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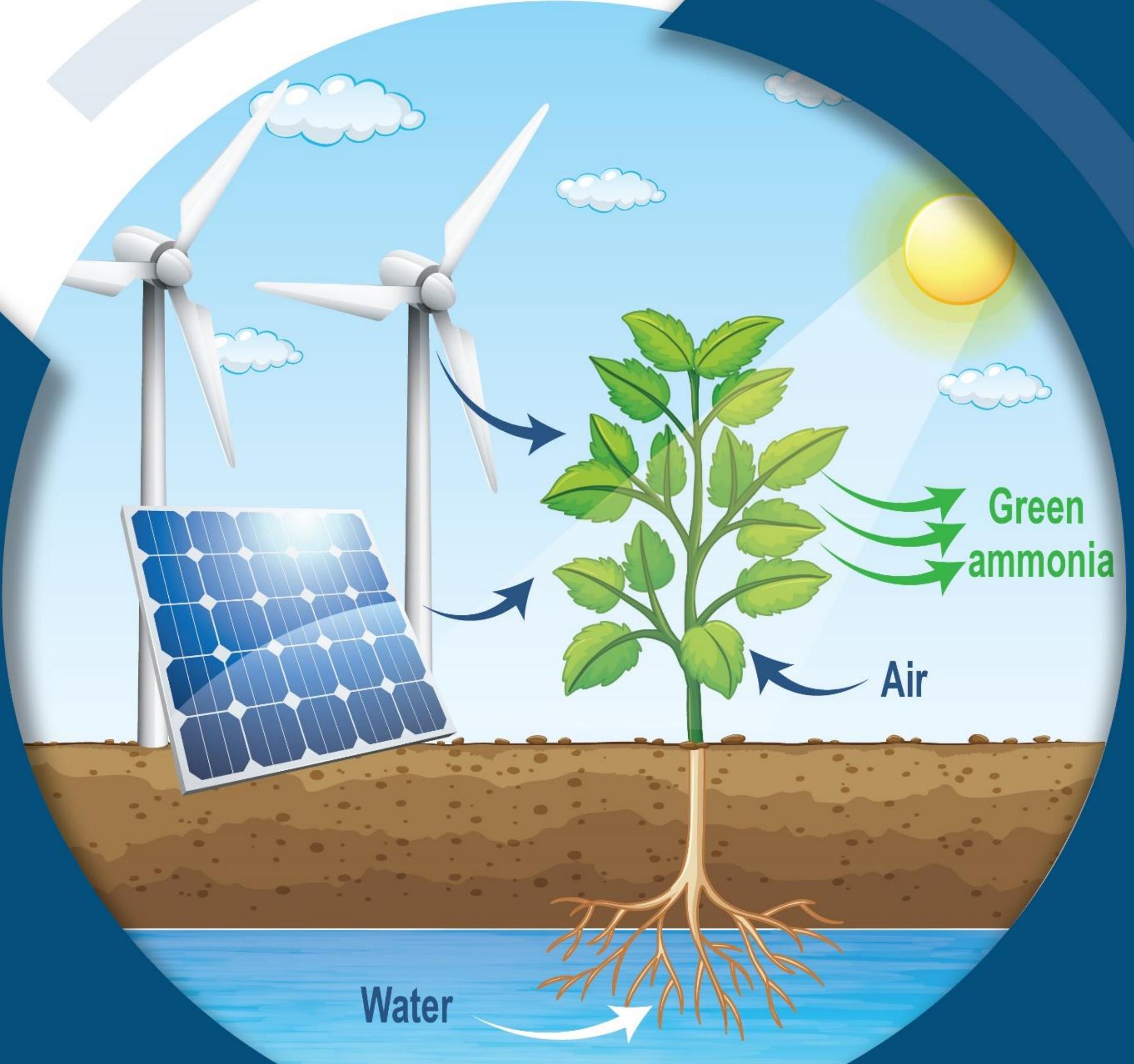
FRAZER-NASH CONSULTANCY
A KBR COMPANY

Ammonia Synthesis Plant from Intermittent Renewable Energy (ASPIRE)

Feasibility Study

Prepared for: Department for Business, Energy & Industrial Strategy

October 2022



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This feasibility study was led by the Science and Technology Facilities Council (STFC) in partnership with Frazer-Nash Consultancy. It has also benefitted from an industrial and academic steering group.

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Executive Summary

Green ammonia is being increasingly recognised as a vector to enable green hydrogen, as a means of decarbonising fossil-fuel produced ammonia and as a carbon-free fuel in its own right. It can be made by combining hydrogen produced from renewable-powered electrolysis of water with nitrogen extracted from the air using the Haber-Bosch process. However, the Haber-Bosch process operates at high temperatures and is not currently suited to the variable operation that would result from an intermittent renewable energy source. This ASPIRE project (**A**mmonia **S**ynthesis **P**lant powered by **I**ntermittent **R**enewable **E**nergy) has developed a novel flexible Haber-Bosch reactor that can technically and cost-effectively produce green ammonia using only water, air and an intermittent renewable energy source.

The design of a flexible green ammonia plant has involved two key technical innovations:

- Parallel reactors to provide a high turn-down ratio of green ammonia production (ability to ramp-up and down).
- Thermal storage to keep non-operating plant warm and to quickly heat it back up to operational temperatures without additional heat input.

All other plant, including the hydrogen production and nitrogen extraction have been kept as generic as possible to minimise design risk. The design has been based on a 10 MW commercial plant, that could be powered by a small onshore windfarm, but a scalability assessment showed that the components selected for a 10 MW plant are scalable up to 200 MW. The key outputs from the study are:

- The plant can run on an intermittent source of electricity from an onshore wind farm of output 10 – 200 MW, associated with the full range of UK onshore wind farm sizes. The design provides a turn-down ratio of up to 20, allowing for utilisation of renewable energy that would conventionally be curtailed.
- Technology exists to develop an operational plant within the next 3 years.
- Through-life cost of the plant is competitive with other green ammonia technologies. The price of ASPIRE green ammonia produced at electricity costs of up to £50/MWh, falls within the current predicted price range for green ammonia, between £570/tonne to £1,100/tonne.
- Through-life carbon emissions would be 0.18 kgCO_2/kg of ammonia, significantly less than existing blue ammonia production (made from natural gas with carbon capture).

A small-scale demonstrator (0.15 MW, 300 kg/day) has been designed to test the commercial scale 10 MW ASPIRE flexible green ammonia plant design. Despite the smaller size, the demonstrator will be able to prove that the key technical challenges of a flexible 10 MW green ammonia plant can be addressed.

Contents

Glossary

ASPIRE	Ammonia Synthesis Plant from Intermittent Renewable Energy
Blue ammonia	Ammonia produced from natural gas with carbon capture and storage
CAPEX	Capital expenditure
ERU	Energy Research Unit (at Harwell)
Green ammonia	Ammonia produced from renewable energy (normally with electrolytic hydrogen production)
Grey ammonia	Ammonia produced from natural gas with no carbon capture and storage
GVA	Gross Value Add
IRR	Internal Rate of Return
LCOA	Levelised Cost of Ammonia
LCOH	Levelised Cost of Hydrogen
PEM	Polymer Electrolyte Membrane
STFC	Science and Technology Facilities Council

1 Introduction

Green ammonia is being increasingly recognised as a vector to enable green hydrogen, as a carbon-free fuel in its own right and as a means of decarbonising fossil-fuel produced ammonia. Analogous to photosynthesis undertaken by plants to produce carbohydrates, green ammonia can be produced using just renewable energy, water and air and offers the potential to be a key player in the future decarbonised energy system.

This study has investigated the feasibility of a novel technique for green ammonia production. ASPIRE (**A**mmonia **S**ynthesis **P**lant from **I**ntermittent **R**enewable **E**nergy) is the result of a rigorous design and technology development exercise combined with a detailed assessment of the commercial needs.

1.1 Background

Ammonia is one of the world's "big four" chemical products. It is the main feedstock for nitrogen-based fertilisers that are vital for global food production, and it is also used in refrigeration, explosives, textiles and pharmaceuticals. The vast majority of ammonia is currently manufactured by combining hydrogen (extracted from natural gas using steam) with nitrogen (extracted from the air) in the Haber-Bosch process. This process produces carbon dioxide that is emitted to atmosphere and the resulting product is generally known as grey ammonia. Currently approximately 1.8% of the world's carbon dioxide emissions come from ammonia production [1], almost as high as the total emissions from the global aviation industry (2.1%) [2]. The carbon dioxide can be captured (resulting in blue ammonia) but capture rates are typically less than 90% and there are still significant carbon emissions associated with the supply of upstream natural gas [3]. Blue and grey ammonia production are also exposed to the economic risks associated with the current volatile natural gas market.

Green ammonia produces no direct carbon emissions during production. Rather than using hydrogen extracted from natural gas, green ammonia uses hydrogen produced from the electrolysis of water that is powered by renewable energy. As a result, there are no direct carbon dioxide emissions. With renewable energy capacity growing rapidly, curtailment of surplus energy is becoming increasingly common, resulting in significant wasted energy and consequently cost. The ability to utilise electricity that would otherwise be curtailed, provides a strong economic case for green ammonia production. As well as providing a method of decarbonising existing grey ammonia, green ammonia can be used to enable a green hydrogen economy and be used as a carbon-free fuel.

Enabling green hydrogen: Hydrogen is likely to have a key role in the future energy system, helping to decarbonise industry, flexible power, transport and heat. However, it is difficult to transport and store. It has a low energy density by volume which means it tends to be compressed or liquified and this has an energy penalty.

Green ammonia can be used as a vector to transport hydrogen. It has better energy density than compressed or even liquefied hydrogen and emits no carbon emissions at the point of use. Ammonia is traded and transported worldwide and has a well-established transport infrastructure. Where hydrogen needs to be transported over long distances, converting it, and then transporting it in the form of ammonia has been shown to be significantly more cost effective than transporting as hydrogen (levelised cost of 4.21 USD/kg H_2 for ammonia compared to 11.77 USD/kg H_2 for hydrogen [4], Figure 1). The production of ammonia from hydrogen adds cost initially but it is significantly cheaper to convert, store and ship than hydrogen.

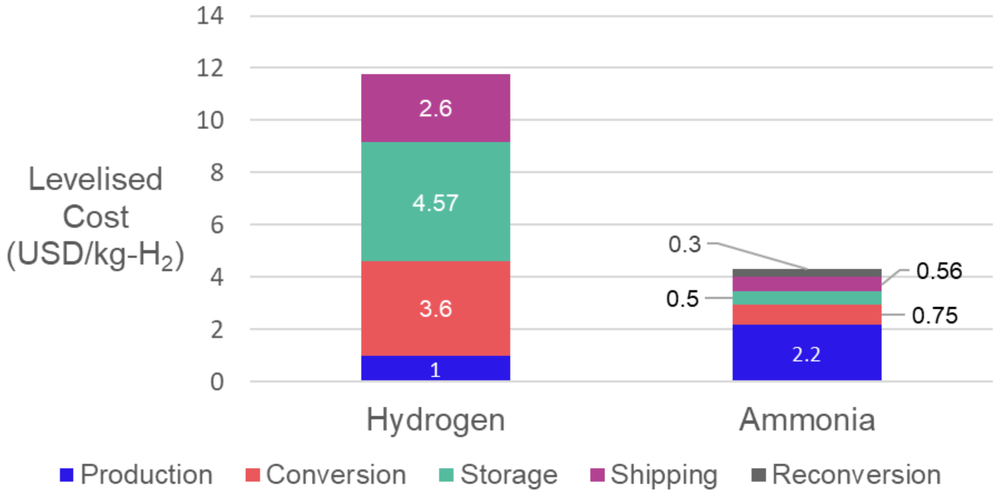

Figure 1. Levelised cost of hydrogen and ammonia throughout the value chain [4].

A carbon-free fuel: Ammonia can be used as a fuel in internal combustion engines and fuel cells to support the transportation sector as well as provide flexible power balancing for the electricity system. One of the prominent markets for ammonia as a carbon-free fuel is for marine propulsion. The global maritime sector demand for ammonia is expected to be around 200 Mt by 2050, a comparable amount to today's global ammonia production [5].

Despite these benefits, green ammonia powered from intermittent renewables has its challenges. Commercial Haber-Bosch synthesis reactors typically operate at steady state high temperature conditions for long periods. They take time to reach these operating conditions and flexible operation can lead to reliability issues from thermal cycling and reduced stability of ammonia production. For green ammonia to work technically and commercially, the whole process of producing hydrogen, extracting nitrogen from the air and combining these within the Haber-Bosch synthesis reactor will need to be effectively powered from intermittent renewable energy. It is this challenge that has been the driver for the ASPIRE project.

1.2 Objectives

Project ASPIRE focuses on achieving the lowest cost generation of green ammonia from intermittent renewable power. The project mission statement is 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 feasibility, a series of requirements were developed at the outset of the project, as follows. These will be revisited in Section 6 and assessed against the design to determine if the ASPIRE mission statement has been achieved.

No.	Claim
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 $kgCO_2/kg\ NH_3$ [1]
6	Technology meets all safety and regulatory requirements.

1.3 Structure of report

This report is structured according to the work packages undertaken in this study:

- Section 2 explores the design development of the flexible reactor. Initially, it describes the candidate technologies for producing green ammonia from intermittent renewables and how these were down-selected to the preferred option. The design has been developed at the 10 MW small commercial scale and assessed for scalability up to 200 MW.
- Section 3 explores the benefits and barriers of this design including a carbon benefits and economic assessment.
- Section 4 explores the proposed Phase 2 demonstration stage (0.15 MW scale) and how this is designed to focus on the key innovations.
- Section 5 considers how the technology could be developed, commercialised and deployed following the demonstration phase.
- Section 6 revisits the claims to assess whether the technology is feasible.

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[1] No standard for green or low carbon ammonia currently exists. The target of 0.42 $kgCO_2/kg\ NH_3$ is based on the application of the BEIS Low Carbon Hydrogen [12] Standard to ammonia (see Section 3.1).

2 Design of a flexible ammonia reactor

2.1 Options assessment

There is significant research interest in alternatives to the Haber-Bosch process, with most of these involving electro-chemical techniques. While these have potential, they are still below Technology Readiness Level 4 and have not demonstrated ability to scale-up [1]. As such this design process has focused on Haber-Bosch but with particular attention to accommodating intermittency.

Three options for producing ammonia from an intermittent renewable power source were considered and these are shown in Figure 2:

1. **Battery storage:** Smooth out the variable electrical power using a large battery. Use uniform electrical power from the large battery to produce hydrogen continuously through electrolysis and feed this into a Haber-Bosch reactor that operates at a uniform rate.
2. **Hydrogen storage:** Use variable electrical power to produce hydrogen and then store this hydrogen in large, compressed gas tanks. Use this storage to smooth out variable hydrogen production so that the Haber-Bosch reactor operates at a uniform rate.
3. **Flexible Haber-Bosch reactor:** Use variable electrical power to produce hydrogen and then feed this into a flexible Haber-Bosch reactor that is able to produce ammonia at a wide range of generation rates.

Options 2 and 3 will require a small amount of battery storage (approximately 30 minutes) as a buffer to accommodate the highly variable input power. The electrolyser in Options 2 and 3 will need to be larger than Option 1 as this will need to be sized on the peak renewable power production rather than the average production. Equally, the Haber-Bosch reactor in Option 3 will need to be larger than that in Options 1 and 2 as it will need to be sized on peak hydrogen production rather than average production. In Figure 2, the straight arrows symbolise constant throughput whilst wavy arrows intermittent throughput.

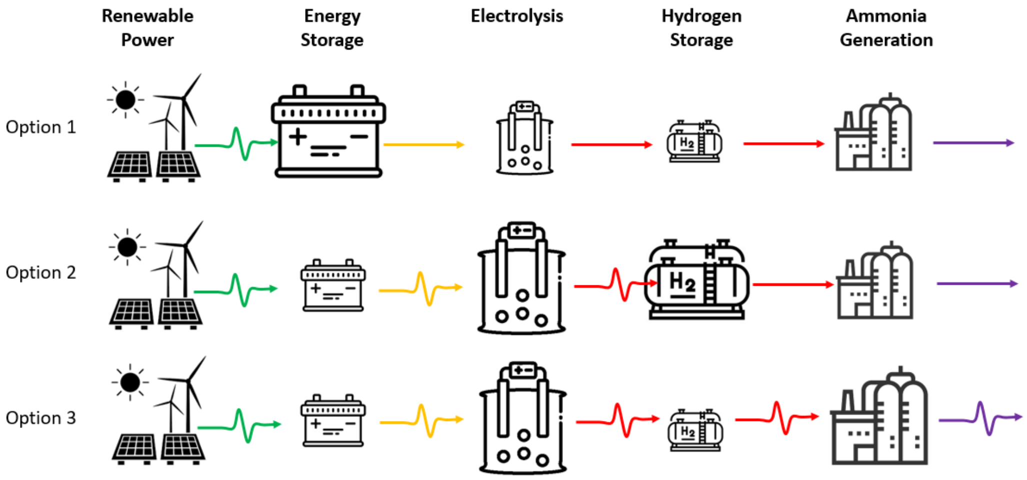

Figure 2: The three options considered for green ammonia production

2.1.1 Transient ammonia plant model

An transient analytical model was developed to simulate the ammonia production from these three options. Using representative wind farm data (Kelmarsh onshore 12.3 MW wind farm in Northampton [6]), Figure 3 shows 3 weeks of power data from the wind farm and the calculated instantaneous ammonia production rates.

In Options 1 and 2 the ammonia is generated at a constant rate when there is adequate hydrogen and power for auxiliary equipment, with sizing of storage based on the ability to produce ammonia for 3 days without power. Options 1 and 2 allow for replenishment of stores in periods of high wind while also generating ammonia. Option 3 is able to closely track the available power, giving a significant increase in ammonia production whilst using the same variable electricity input.

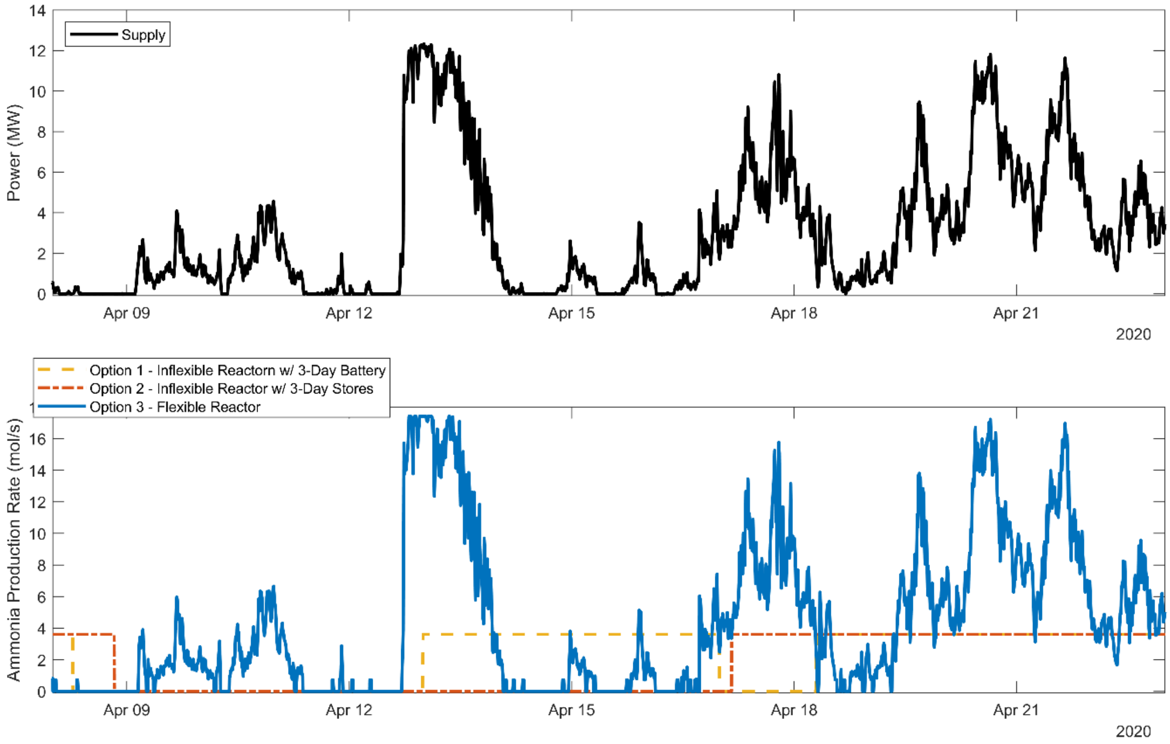

Figure 3. Power generation for Kelmarsh windfarm (top). Ammonia production rate for each design option (bottom).

The Levelised Cost of Ammonia (LCOA) was calculated for each of the three options. Option 3 Flexible Reactor has an LCOA of £956/tonne, which is substantially lower than Options 1 and 2 at £2,330/tonne and £1,640/tonne respectively. This reduced LCOA for Option 3 is largely due to its lower CAPEX achieved by minimising the amount of battery or hydrogen storage.

Option 3 was therefore identified as the most feasible option and was taken forward to the design stage.

2.2 Design development

The selected design was based on the Option 3 Flexible Haber-Bosch reactor at 10 MW capacity, deemed to be the smallest commercially viable plant for deployment with onshore windfarms. A flexible ammonia reactor needs to be able to ramp up and down ammonia production based on the supply of hydrogen and nitrogen, with two innovations being developed to enable this:

- Parallel reactors, operating in different modes, to provide a high turn-down ratio of ammonia production,
- Thermal storage and integration of this to the reactors to keep non-operating plant warm and to heat it back up quickly to be operational again.

2.2.1 Parallel synthesis reactors

The main component of the Haber-Bosch plant is the synthesis reactor; a module of long metal tube containing catalyst, which when heated to high temperature promotes the chemical reaction between hydrogen and nitrogen to form ammonia (Figure 4 left). When the hydrogen supply is uniform a single module of tubes provides a good yield of ammonia. However, if the supply of hydrogen falls, for example due to low wind conditions, less ammonia is produced and the temperature becomes unstable. In turn, this reduces the yield of ammonia production.

Rather than using a single large reactor module, a series of modules have been developed that are opened or closed sequentially to facilitate different ammonia production rates. At the minimum generation rate, only a small module is used and as the hydrogen supply increases more modules are introduced (Figure 4 right).

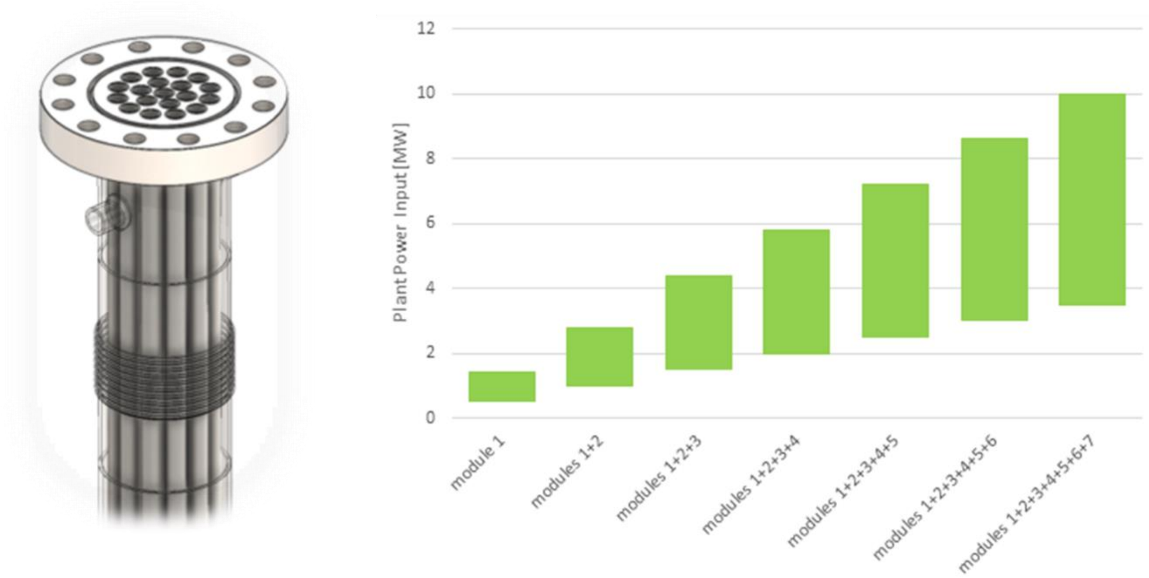

Figure 4: Typical reactor module (left) and a simplified schematic of the sequential opening of reactor modules to vary ammonia production (right).

A single reactor module (Figure 5) consists of a set of stainless-steel high-pressure reactor tubes. The hydrogen and nitrogen are introduced at the right-hand side and progressively synthesise ammonia as they travel to the left. The analytical ammonia production model was used in conjunction with computational fluid dynamic simulations to demonstrate that our reactor module design optimised the ammonia production for the anticipated hydrogen and nitrogen throughput, temperatures and pressures.

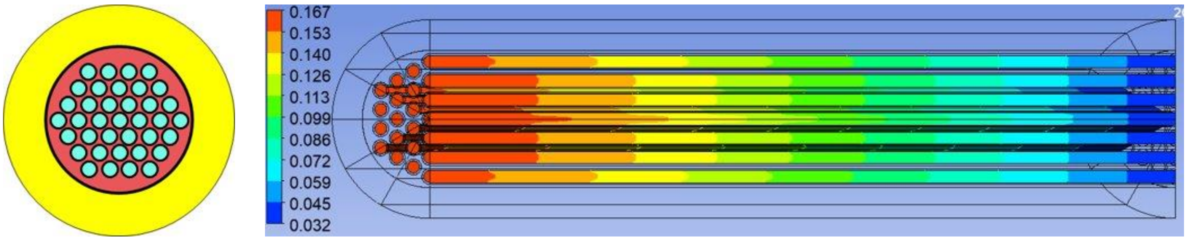

Figure 5: Reactor cross-section design (left) and ammonia synthesis in tubes where the colour shows the mass fraction of ammonia achieved along the reactor at maximum generation rate (right).

The use of parallel reactors gives the ability to operate flexibly but it creates another technical challenge; how to keep the reactors warm when they are not operating and this led to the second innovation that has been developed, thermal storage.

2.2.2 Thermal storage

A thermal store has been developed to maintain temperature in idle reactor modules so that they can be brought online quickly and without use of electrical heating (Figure 6). The production of ammonia in the reactor modules is exothermic and this heat is captured by an inert gas flowing round the reactor tubes when they are operational. The inert gas is used to heat up gravel in the store and in turn, this heat can be used to maintain modules in an idle state and restart modules that have been shut down.

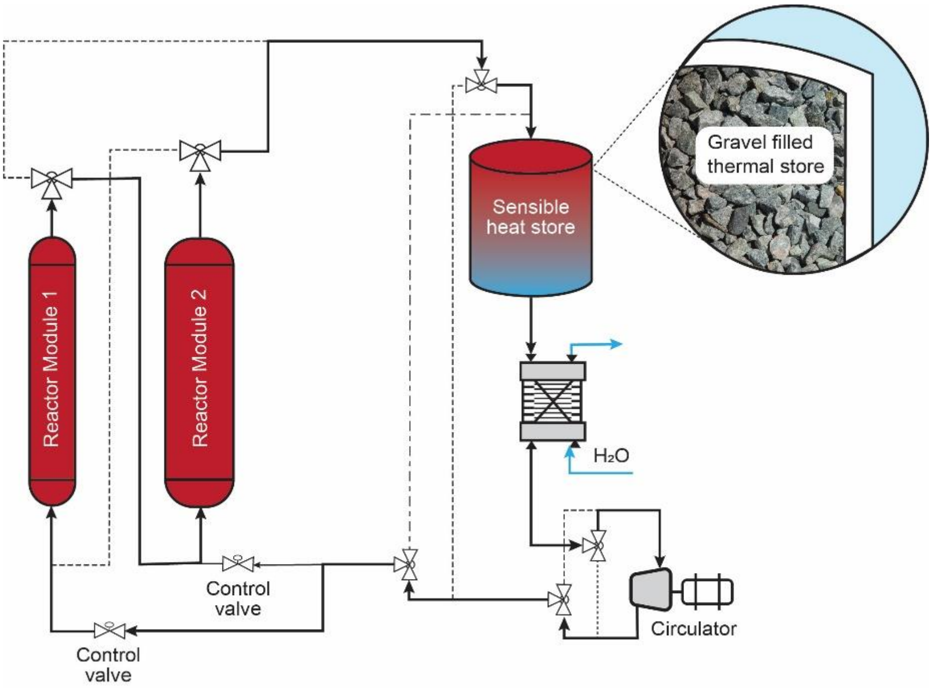

Figure 6: Gravel-filled thermal store that is used to reheat the reactor modules to temperature when they have shut down. The gravel store is replenished using heat from the synthesis reactor.

The thermal management system is designed to facilitate flexibility and reduce energy loss by enabling redistribution of exothermic heat throughout the system. Control valves are used to provide four operating modes:

1. Maintaining idle reactor modules at an active temperature so they can be brought online quickly.
2. Storing excess thermal energy in a thermal store when all reactors are operational.
3. Recovering energy from the thermal store to reheat reactors after a shutdown.
4. Potential utilisation of heat for other processes, such as electrolyser heating or supplying an electricity generator, during times the reactors are online and thermal store is full.

The inert gas leaves the reactor at around 500 °C. It flows through the gravel, transferring high grade heat, creating a stratified temperature gradient down the store. After a shutdown when the reactor needs to be reheated, heat is extracted from the store by flowing the gas backwards through the store, entering at ambient temperature and leaving near 500 °C. The reactor tubes can be reheated from ambient temperature within 15 minutes. The thermal store is expected to lose some heat over time but after 55 hours it is expected that there will still be sufficient to reheat the reactor modules to around 350 °C. This is enough for catalyst activation to restart the exothermic reaction.

2.2.3 Plant overview

A detailed technology selection exercise was conducted for the rest of the plant. In particular, the electrolyser and compressors were selected with high turn-down ratios to facilitate load following. The plant design can achieve turn-down ratios of up to 20, meaning that the plant can operate with a power input of 5% of the plant capacity. Design selections were made so that all components are at a Technology Readiness Level of at least 4 and in most cases higher than this. The plant design showing all the connected subsystems is shown in Figure 7.

Hydrogen production: Hydrogen generation will be accomplished by two 5 MW proton exchange membrane (PEM) electrolysers. PEM electrolysers have been selected as they operate below 100°C and have a fast start time of less than 5 minutes with good partial load efficiency, providing the ability to work intermittently.

Water purification: Water purification processes are very well established. Reverse Osmosis with desalination is a complete process with integrated pre/post treatment steps which give the desired output water quality and is the favoured option for ASPIRE.

Nitrogen production: Nitrogen generation will be accomplished using membrane separation, which is a well-established and economically viable technology.

Compressors: Reciprocating diaphragm compressors have been selected for the top up compressors as they provide high pressure ratio capability, high turn-down ratios and have a sealed mechanism making them suitable for use with explosive gases.

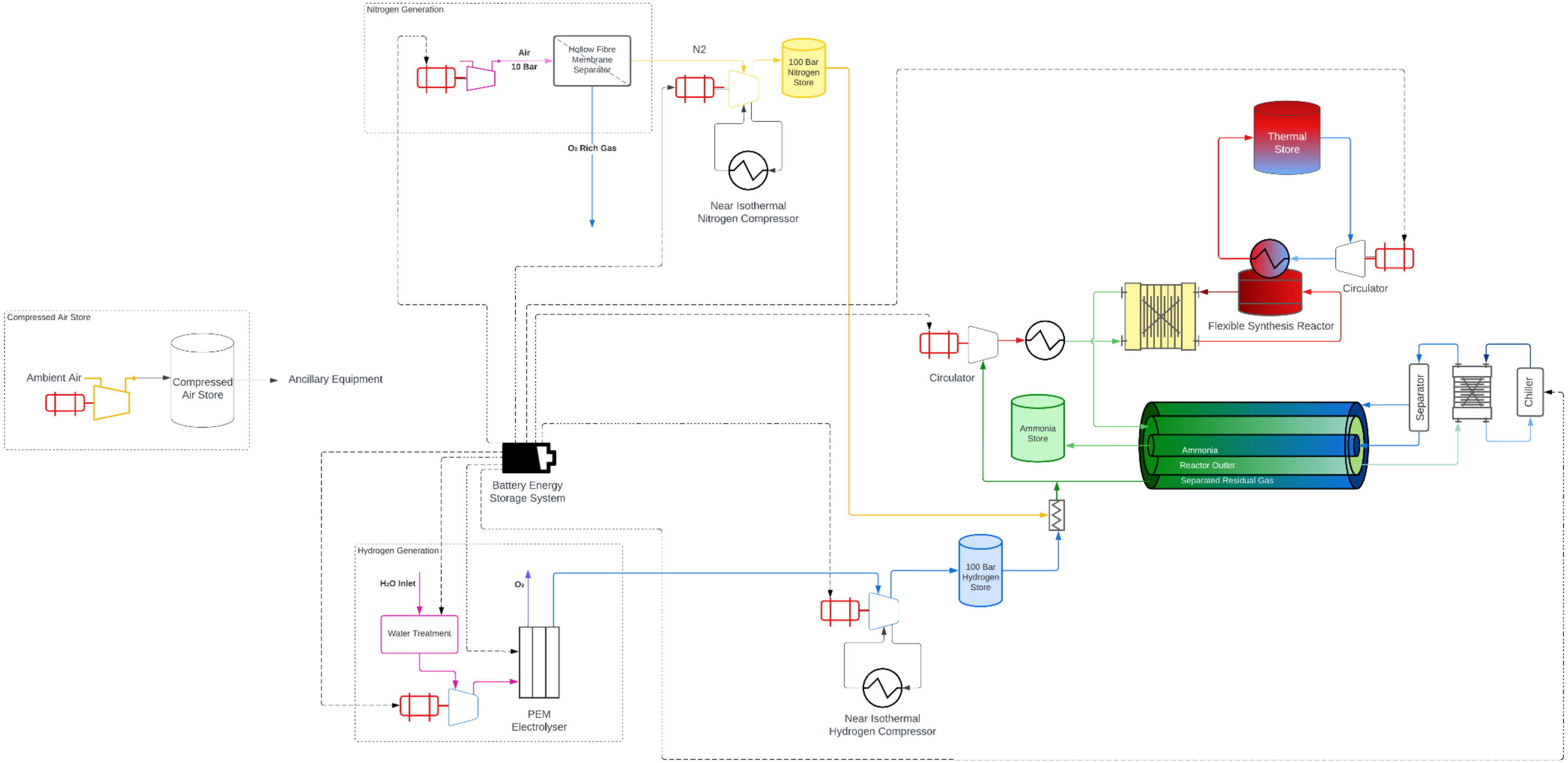

Figure 7: Plant layout showing the key sub-systems

2.3 Conceptual mock-up

The 10MW ASPIRE plant could fit on a footprint of 12 x 12 m^2 and would include several separate containers to house the different subsystems (Figure 8).

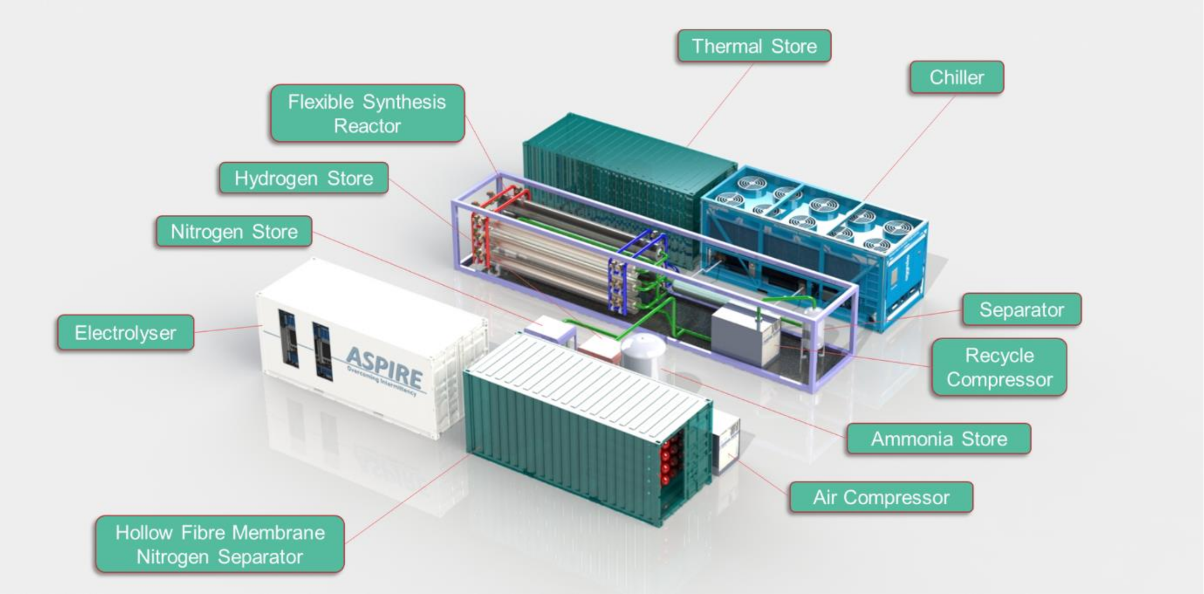

Figure 8: Render of 10 MW ASPIRE design

2.4 Scalability assessment

All the key technologies selected for the 10 MW design can be scaled and utilised at the 200 MW range, typically associated with the maximum size of onshore wind farms. Scaling from 10 MW to 200 MW does offer the potential to introduce different technologies. However, following the findings of the technology assessment, these different technologies present no significant benefits and a 200 MW ammonia plant could credibly be based on the same technologies as the 10 MW plant. The 10 MW ASPIRE flexible Haber-Bosch reactor plant has been designed to focus on flexible ammonia production and reduce the amount of electrical, hydrogen and ammonia storage on site. At 200 MW scale, this design philosophy has benefits as storage would tend to scale linearly with plant size. At 200 MW scale, the amount of storage required has not been found to present any initial concerns. At larger scale, there are likely to be process efficiency improvements (e.g. reduced heat loss). However, these have not been considered in this scalability assessment.

3 Benefits and barriers

This section looks at the benefits and barriers to the ASPIRE design, and green ammonia in general, focussing on carbon benefits, economic justification and key external factors.

3.1 Carbon benefits assessment

A Carbon Benefits Assessment was undertaken for the 10 MW ASPIRE flexible Haber-Bosch reactor plant over a 25 year lifetime, based on the PAS 2080 methodology. This is a global standard for managing infrastructure carbon and has been authored to meet World Trade Organisation requirements [7]. The methodology considers the whole value chain, aiming to reduce carbon and cost through more intelligent design, construction and use. The standard ensures carbon is consistently and transparently quantified at key points in infrastructure delivery, which promotes sharing of data along the value chain.

The total carbon emissions associated with the full life cycle of the 10 MW green ammonia plant were calculated as 14,520 tonnes CO_2e, with the largest emissions occurring within the use stage. Figure 9 highlights the carbon emission weighting of each activity for the whole life cycle of the ammonia plant. It is evident that the operational energy use is the highest contributing factor over a 25-year operating period. Even though the plant will use wind energy that does not emit greenhouse gases, the electricity will still incur transmission and distribution emissions associated with the supply of the electricity.

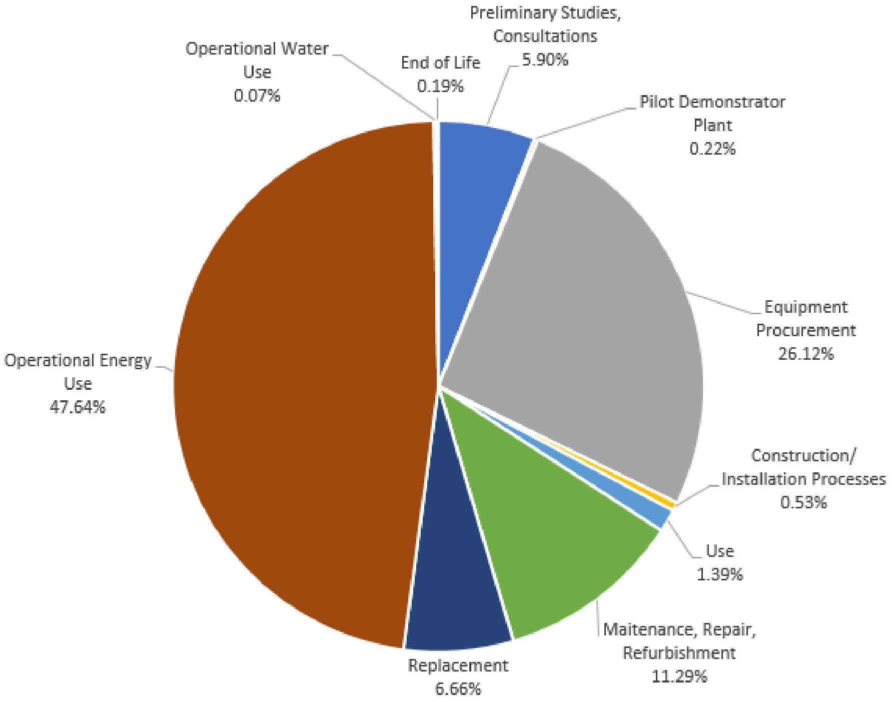

Figure 9: Breakdown of carbon emissions for each activity

The plant is estimated to produce 3,190 tonnes of ammonia per year equating to a total of 79,750 tonnes of ammonia produced during the 25-year operational life. This is estimated to produce average carbon emissions of 0.18 $kgCO_2e$/ kg ammonia. There is currently no low carbon standard for green ammonia. However, adapting from the Low Carbon Hydrogen Standard [8], a threshold for low carbon ammonia has been calculated at 0.42 $kgCO_2e$/ kg ammonia produced[2]. Therefore, the designed plant powered by intermittent renewables can therefore be considered to produce low carbon ammonia.

The results of the carbon benefits assessment are consistent with Smith et al. [9] who found that wind powered ammonia generation typically has a carbon intensity of 0.12 – 0.53 $kgCO_2e$/ kg ammonia produced. Ammonia produced from natural gas without carbon capture produces around 2.6 $kgCO_2e$/ kg ammonia [10].

3.2 Economic benefits assessment

The economic case for ASPIRE was based on a cashflow assessment in conjunction with an economic impact model, developed using HM Treasury Green Book methodology. The cashflow model was developed to predict the price of ASPIRE ammonia. This is shown for electricity prices of £20 and £50/MWh in Figure 10. The ranges reflect the uncertainty in capital and operational costs for ASPIRE.

Figure 10: Comparison of ASPIRE and grey ammonia prices

The price of grey ammonia is coupled to natural gas prices, which have risen significantly in the last two years, and as such the predicted price of ASPIRE green ammonia compares very favourably with current grey ammonia prices. However, it is currently more expensive than the historic, and possibly the future price of grey ammonia. Green ammonia produced by ASPIRE would be insulated from the volatility of grey ammonia pricing which will help to incentivise investment decisions.

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[2] For low carbon hydrogen production, the GHG emissions intensity must not exceed 20 gCO_2e/MJ_{LHV} [8]. 20 gCO_2e/MJ is equivalent to 2.4 $kgCO_2/kgH_2$ based on a LHV of 120 MJ/kgH_2. 1 kg of hydrogen produces 5.7 kg of ammonia so low carbon ammonia must not exceed 0.42 $kgCO_2$/kg ammonia.

Bridging the gap between the price of ASPIRE green ammonia and the typical cost of grey ammonia will require a carbon price or subsidy. Based on the carbon benefits assessment, ASPIRE will save 2.4 tonnes CO_2 / tonne of ammonia compared with existing grey ammonia production methods. A carbon price of £300/tonne CO_2 will therefore be equivalent to a subsidy of £725/tonne of ammonia and sufficient to bridge the gap between lower grey and mid ASPIRE prices (red arrow in Figure 10). This will also bring the payback period to 7 years and achieve an Internal Rate of Return (IRR) of 20%, which could accelerate adoption of the technology and make it more competitive versus other renewable technologies. The key to accelerating the shift towards green hydrogen and green ammonia is addressing the cost disparity between green and grey ammonia but also improving the flexibility of green ammonia plants. To be cost competitive, it is critical that a green ammonia synthesis plant can take advantage of low-cost power generated from renewable sources. A significant benefit to renewable operators is that ASPIRE plant operation could be optimised based on economics; producing ammonia when electricity prices are low and selling the electricity when the price is high.

Gross Value Add (GVA) and job creation

The economic impact of ASPIRE has been calculated using a static input-output model. A 10 MW plant is predicted to deliver £3.3M of GVA. The operational phase of an ASPIRE plant will provide direct, indirect, and induced jobs creation. A 10 MW ASPIRE plant is assumed to be operated with a small core staff of 16 but an additional 38 jobs will be created in the supply chain. At 200 MW, the GVA increases to over £60M and the number of supply chain jobs increases to around 760.

3.3 Enablers

Security of Supply – Being powered by renewable energy, ASPIRE has no reliance on gas supplies from other countries. This provides energy and chemical independence.

Flexible design – The ability of ASPIRE to operate flexibly based on changing power input from renewables means that it can be applied to off-grid locations where there is no back-up. It also means that it can use curtailed renewable energy and this will present significant cost benefits for ASPIRE.

Cost reduction - ASPIRE’s LCOA is expected to decrease over time. This is due to the advancement and cost reduction of plant technologies (e.g. electrolyser) and the predicted price reduction of renewable electricity towards 2050.

3.4 Barriers

Toxicity – ammonia is highly toxic, presenting significant safety concerns if it is used beyond its current application in safety critical industries. However, ammonia infrastructure is well understood and there are industry established procedures for ammonia handling. The use of ammonia more widely will, however, require significant testing and safety accreditation over the next few years.

4 Phase 2 demonstration stage

A small-scale 0.15 MW (300 kg/day) demonstrator has been designed to test the performance of the 10 MW ASPIRE Flexible Haber-Bosch Reactor plant. Despite the smaller size, the demonstrator will be able to prove that the key technical challenges of a flexible ammonia plant can be addressed. This will form the basis for the ASPIRE Phase 2 application to the Low Carbon Hydrogen Supply 2 Competition. This section summarises the development of the scaled down 300 kg/day 0.15 MW ASPIRE Flexible Haber-Bosch Reactor ammonia demonstrator plant.

4.1 Objectives

The proposed demonstrator has been designed with the primary objective of de-risking and demonstrating novel aspects of the ASPIRE design, which are the flexible synthesis reactor and the integration of the thermal stores and management system. The demonstrator will be a complete flexible ammonia plant, allowing the performance and interfaces between novel flexible synthesis loop and the more established technologies to be validated. The detailed objectives are to demonstrate the following key principles of the ASPIRE design:

- High turn-down ratio modular reactor based on a co-current flow indirectly cooled reactor.
- Use of an inert gas circuit and a thermal store to maintain temperature of idle reactors thus delivering flexibility and rapid response to changes in generation rate.
- Lower ammonia synthesis pressures and associated energy savings using state of the art synthesis catalysts.
- The ability to run an ammonia plant autonomously from an intermittent power supply with very low curtailment of the available renewable power.
- Development of control/operation strategies for flexible chemical production facilities, including the interface between weather prediction and future plant operating strategy.

The main components of the demonstrator are shown in Figure 11.

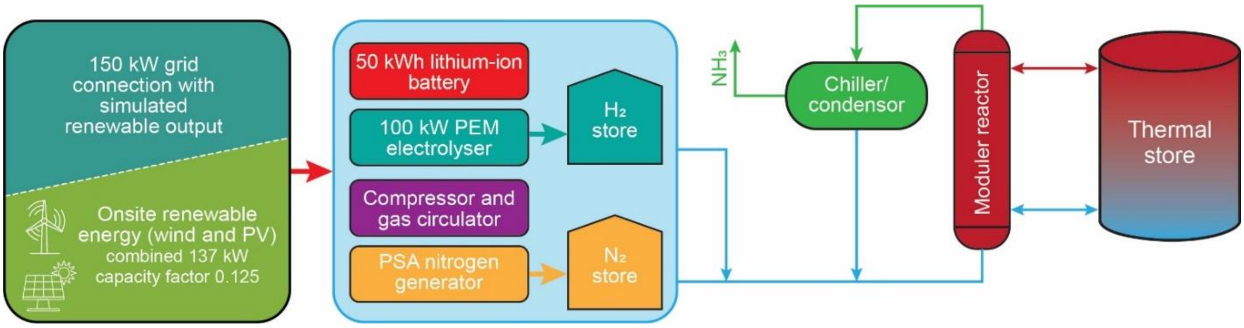


Figure 11 ASPIRE demonstrator key components

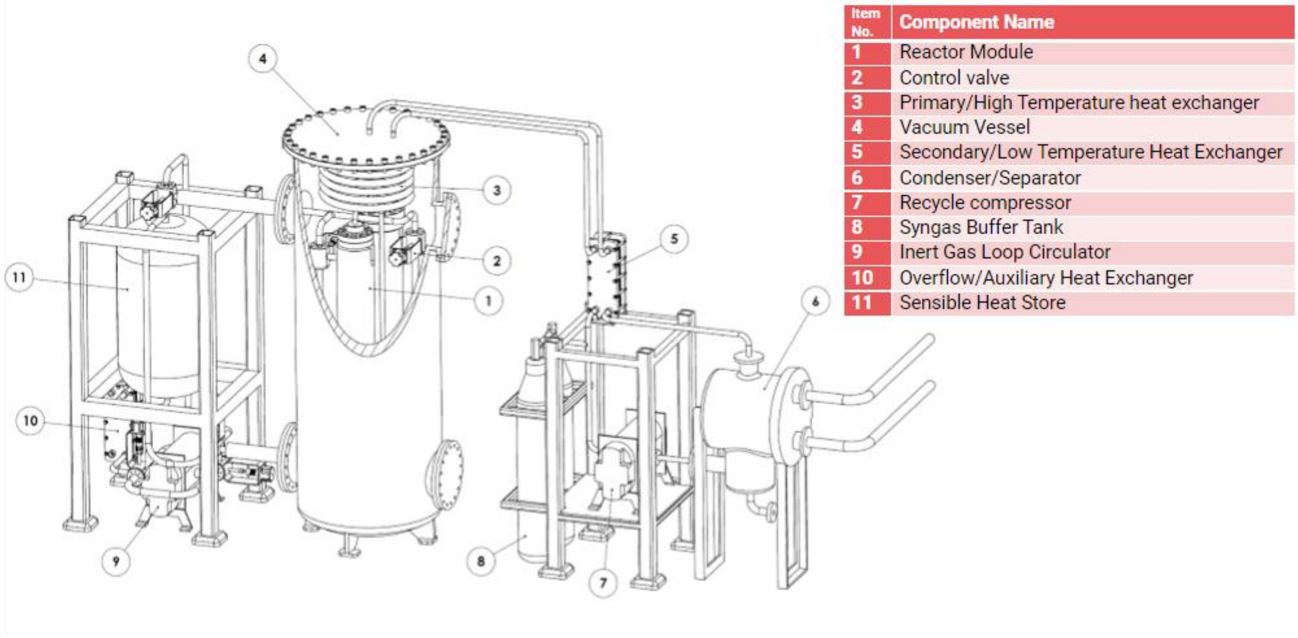
4.2 Adaption of commercial 10 MW design to demonstrator plant

The Phase 2 design is centred around a modular reactor and thermal management system. There is one small reactor module and one large reactor module which are thermally coupled to each other and to a thermal store via an inert gas loop. The modular reactor and thermal management system facilitate flexible operation, load tracking and good use of an intermittent supply. They also constitute the main novelty within the ASPIRE design and are the subject of a patent application. The modular reactor and thermal management system are part of a conventional Haber Bosch system with the exception that the balance of plant components in particular the compressors and chiller are selected for high turn down ratio. The complete ammonia synthesis loop fits within a 20 ft shipping container, with the assembly shown in Figure 12. The synthesis loop would be fed by hydrogen from a new PEM electrolyser and nitrogen from a pressure swing adsorption-based air separator. The P&ID diagram is shown in Figure 13.

The design strategy adopted by the small scale 0.15 MW version of the ASPIRE design is the same as proposed for the commercial scale 10 MW system. The demonstrator will enable the team to prove the main innovative steps of the design but also show its successful interface with the conventional synthesis loop. As such the learning from this demonstrator would be highly valuable for designing commercial scale flexible ammonia plant.

4.2.1 Scaling the thermal management system

The thermal management system was adapted for the demonstrator plant. As there are only two reactor modules, rather than the seven used in the 10 MW plant, pipe routing options were simplified. This meant that an option to bypass the thermal store and transfer heat directly from one module to another was more feasible. This layout reduces heat loss in pipes when maintaining the temperature of one module from another. It also reduces cost as only one larger thermal store is needed. The larger container also helps to reduce thermal losses at this smaller scale.



Item No.	Component Name
1	Reactor Module
2	Control valve
3	Primary/High Temperature heat exchanger
4	Vacuum Vessel
5	Secondary/Low Temperature Heat Exchanger
6	Condenser/Separator
7	Recycle compressor
8	Syngas Buffer Tank
9	Inert Gas Loop Circulator
10	Overflow/Auxiliary Heat Exchanger
11	Sensible Heat Store

Figure 12: Assembly of ASPIRE demonstrator synthesis loop

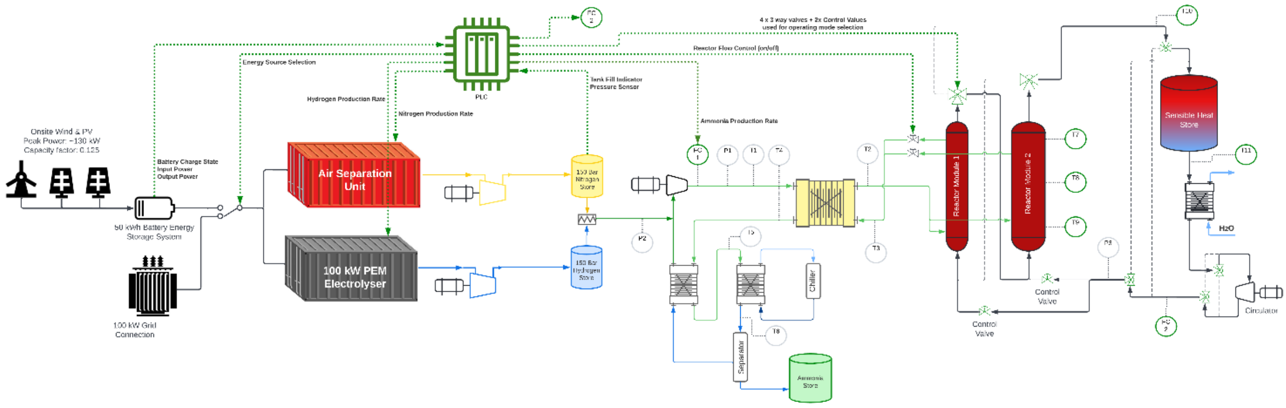


Figure 13: P&ID of the complete ASPIRE demonstrator

4.3 Demonstrator performance

STFC already have use of a 15 kW wind turbine and have planned for an additional 122 kW of solar panels to provide enough renewable power to run the demonstrator. The capacity factors of the wind turbine and solar panels are 24% and 11% respectively. This gives a maximum total power output of around 137 kW and an expected average power output of 17 kW. The ASPIRE demonstration is expected to be able to effectively use 98% of the available renewable energy, capable of producing approximately 14 tonnes ammonia per year.

4.4 Costed development plan

The proposed demonstrator will be sited at the Energy Research Unit test site at STFC's Rutherford Appleton Laboratory (Harwell). Two additional shipping containers housing the ASPIRE flexible reactor and the new modular electrolyser will be located on the existing site as shown in Figure 14 and Figure 15.

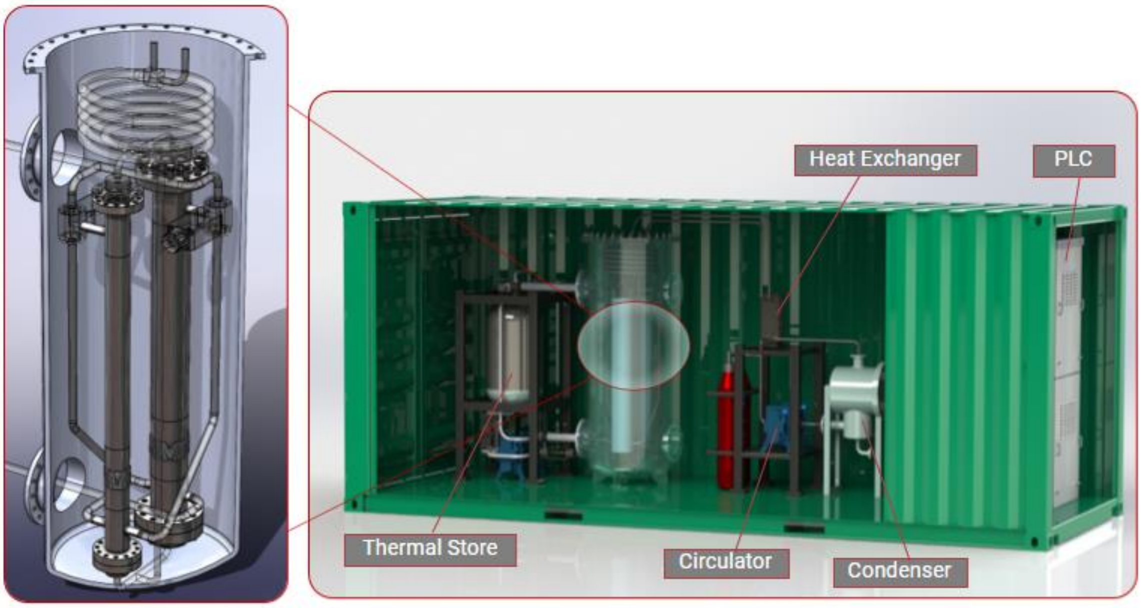


Figure 14: ASPIRE demonstrator modular reactor and synthesis loop within 20 ft container

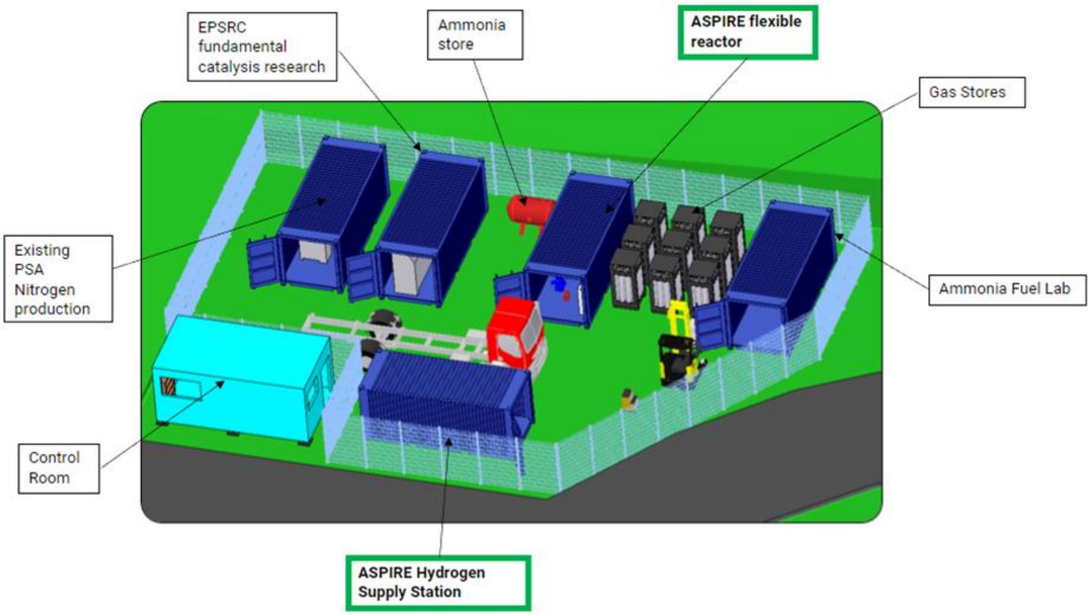


Figure 15 ASPIRE synthesis loop container and PEM electrolyser locations at ERU test site

The Phase 2 plan includes £750k for finalising the engineering design to the point of drawings for manufacture. The effort cost to cover the procurement, build and commissioning of the plant, as well as the project management and monitoring activities and design and safety reviews is estimated at £1.2M, making a total effort cost of nearly £2M. The capital expenditure for off the shelf components, along with materials and components to be manufactured, is estimated at around £2.7M. The total budget including effort and capital expenditure is therefore estimated to be £4.7M. Figure 16 shows a breakdown of the effort cost by work package.

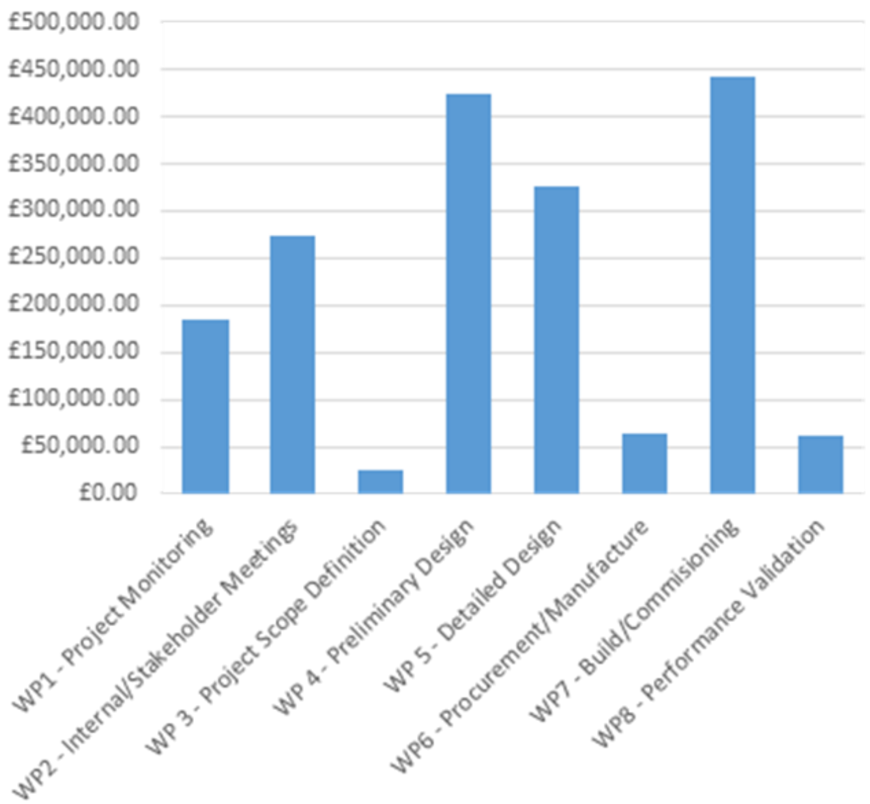
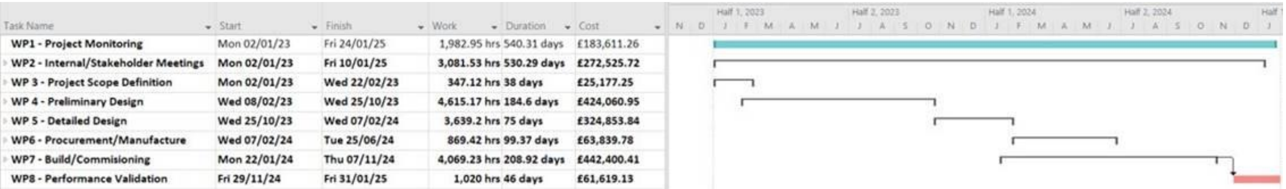


Figure 16: Phase 2 ASPIRE demonstration effort spend by work package

The schedule is designed to complete the demonstrator and allow some testing before the end of the two year phase 2 program as shown in Figure 17.



Task Name	Start	Finish	Work	Duration	Cost
WP1 - Project Monitoring	Mon 02/01/23	Fri 24/01/25	1,982.95 hrs	540.31 days	£183,611.26
WP2 - Internal/Stakeholder Meetings	Mon 02/01/23	Fri 10/01/25	3,081.53 hrs	530.29 days	£272,525.72
WP 3 - Project Scope Definition	Mon 02/01/23	Wed 22/02/23	347.12 hrs	38 days	£25,177.25
WP 4 - Preliminary Design	Wed 08/02/23	Wed 25/10/23	4,615.17 hrs	184.6 days	£424,060.95
WP 5 - Detailed Design	Wed 25/10/23	Wed 07/02/24	3,639.2 hrs	75 days	£324,853.84
WP6 - Procurement/Manufacture	Wed 07/02/24	Tue 25/06/24	869.42 hrs	99.37 days	£63,839.78
WP7 - Build/Commisioning	Mon 22/01/24	Thu 07/11/24	4,069.23 hrs	208.92 days	£442,400.41
WP8 - Performance Validation	Fri 29/11/24	Fri 31/01/25	1,020 hrs	46 days	£61,619.13

Figure 17: Schedule for Phase 2 ASPIRE demonstration

5 Commercial development plan

This section considers the roll-out potential and route to market for the ASPIRE technology.

5.1 Rollout potential

The future market for green ammonia comprises 3 key applications:

- enabling green hydrogen
- displacing grey ammonia
- the direct use as a carbon-free fuel

The potential market for these applications is shown in Figure 18. Based on stated government policies, by 2030, the annual demand for ammonia could increase from around 200 Mt to over 500 Mt, mostly due to the use of ammonia as a hydrogen carrier and as a fuel for shipping. Even at a conservative price of £300/tonne this is a new £90 billion market. By 2050, the use of ammonia as a hydrogen carrier and fuel for shipping could be worth £135 billion.

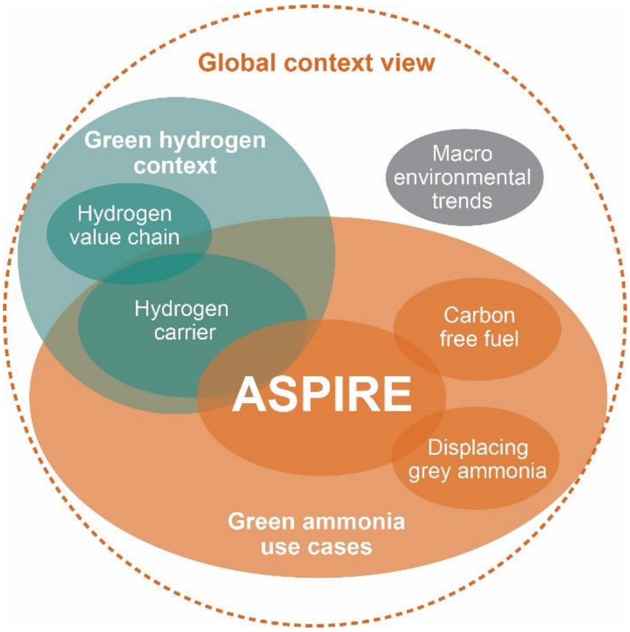


Figure 18: Relationship between green ammonia use cases and ASPIRE

The three applications for green ammonia are all dependent on the need to decarbonise. However, aside from this they are largely independent, and this will provide diversity of markets that will provide reassurance for investment decisions. For example, grey ammonia will need to be displaced, whether or not hydrogen takes a substantial role in the future energy system. Equally, shipping and other large industries may use green ammonia rather than alternatives such as biofuels, either with or without broader use of hydrogen. The diversity of markets is shown in Figure 18.

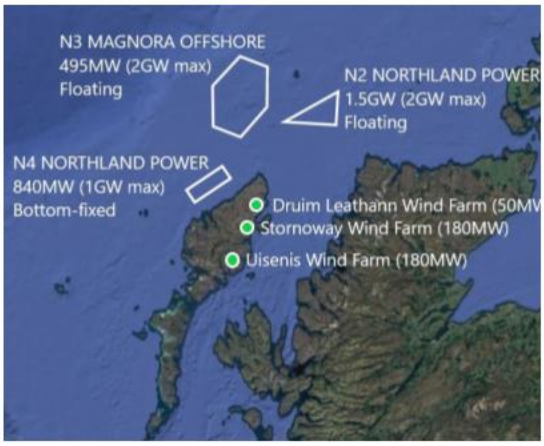
In the next decade, the first markets for ASPIRE could be to support off-grid hydrogen applications with a space or cost constraint that means ammonia is more suitable for facilitating transportation or storage. This includes but is not limited to:

- Renewable energy sites without a grid connection,
- Renewable energy sites that curtail significant quantities of energy,
- Hydrogen refuelling stations.

The Comhairle nan Eilean Siar ("Western Isles Council"), based in Stornoway, Isle of Lewis is proactively pursuing green hydrogen and green ammonia, aiming to expedite progress towards Net Zero and fully exploit the natural resources available. The ASPIRE team have been in discussions with the CnES throughout the project.

The western isles are one of Europe's best wind resources:

- 420MW consented Onshore wind
- 2,835MW consented Offshore wind (currently in the Scotwind leading round)



Western isles wind farm locations and capacities as a result of the Scotwind leasing round.

The ASPIRE design could be implemented through building a 10MW green ammonia plant at the Energy Hub site in Arnish (circled in pink); a port in Stornoway.

Some of the ambitions for the CnES include:

- A plan to convert Stornoway SIU gas network from natural gas to hydrogen
- Potential demand for ammonia or hydrogen for intra-island ferries
    - Average weekly demand of 8.3 tonnes H_2
- Hydrogen refuelling stations for conversion of council vehicles to hydrogen
- Export opportunity for ammonia and/or ammonia as a hydrogen carrier to Northern Europe, particularly the Netherlands

5.2 Route to market

Assuming that the demonstration phase is funded and is ultimately successful, the commercial development of ASPIRE is aided by two key factors:

- The ammonia supply chain (producers) is broadening and is becoming much more competitive.

- There is an increasing desire to become less reliant on natural gas as its pricing is extremely volatile.

The current grey ammonia market is dominated by a few large multi-nationals who develop and licence technology for large (multi-Gigawatt) projects. These companies are developing projects in blue ammonia at similar scale as well as moving into the green ammonia market. As this study has shown, green ammonia plants can be developed at significantly smaller scale than grey or blue plants, so this presents a potentially lower barrier to entry for new smaller players entering the market. As the hydrogen is typically electrolytically produced, the green ammonia market is also seeing new market entrants from green hydrogen developers as part of their hydrogen project portfolio. As a consequence, the ammonia market supply chain is becoming much broader.

The increased interest in green ammonia combined with the broadening of the ammonia supply chain offers various commercialisation routes for ASPIRE. Following the completion of a potential demonstration phase the key commercialisation options for the ASPIRE plant are likely to include creation of a spin-out company to allow one of the following:

- **Licensing:** Licence IP to a developer organisation larger than the spin-out
- **Joint Venture:** Work alongside developers to generate subsequent IP of more mature technology in an operational context.
- **Acquisition:** Large organisation takes ownership of the technology. Both transactions result in the consolidation of assets and liabilities into a single entity.

Figure 19 outlines some key milestones on the route to commercialisation. Beyond 2030, ASPIRE will be a key enabler for an international energy transition; aiding key markets such as shipping and incentivising the ramp up in production and up-skilling of key technologies and workers in the UK.

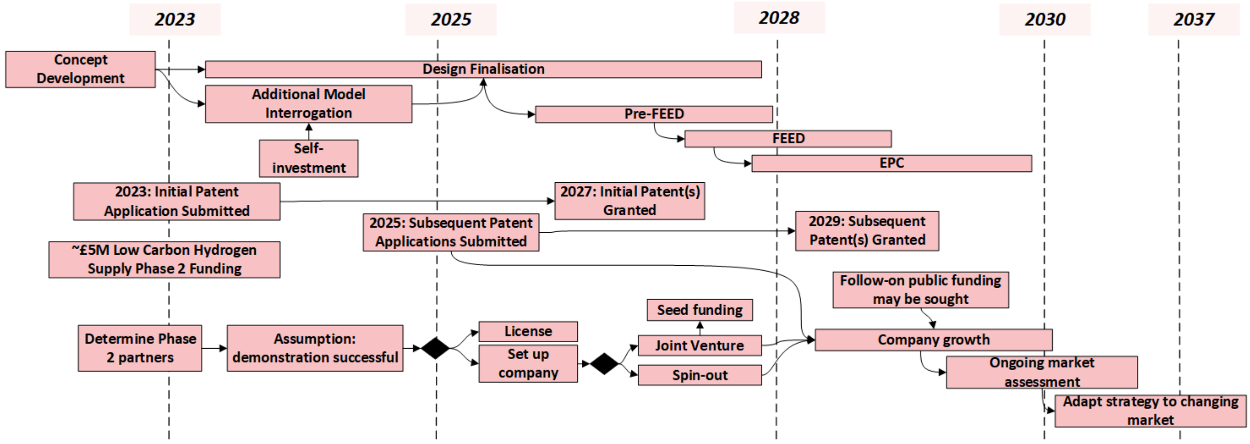


Figure 19. ASPIRE commercialisation roadmap

The ASPIRE technology has been developed to work with both wind and solar power and this opens up significant potential for deploying the technology overseas, particularly in countries like Australia that are actively looking at large scale green ammonia production.

Following the 2 year demonstration phase further testing may be required to optimise the technology (e.g. in ammonia catalyst development for flexible reactor operation) but is envisaged that the demonstrator will be sufficient to develop initial commercial opportunities.

5.3 Dissemination activities

Key to the commercialisation of green ammonia is dissemination of the research and possibilities for the technology. Dissemination activities that have occurred during and on completion of the ASPIRE project include:

- Two steering group meetings where high-level project goals were presented to the project partners on the steering committee
- Presentation of ASPIRE Project at Cogeneration event held at Nuclear Advanced Materials Research Centre
- Members of the ASPIRE team Participated in the 1st ammonia symposium at Cardiff University with 45 delegates visiting STFC to see current facilities and hear about the ASPIRE project
- Engagement of an undergraduate student in the project as part of a placement at STFC
- Presentation of case study results to our project partners at Comhairle nan Eilean Siar
- Journal paper on the topic of flexible ammonia reactors in draft form – plan for ASPIRE work to make contribution to the academic literature
- Publication of a patent filing on key technology
- Findings will also be disseminated through the UKERC Energy Data Centre
- Presentation of project outputs at a Green Ammonia Working Group meeting

6 Conclusions

The ASPIRE project has achieved the primary objective by demonstrating a technical and commercially feasible design approach for an ammonia synthesis plant, powered solely by intermittent renewable energy. Assessments of candidate technology and dynamic modelling of transient ammonia synthesis were used to inform an outline design, which resulted in a novel flexible modular reactor with integrated thermal storage and management. The design allows for high turn-down ratios, permitting nearly 100% utilisation of power generation from renewable sites, reducing the requirement for costly curtailment.

At project commencement key requirements were outlined that would need to be achieved to demonstrate feasibility of the design. The following summarises the findings that support the feasibility requirements:

1. **The plant can run on an intermittent source of electricity from a wind farm of output 10 – 200 MW, associated with onshore wind farm sizes.** Outline design of a 10 MW ASPIRE plant has demonstrated that a modular flexible reactor with thermal storage and management can achieve turn-down ratios of up to 20, allowing for utilisation of renewable energy that would conventionally be curtailed. A scalability assessment demonstrated that the modular plant design can be scaled up to 200 MW without requiring any notable system alterations. Reduced capital costs, due to having lower capacity for electricity and hydrogen storage capacity, whilst simultaneously utilising more generated power, offers the lowest LCOA compared to other design options that were explored, with larger storage systems (battery and hydrogen).
2. **Technology exists to develop an operational plant within the next 3 years.** The novel aspects of the plant will undergo bespoke design and manufacture for demonstration during consequent projects. All ancillary equipment is currently commercially available at the size required for both demonstrator and 10 MW plants. Independent review of the outline design has indicated that an operational plant is achievable by 2025, with a demonstration plant being planned for construction at Rutherford Appleton Laboratory in Oxfordshire as part of Phase 2.
3. **There is a market for green ammonia produced from intermittent renewables at this scale.** An assessment of the market potential for green ammonia highlighted that there is a robust market for green ammonia, solely as a replacement for carbon intensive grey ammonia. However, the green ammonia market also extends to the use of ammonia as a carbon free fuel, for power generation and transportation, and as a hydrogen carrier, simultaneously stimulating the green hydrogen marketplace. A financial cashflow analysis demonstrated that the ASPIRE design will generate low carbon ammonia at a cost that is competitive with traditional grey ammonia, whilst remaining insulated from the volatile natural gas market. ASPIRE ammonia is expected to gradually reduce in price as capital cost for hydrogen production and storage equipment reduces in time, whilst natural gas costs remain uncertain.

Whilst ASPIRE ammonia is lower than the peak 2022 grey ammonia price, it is proposed that subsidisation and carbon taxes may maintain this lower price by bridging any gaps between green and grey ammonia prices, should natural gas costs return to historic levels.

4. **Through-life cost of the green ammonia produced from intermittent renewable power is competitive with other green ammonia technologies.** The price of ASPIRE green ammonia produced at electricity costs of up to £50/MWh, falls within the current predicted price range for green ammonia, between £570/tonne to £1,100/tonne [11]. By 2050, the forecasted ammonia price is between £245/tonne and £282/tonne, with ASPIRE green ammonia expected to fall closer to the lower end of this range as the cost of curtailed power can be assumed to be lower than the costs used in this analysis.
5. **Through-life carbon emissions of the green ammonia is <0.42 kgCO_2/kg NH_3.** A detailed carbon benefits assessment that used the PAS2008 methodology to estimate the through life carbon emissions associated with the 10 MW design. The results demonstrated that the plant would produce a levelised carbon emission of 0.18 kg CO_2/kg of ammonia produced, less than 50% of the designated threshold for being categorised as low carbon ammonia.
6. **The technology meets all safety and regulatory requirements.** An independent design review was undertaken to determine whether the design was technically feasible, but also whether the necessary safety and regulatory requirements for an ammonia site can be adhered to. The review did not raise any concerns about safety and regulatory standards being unachievable for the ASPIRE plant, based on the maturity of the design.

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