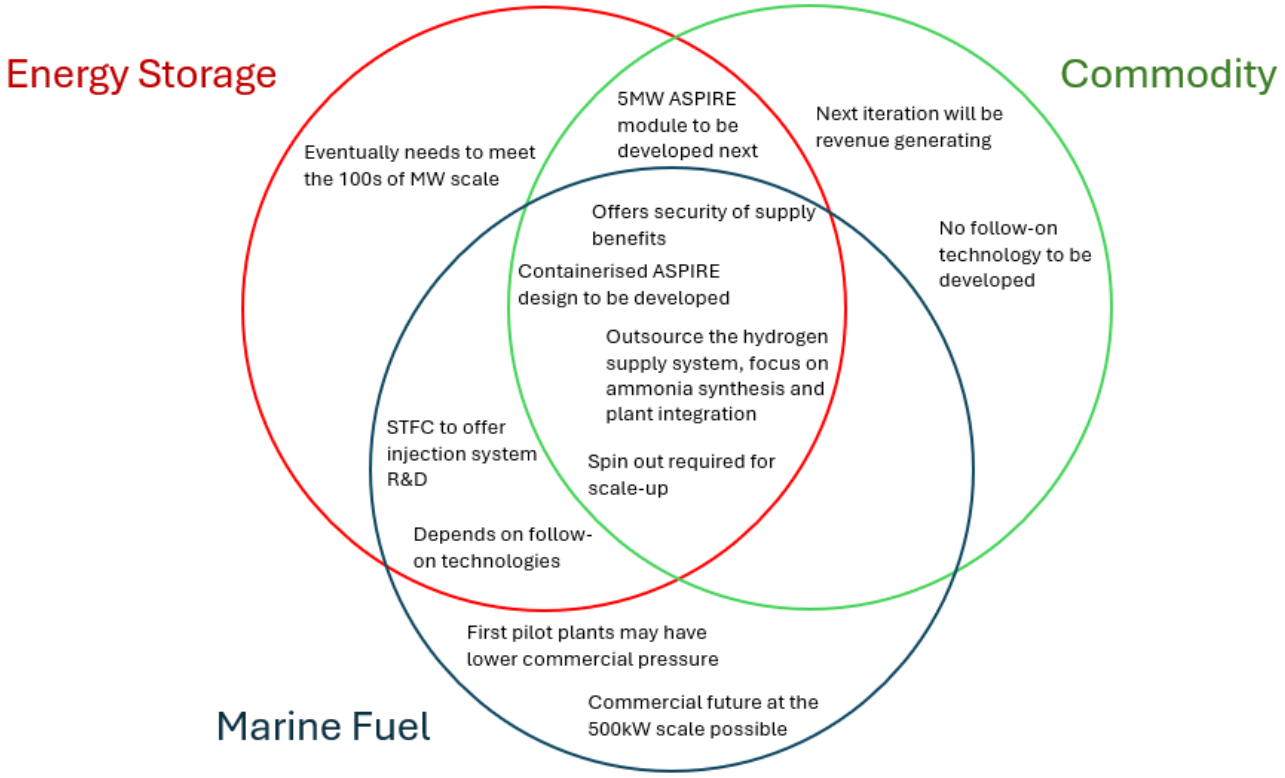


Figure 29: Venn Diagram of Routes to Commercialisation

8.1. Route to Market Assessment (RTM)

Only a high-level RTM assessment can be performed at this stage prior to securing the first commercial customer. Generally, STFC remain open to all three target markets.

Market Segmentation and Trends

ASPIRE has the potential to break into existing ammonia markets and meet emerging markets. For any end use, ASPIRE brings carbon-saving benefits and ensures security of supply by not relying on imports/global supply chains.

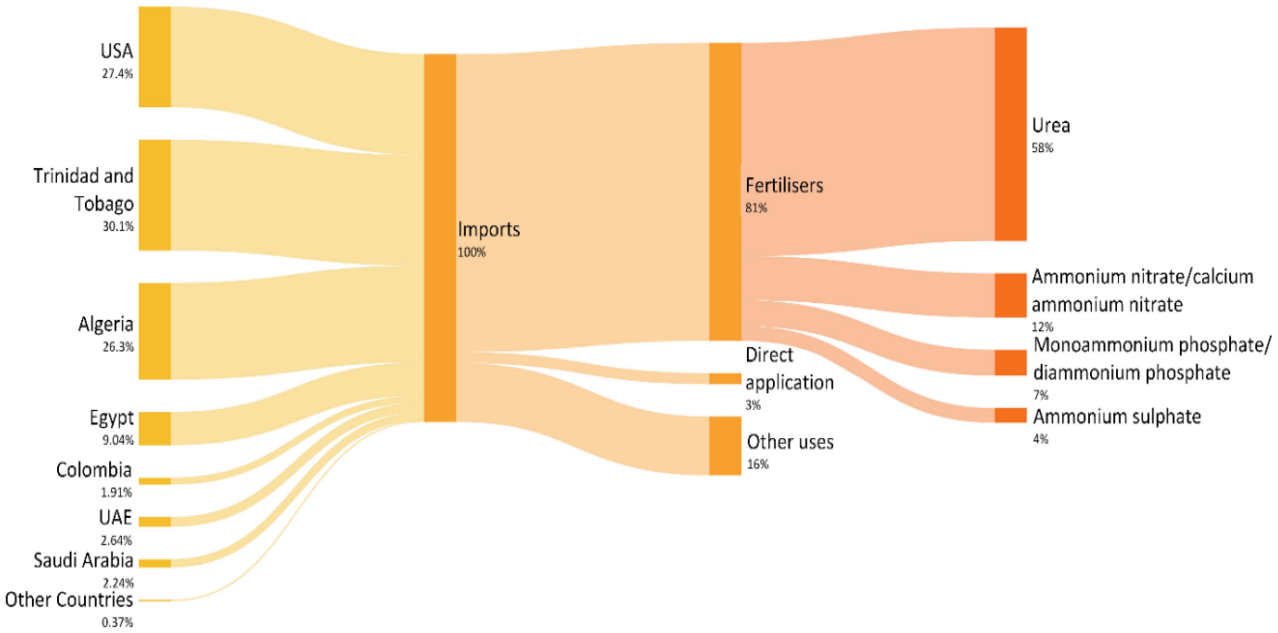


Figure 30: Sankey Diagram of Ammonia Import and Usage in the UK in 2024

- Agricultural (or other users of green ammonia as a commodity):
  - Some early-stage companies are securing commercial customers in Africa and North America where no additional technology is required after to utilise ammonia after production, due to agricultural practises involving direct ammonia application.
  - Localised green ammonia production and usage in the UK Agriculture sector have yet to be adopted. This is partially due to farming practises in the UK favouring ammonia derivatives. These derivatives require downstream processing and reinforce centralised processing of ammonia which is not conducive to small scale production (see Figure 32). Follow on processing to an ASPIRE design (to make Urea) may be required to break into UK markets.

- Energy storage:
  - Still at an R&D phase, awaiting an industrial round-trip demonstration.
  - Ammonia combustion in internal combustion engines and gas turbines is being heavily researched.
  - For ammonia storage solutions, the technology would need to include supply systems (ASPIRE in its current form) plus an ammonia-to-power solution. As a round-trip electricity storage system, it is not possible to separate the systems – unlike in the case of a refuelling station for marine fuel.
  - Market trends indicate that the need for grid-scale energy storage is growing.
  - Target application is energy grids with high grid potential.

- Marine fuel:
  - ASPIRE meets the refuelling side of this market, which could be decoupled from the engine component.
  - Ammonia propulsion is still at an R&D phase, with some notable demonstrators.
  - eMethanol is a competitor to green ammonia as a shipping fuel, therefore it is strategic to implement small ammonia refuelling stations in order to draw the market towards green ammonia.

  - Large scale R&D projects are in progress.
  - Currently, the route to decarbonisation is unclear at the small scale and ammonia could offer a pathway.

- Research & Education:
  - Small sector that may offer a customer base suited to the 500kW scale and the maturing of the ASPIRE design.
  - Several UK Universities (e.g. Cardiff, Nottingham) are performing ammonia-to-power research and are currently reliant upon grey ammonia supply.

Selection of Distribution Channels

ASPIRE has some high-value knowledge that may be licensable in the short term, but further R&D is needed to make it into a repeatable, mature product for sale on the market. For the energy storage and marine fuel markets, follow-on technology must be developed.

- Licensing:
  - This arrangement can be used initially for the agricultural market because there are companies who could benefit from the ASPIRE design on their current sites. A license agreement for aspects of the ASPIRE design would generate revenue, without the burden of manufacturing, and allow STFC to invest time into the development the technologies required for the energy storage and marine fuel markets.
- Direct sales:
  - Direct sale of a 500kW ASPIRE as a marine refuelling plant demo would provide an initial step in the marine fuel market. The marina customer would use the facility for R&D and a demonstration to marina users, offering both the ASPIRE team and the marina customer the chance to gain publicity and raise investment.
  - Direct sale of a 500kW ASPIRE to an R&D facility customer requiring a modest supply of green ammonia is another near-term distribution channel. Whilst bringing the benefit of a genuine green ammonia supply to a research institution, this would allow the team to develop ASPIRE into the 500kW module.
  - In the long term, an ASPIRE spin-out may grow to create its own production facilities to fulfil direct sale orders.

Supply Chain Management

Only a single prototype plant has been completed at this stage (ASPIRE MK0), so supply chains are immature. Key points are listed below:

- Containerising the ASPIRE design to a specific scale is key to locking in a price and delivering it as a product to potential customers across all markets. Two scales are predicted, the 500kW system (very similar to MK0) and the 5MW system (significantly scaled up version of MK0).
- Product simplification to an “ammonia synthesis subsystem + master control system {+ maybe nitrogen supply}” is required to move the risk to the hydrogen supplier. PEM supply should not be the responsibility of the ASPIRE team. STFC will require a strategic alliance with a PEM supplier, but they must not be a subcontractor instead they should have their own contract to supply hydrogen to the customer.
- Long lead items should be ordered first for any new builds, ASPIRE MK0 has revealed what the longest lead items are, and where spares are most necessary.

8.2. Scalability and Applicability to Other Sites

Developing the ASPIRE design into a repeatable, containerised module, which does not include the electrolyser, makes it easy to scale and apply to other sites. Containerising the ASPIRE design with climate control inside (heaters and ventilation) would make it weatherproof and robust to any deployment location. The MK0 system was built in a wet UK environment and has provided many learning opportunities.

Regarding the scale of a module, the techno-economic analysis shows that the costs of having "wasted" capacity for the ammonia synthesis subsystem is negligible. The main drivers of cost are the electrolyser and renewables, where oversizing significantly increases the levelised cost of the product ammonia. Therefore, it is strategically better to focus on one or two containerised scales for the ASPIRE container, rather than offer bespoke sizing for each future site. To scale-up, we envisage installing multiple ASPIRE containers in parallel; for example, 20MW system could involve 4 x 5MW containers. This also brings operational benefits should failures arise as a single module could be repaired while the others continue to operate.

Finally, we think that this modular approach allows us to pivot in response to market conditions. For example, if a 500kW ASPIRE were developed for a small harbour with the intention of becoming a refuelling station but then e-Methanol were to start dominating the marine fuel market, the design of 500kW module we have developed could be quickly adapted to the agricultural supply sector.

8.3. Access to Revenue Support Mechanisms

Commodity: Mechanism to address the green-grey ammonia price gap

Policies are required to bridge the price gap between grey and green ammonia. These may be enforced as subsidies for green production or penalties on fossil-produced ammonia. The CBAM in the UK, due to begin in January 2027, will immediately support green ammonia. Import taxation also has the potential to make local production cost competitive. Subsidies for green hydrogen that guarantee a levelised cost of hydrogen can significantly reduce the levelised cost of ammonia.

Energy Storage: Reward for high-inertia energy storage solutions

One further advantage offered by ammonia energy storage solutions over battery storage is that it will provide power via high inertia means (gas turbines) so introducing these to the national grid builds in resilience with storage capacity. A support mechanism that rewards storage solutions with inherent resilience could encourage investment here.

Energy Storage: Mechanism to reward the storage of energy that would otherwise be curtailed

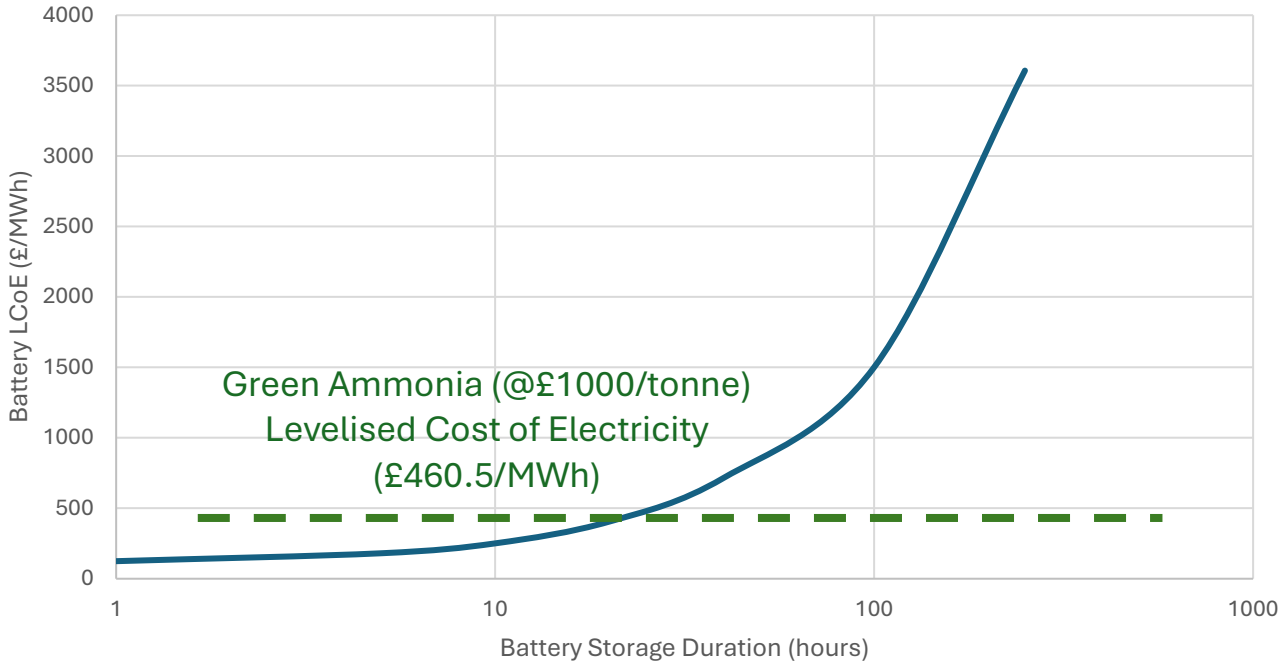


Figure 31: Levelised Cost of Energy Storage of Batteries vs Ammonia

The merit of an ammonia-based energy storage system is the large storage capacity it could offer; the cost per MWh of storage is very competitive (see Figure 33 Levelised Cost of Batteries). Once the production facility (ASPIRE) and the ammonia-to-power (follow-on technology) systems are built, the storage of liquid ammonia is cheap and scalable. Though not achieving very high round trip efficiencies, an ammonia energy storage solution would offer a useful end for surplus wind energy and a sustainable method for providing power through renewable droughts. A support mechanism that rewarded the storage of energy that would be curtailed is necessary to incentivise investment here. Perhaps this could be cost neutral to the UK Government if it reduces the curtailment payments that are to be made.

Marine Fuel: Mechanism to support local supply of renewable fuels

Local supply initiatives designed to reward communities that are self-sufficient could help localised roll-out. For example, support for marinas, farms, remote communities (e.g. Scottish Islands) which can supply their own green fuels.

Scale Up Funding

The DESNZ Phase 2 funding has allowed us to build an initial prototype system which has demonstrated the technology and provided invaluable IP development opportunities. However, there is a step between this point and a marketable product. There is now a round of upgrades required to fix some of the issues we encountered and a need to revise the design to a marketable containerised solution, but the funding has ended. A follow-on round of public R&D funding would help make ASPIRE into a strong investment opportunity, without leaving the project vulnerable to failure at the last hurdle or having to take an undesirable funding arrangement.

8.4 Outcome(s) of Conversations with Prospective End-Users

Section 8 describes the plans that have arisen as a result of some of the conversations we have had with prospective end users of the ASPIRE technology.

9. Conclusion and Next Steps

1. <u>Conclusions</u>

A novel flexible e-ammonia plant has been developed from concept to TRL7 from April 2023-January 2026. The ASPIRE flexible synthesis loop design and control strategy has been proven by the building and testing of the 150kW ASPIRE MK0 at the Rutherford Appleton Laboratory, which has produced over 100kg of e-ammonia (electrolytic ammonia) from water, air and grid electricity during initial testing. ASPIRE MK0 is underpinned by a rigorous safety case which passes all pressure safety, process safety, DSEAR, fire safety and environmental regulations. This is a strong basis for scaled-up designs.

Though initial results have revealed 40% efficiency at 30% of maximum generation rate, hardware failures related to gas quality control mean that the ASPIRE MK0 has not received a complete performance test at the closure of Phase 2. The plant is in need of some minor upgrades and repairs, which STFC intends to complete in Q2 2026 in order to obtain a publishable set of results. Only then could the complete efficiency vs turndown relationship and utilisation of available power be determined. This remains a critical next step for STFC, for which funding is being sought.

Technoeconomic modelling of a 5MW iteration of the ASPIRE design complemented the practical effort, providing estimates of levelised costs of ammonia in the UK and the carbon intensity of the product. The most likely price prediction is £855/tonne NH_3, when making use of the HAR subsidy. This prediction is promising and is not far from being competitive with market prices. Furthermore, this modelling confirmed that the flexible synthesis with small hydrogen stores approach, the core design philosophy of ASPIRE, resulted in the best price; inflexible synthesis with hydrogen storage coming in around £2248/tonne NH_3 for comparison.

In 2024 the energy island component of the project was descoped due to escalating costs, meaning that ASPIRE MK0 would not produce “deep green” ammonia; the national grid would provide the power rather than local renewables. Though disappointing initially, this prompted research into renewable power purchase agreements, grid curtailment issues, upcoming regulations for RFNBO production and modelling how the operating strategy could affect the carbon intensity of the product. STFC highlight the need for a standard for green ammonia. Using the UK’s standard for green hydrogen <20 gCO2e/MJ H2 [18], arrive at <0.373kgCO2e/kgNH3 as a potential requirement for green ammonia in addition to it having to be e-ammonia, rather than fossil fuel derived. For reference, the carbon intensity of grey ammonia is around 2kgCO2e/kgNH3. As our understanding matured, we realised that the core value of ASPIRE was that it was dedicated to e-ammonia and, when grid connected, what remained was to investigate the relationship between operating strategy, carbon intensity and levelised cost; in other words, introducing “shades of green”.

Modelling revealed that at the 5MW scale in the UK, the ASPIRE response rate and turndown capability would allow the product to achieve a carbon intensity of 0.27kgCO2e/kgNH3 running from the grid in a renewable PPA, whereas this would only drop to 0.2kgCO2e/kgNH3 for a "deep green" configuration which would incur an extra 25% in levelised cost. The ASPIRE design can cope with either power supply configuration, and the economically viable option will depend on the location of installation. There may be a need to go for the "deep green" option in some remote areas or areas with very high grid connection costs, but these results show there are major carbon benefits and reasonable economic prospects for green ammonia as a commodity for grid connected ASPIRE plants in the UK.

In addition to the ammonia as a commodity market, STFC are keen to investigate the significant potential markets of ammonia for energy storage and as a marine fuel. Commercialisation plans, which involve developing the site of ASPIRE MK0 to include an ammonia-to-power demonstrator as an initial step, have been prepared to access these markets. A common theme of taking the ASPIRE technology to market is to containerise the feed and synthesis subsystems into a module of a fixed size (for 500kW and 5MW total power requirement seem most likely at this stage). The ASPIRE "product" may not include the electrolyser but rather require a collaboration with an electrolyser supplier for each installation; a customer would always require the ASPIRE module and an electrolyser. Physically and in terms of control it would be identical to the ASPIRE MK0 arrangement, but the electrolyser would financially be a co-dependent system from which ASPIRE buys hydrogen over a metered connection. This would move the technical risks to the electrolyser supplier and, in the UK, could make effective use of the HAR subsidy. STFC considers it a priority to develop the ASPIRE design into a containerised module and has applied for several funding sources to perform the necessary design work.

2. <u>Next Steps</u>

There is a need to find new funding to be able to run the ASPIRE demonstration plant for a longer period which will enable us to provide meaningful data on reliability of this approach to green ammonia production.

It is pleasing to be able to report that conversations have already taken place with prospective end users of the ASPIRE MK0 demonstrator at RAL, as a research facility. STFC's Energy Research Unit is a co-investigator in a new £3m research project funded by EPSRC titled "Winter Ammonia", which will start in Spring 2026. The project is focused on distributing energy for space heating in the form of aqueous ammonia and ASPIRE MK0 will be providing real data to the consortium on the achievable efficiency and cost of a purpose-built green ammonia plant. This funding should allow some ongoing testing and operation of the ASPIRE plant.

Another prospective end user of the ASPIRE MK0 plant for research purposes is to improve electrolyser start-up times and efficiency using thermal management and storage systems to maintain the stack at optimum temperature during transients and startups following periods of being in stand-by.

STFC will also continue to engage with industry and government during this period as successful continued operation may catalyse funding for a larger scale pilot plant. A comprehensive commercialisation strategy has been developed considering potential customers and routes to market and will be used to direct future dissemination activities.

9.1. Was the Project Able to Achieve its Objectives

The technical feasibility objectives

1. **Demonstrate a novel level of flexibility for a green ammonia plant.**
   During the testing, the ASPIRE MK0 demonstrator successfully proved flexibility down to 30% of rated capacity. Although not proven by current testing, it is likely that the power load could flex lower than 30% because, hydrogen was oversupplied to the loop throughout the testing period due to sensor failure. As hydrogen generation accounts for most of the power consumption of the plant (around 80%), then it is likely this overproduction means the plant could have been operating at a lower power setpoint than what is represented in the results. Overall, the ASPIRE MK0 demonstrator is yet to prove turndown to 10% of maximum generation rate but more testing should prove this is possible - flexibility to 30% still demonstrates significant flexibility when compared to conventional Haber-Bosch synthesis.

   During the limited testing period, one test window was identified to have fed a near correct feed gas mixture. At this point, the plant was found to have a power to ammonia efficiency of 40%. This point was achieved at 30% of maximum generation rate and plant efficiency is expected to increase as we move towards maximum generation rate. The 40% efficiency corresponds to an energy consumption of 15.6MWh/tNH3. However, at maximum generation rate plant characterisation achieved so far leads us to believe we can generate ammonia for 12MWh/tNH3. For comparison grey ammonia production, primarily using steam-methane reforming (SMR), consumes approximately 8-12MWh/tNH3 with natural gas serving as both the feedstock and energy source. The results obtained from running the ASPIRE plant so far demonstrate that the plant design system is efficiently flexible and can be scaled. The testing also demonstrated that excess thermal energy from the synthesis process could be captured in a thermal store with 10.5kWh of thermal energy captured during plant operation over around 12 hours. Commercial operation of the plant would require an off taker for the thermal store to enable more energy to be captured.

2. **Demonstrate the rapid response provided by the thermally managed modular reactor system.**
   Each system independently demonstrated near instantaneous power response to a change in demand. This meant the entire plant load would respond almost instantly to a change in plant setpoint. From the renewable setpoint test, it was also observed that the plant could change production rate within minutes of a change in setpoint especially when the change in demand was small. This meant the plant could easily follow a renewable profile with an update period of 5 minutes, which is significantly more flexible than current PPA agreements require. However, the plant's response time to larger jumps in power is less clear. When following the setpoint profile, ammonia production rate could drop from a high production rate to low production within a few minutes. The response to an instant large increase in power is harder to quantify due to the variations in feed gas mixture throughout the testing. From the data collected, an initial jump in production can be seen when the setpoint changes but we suspect that for the plant to realise full production capability at this setpoint, it may take around 30 minutes for the reactor to recover temperature following the initial drop caused by an increase in circulation rate. Despite exact figures being difficult to quantify, the ASPIRE plant design can flex both power consumption and production rate rapidly enough that the plant could run islanded directly coupled with renewables or on grid and meet the requirements of a PPA once the plant is at operational temperature. However, from a cold start, the plant took around 10 hours to

successfully heat-up to synthesis temperature. This was deemed to be a consequence of pre-heater design, where project pressures had led to a lower power heater being procured and the design leading to a waste of almost half the heat being supplied. Furthermore, the ramp rate of the electrolyser could take several hours if ambient conditions were close to 0°C. However, as these processes can be completed simultaneously, the cold start time of the plant is limited by reactor heat up time. Whilst a 10-hour cold start is significantly worse than what the ASPIRE MK0 plant was intended to achieve, this is still faster than conventional ammonia synthesis processes from cold start and the team are aware of potential design changes that could reduce heat-up time to near what was specified in the objectives.

3. **Demonstrate the running of an ammonia plant autonomously from an intermittent power supply with very low curtailment.**
   The ASPIRE MK0 plant was run on a simulated renewable power supply from the grid. The plant had a power utilisation of 111%, consuming more power than the renewables could supply. This is likely a consequence of the oversupply of hydrogen during this testing, but it could also be due to poor setpoint choice for a given power supply. Further testing would enable the plant setpoint to be more closely tuned to a specific power consumption which would enable closer mapping of the renewable profile, resulting in a utilisation closer to 100%. It is critical that this setpoint tuning is completed because a plant with a high drift error from 100% utilisation could either incur penalties from their PPA provider or it could fail to use all the energy within a specific window leading to suboptimal ammonia production. Alternatively, an islanded plant would overly depend on its battery, again leading to suboptimal ammonia production.

   For small scale green ammonia production, autonomous operation is important to keep the cost of ammonia production low. Due to the location of the ASPIRE MK0 site at RAL, a policy of 2 operators on site was employed to continuously monitor the plant during operation. The ASPIRE MK0 plant control system also occasionally required some input from plant operators to assist with operation. In its current form, the ASPIRE control software is not ready for commercial deployment due to minor changes required for the plant to become fully automated. Despite this, all plant safety conditions are setup to be transferrable and scalable and are ready for an automated plant.

4. **Demonstrate that the LCOA from the ASPIRE design is significantly cheaper than if the demonstrator of this scale was to be made flexible via batteries and/or hydrogen storage.**
   From the modelling of a 5MW ASPIRE plant and non-flexible plants of the same scale, the LCOA for a flexible synthesis plant (~£700-£1000/tonne including HARS) is significantly cheaper than a plant with large hydrogen storage that can operate continuously (£2248/tonne including HARS). A sensitivity study on quantity of hydrogen storage for a given plant size was conducted, and it was found that by minimising storage and having a plant that could start up rapidly would minimise LCOA. This approach tends towards flexible synthesis as the optimum solution. Large battery storage was also considered but the inherent costs of storing a large quantity of energy in batteries meant this approach was quickly ruled out. Flexible ammonia synthesis is therefore ready for commercial deployment as the primary approach to green ammonia production.

Below is a review of Phase 2 of ASPIRE with respect to the commercial feasibility objectives:

1. **Plant is able to run on an intermittent source of electricity from an onshore wind farm of output 10 – 200MW.**
   The ASPIRE MK0 demonstrator has proven that the ASPIRE technology has the necessary capabilities to run from an onshore windfarm of size 10-200MW in a grid-connected configuration which would accommodate a renewable PPA with 60-minute stringency, ready for the regulations due in 2030. Namely, the turndown capability and response rate are adequate to match a windfarm power output on an hourly basis. However, significant scale-up efforts would be required to meet the 10-200MW scale and commercialisation research has concluded that there may be a potential market for even smaller plants (500kW to 5MW).

2. **Technology exists to develop an operational plant within the next 3 years.**
   The novel aspects of the plant (reactor, synthesis loop etc) would need bespoke design and manufacture for larger scales, but no issues are foreseen here. All ancillary equipment is currently commercially available at the size required for the MK0 size (150kW) up to 5MW and larger. So, the technology exists; it is a question of design, procurement, integration and fabrication. STFC are confident that a 500kW ASPIRE iteration could be designed, built and commissioned within three years because it would be similar to ASPIRE MK0. At the 5MW scale, we think the technology exists but that it would be difficult to complete an ASPIRE of that scale including commissioning within the timeframe, due to the initial design effort required. In addition, an electrolyser from our supplier at this scale would require a level of product development for them to achieve. Perhaps 4 years to reach complete operation at 5MW scale is more realistic. Following the 5MW development, scale up to between 10-200MW could be possible using a modular approach in another 2 years provided the production capacity can be found.

3. **There is a market for green ammonia produced from renewables at this scale.**
   Three markets were identified for ammonia produced in this manner: ammonia as a feedstock, energy storage and marine fuel. The ammonia as a feedstock market is active already with green ammonia being traded already. The best LCOA predicted from a 5MW scale ASPIRE is £1056/tonne NH_3 which, though more expensive that the average price of grey ammonia, is within some of the higher fluctuations of the ammonia price. As explained in section 8, STFC are aware of business opportunities starting to be realised where localised production of green ammonia as a feedstock is cheaper due to the savings on transport and import taxes. The 5MW scale is considered the smallest commercially viable scale here. As an energy storage solution and a marine fuel, there are large potential markets, but accessing them requires some technological development on the off-taker's part (e.g. ammonia gas turbines or ammonia marine propulsion systems). For energy storage, the larger of the scales is more likely (10-200MW). For marine fuel, there is the potential to meet the requirements of small-scale marine with smaller scale plants (500kW-5MW), but the industrial marine sector would require the larger scale.

4. **Through-life cost of the green ammonia produced from intermittent renewable power is competitive with other green ammonia technologies.**
   From the levelised cost modelling of a 5MW ASPIRE plant, it was concluded that flexible green ammonia could be produced at a competitive price if sufficiently subsidised and the plant was configured on grid with a PPA. The most likely cost of ammonia this plant would produce is £855 per tonne. We expect this to be significantly cheaper than alternative green ammonia approaches which require long duration hydrogen or battery storage. However, this appears slightly more expensive than the indicated green ammonia price, but this is because current green ammonia prices are for blended green and grey ammonia plants, which are not compatible with net-zero targets. To enable competition with green ammonia produced offshore, green ammonia in the UK needs to be subsidised by HAR. This is potentially even cheaper than offshore ammonia once shipping costs and import taxes have been accounted for and there is an added benefit of improving both food and energy security. To encourage green ammonia as an energy vector, it would be tactical to introduce subsidies which encourage renewable plant operators to store excess energy when the national grid is at capacity, instead of paying for them to curtail the energy.

5. **Ammonia produced is low carbon and has through-life carbon emissions <0.42 kgCO2/kg NH_3.**
   The ASPIRE product is predicted to have a carbon intensity of 0.21kgCO_2 in an off-grid installation and between 0.26-0.37kgCO_2eq/kg for a grid connected installation. In the case of a grid-connection, the operating strategy of ASPIRE affects its through-life carbon emissions because the carbon intensity of the product depends on the carbon intensity of the grid at the time that the power was consumed. The 0.26-0.37kgCO_2eq/kg figures are representative of ammonia produced under renewable PPA agreements.

6. **Technology meets all safety and regulatory requirements.**
   One of the significant achievements of the ASPIRE MK0 design is its rigorous safety case. This workload is somewhat scale-independent because no more actuators or pressure systems are expected in a larger system. Though safety reviews will need to be conducted again at any new scale, having a previous successful example will accelerate the development of scale-up significantly. In terms of pressure safety, STFC met the Pressure Systems Safety Regulations (PSSR) by obtaining a Written Scheme of Examination (WSE) for the plant before operation, and an STFC engineer sized all relief devices according to BS EN ISO 4126. A three-stage HAZOP study was conducted by FNC to arrive at the safety and process control. This fed into a Layer Of Protection Analysis (LOPA) and highlighted the most safety critical functions of the safety system, which led to several safety instrumented functions which had their safety integrity level confirmed by an external contractor.

   To safely navigate the processing of hydrogen and ammonia, a DSEAR assessment of the design was undertaken, including a final inspection and sign-off of the installation to confirm that the hardware installations were suitable for their respective environments in the plant. A qualified CompEx electrician (Gas and Vapours Ex01–Ex04**)** performed the installation and inspections of the hardware inside the hazardous zones.

A fire risk assessment was conducted by an independent fire safety company and all actions completed before operation began. Finally, full planning permission was obtained for the plant which involved satisfying a ground-water contamination assessment mandated by the Environment Agency.

9.2. Lessons Learned

On reflection the following are examples of lessons learned and reported during the project with potential mitigation to prevent reoccurrence for future projects.

No.	Lesson Learned	Potential Mitigation
1	An off-grid energy island suitable for a flexible chemical plant requires bespoke battery storage system design. Lots of commercially available battery storage systems are designed to simply maximise storage capacity rather than play a short-term balancing role and maintain microgrid frequency.	1. Setting out the unique electrical requirements from the outset of the project with specific mention of the grid forming, maintaining grid frequency, AC coupling, small storage capacity, high charge and discharge rate requirements will avoid attracting the wrong solutions. 2. Ensure the procurement process includes some collaborative design from the supplier. 3. Ensure that the team has a power systems engineer.
2	Automatic venting of feed gases for gas quality control is necessary for autonomous operation.	1. Designing in capability to temporarily vent of substandard hydrogen or substandard feed gas based on a quality reading, rather than a simple trip condition would keep the plant hardware safe, remove the need for manual intervention, and give the purification systems a chance to recover if the quality were to drop temporarily. 2. It should not be taken for granted that the reported purity from a purification unit will always be achieved. In the future, ensure the design is resilient to this.
3	Being able to perform maintenance on synthesis loop without deactivating the catalyst would be useful.	1. Design in isolation valves around the reactor so that the rest of the process lines can be exposed to air if maintenance is required.

4	Valve position proven more reliable than flow meter with integrated control.	1. If a need for flow control arises, opt for a control valve with positional feedback over an integrated flow controller because they are easier to troubleshoot, maintain and repair.
5	Hydrogen and synthesis loop flow meters can stop working when exposed to condensate/moisture.	1. Flow meters that are robust to moisture should be sourced or the design must ensure flow meters are not exposed to moisture.
6	Novel PEM membranes may have low reliability.	1. Request high-reliability membranes from an electrolyser supplier.
7	Post demonstration plant funding is needed to bring to gap to commercialisation.	1. Ensure that projects that follow-on funding for Phase 2 projects is available so that teams can implement their technical learning before seeking to commercialise.
8	No contingency in an R&D project that is aiming to get from TRL 3 to TRL 7 is a recipe for not achieving timelines and budgets.	1. If contingency cannot be added due to the fiscal rules of the bid it should be added by adding conservative costs for equipment.

10. End Matter

10.1. References

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11. Appendices

Appendix 1 – Summary of Project Deliverables

Work Package	Description	Del. ID	Deliverable Description	Delivery Date
1	Project Monitoring	1.01	Submission of Accruals FY 22/23	Mar. '23
		1.02	Signed Consortium Agreement	Mar. '23
		1.03	NZIP KPI Submission	Mar. '23
		1.04	Submission of Accruals FY 23/23	Mar. '24
		1.05	NZIP KPI Submission YR 1	Mar. '24
		1.06	NZIP KPI End of Project	Jan. '26
		1.07	Draft Final Report	Mar. '25
		1.08	Final Report	Jan. '26
2	Project Meetings and Dissemination	2.01	Quarter Progress Report (1)	May '23
		2.02	Quarter Progress Report (2)	Aug. '23
		2.03	Quarter Progress Report (3)	Nov. '23
		2.04	Quarter Progress Report (4)	Feb. '24
		2.05	Quarter Progress Report (5)	May. '24
		2.06	Quarter Progress Report (6)	Aug. '24
		2.07	Quarter Progress Report (7)	Nov. '24
		2.08	Quarter Progress Report (8)	Feb. '25
3	Project Scope Definition	3.01	Design and Process Governance	Jul. '23
4	Preliminary Design	4.01	Mechanical and Electrical	Jul. '23
5	Detailed Design	5.01	Long Lead Time Procurement	Nov. '23
		5.02	Final Mech./Elec. Design	Feb. '24
		5.03	Hydrogen Compressor Order	Oct. '23
6	Control Software	6.01	Design and Development	Nov. '23
		6.02	Control Software Development	Nov. '24
7	Operational Edge Case/ Scale-Up Modelling	7.01	Logic Optimisation (Provisional)	Sep. '23
		7.02	Logic Optimisation (Final)	Jan. '24
		7.03	Scale-Up Study	Sep. '24
		7.04	Transient Digital Design/Develop.	Mar. '25
8	Catalyst Development	8.01	Catalyst Development (Perform.)	Sep. '23
		8.02	Catalyst Performance Modelling	Feb. '25
		8.03	Reactor Catalyst Delivery	Aug. '24
		8.04	Catalyst Ageing Study	Mar. '25
		8.05	Catalyst Performance Modelling	Mar. '25
		8.06	Reactor Performance (Catalyst)	Mar. '25
		8.07	Engineering Support (Testing)	Nov. '25
9	Procurement and Manufacturing	9.01	Drawings (Spec. Confirm.)	Feb. '24
		9.02	Contract Order Confirmation	Apr. '24
10	Build/Commissioning	10.1	Site Assessment	May '24
		10.2	Electrical Hardware Order	Sep. '24
11	Performance Validation Commissioning	11.01	Plant Sign-Off Report	Mar. '25
		11.02	Commissioning (Control)	Sep. '25
		11.03	Commissioning (Results)	Dec. '25
		11.04	Plant CAPEX Procurement	Sep. '24
12	Business	12.01	Commercialisation Report	Nov. '24

Appendix 2 – Inflexible Green Ammonia Plant Approaches

Appendix 2.1 – Rapid Response Plant

Several rapid response plant cases were modelled to assess which would give the lowest levelised cost.

Table 2: Rapid Response Green Ammonia Plant Store Sizes and Levelised Cost

Case No.	ASPIRE Constant Capacity (MW)	Hydrogen Storage (Days)	Battery Storage (Days)	Weighting Towards Hydrogen	Weighting Towards Battery	LCOA (£/tNH3)	Capacity Factor
1	5	10	0	1	0	1768.4	0.3149
2	5	7	0	1	0	1540.4	0.3231
3	5	2	0	1	0	1198.9	0.3317
4	3	10	0	1	0	1496.3	0.3099
5	3	7	0	1	0	1355.3	0.3162
6	3	2	0	1	0	1144.6	0.3221
7	2	2	0	1	0	1262	0.272
8	3	2	2	1	0	3416.8	0.3232
9	3	2	2	0.9	0.1	3623	0.3034
10	3	2	0.5	1	0	1712.6	0.3227

Appendix 2.2 – Steady State Large Battery Store Plant

A continuous operation steady state plant was modelled. It was noticed that for long term energy storage, battery CAPEX dominates levelised cost and is noncompetitive with other technology approaches.

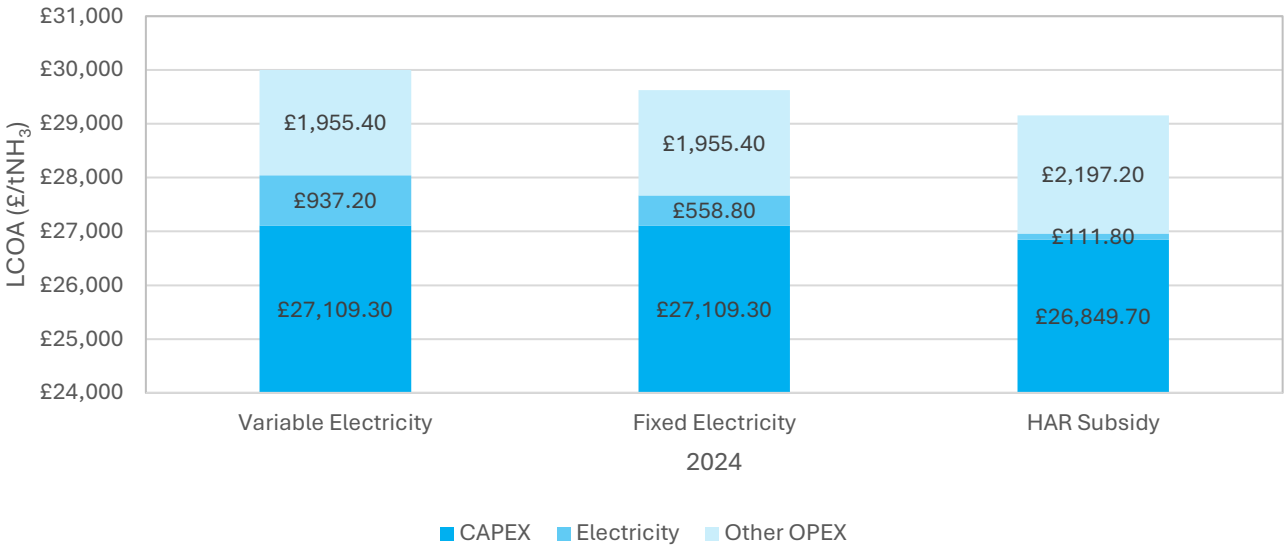


Figure 32: Levelised Cost of Green Ammonia from a Steady State Operation Plant with Large Battery Storage

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