$GreeNH_3$

Stream 1, Phase 1

BEIS Low Carbon Hydrogen Supply 2 Competition

Zero Carbon Hydrogen Category

Lead Partner: Supercritical Solutions

Partners: ScottishPower & Proton Ventures

Contents

Glossary

Term	Definition
£	Great Britain Pound
$	United States Dollar
AIV	Acoustic Induced Vibration
ATEX	Explosive Atmosphere Directive
bn	billion
BOP	Balance of Plant
CapEx	Capital Expenditure
COMAH	Control of Major Accident Hazards
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
EPC	Engineering, Procurement and Construction
FEED	Front End Engineering Design
$GreeNH_3$	Green Ammonia (Project/Plant)
H_2	Hydrogen
HMG	His Majesty's Government
HTF	Heat transfer fluid
HP	High Pressure
IEA	International Energy Agency
IMO	International Maritime Organisation
kg	Kilogram(s)
kW	Kilowatt
kWh	Kilowatt hour
LCOA	Levelised cost of ammonia
LCOH	Levelised cost of hydrogen
$LCOH^{200}$	Levelised cost of hydrogen at 200 bar pressure
LH_2	Liquid hydrogen
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
LP	Low Pressure
NH_3	Anhydrous Ammonia
NFuel	Proton Ventures' modular ammonia system concept
NRE	Non-refundable Engineering
OpEx	Operating Expenditure
PEM	Polymer Electrolyte Membrane / Proton Exchange Membrane
PFAS	Polyfluoroalkyl Substances
PFD	Process Flow Diagram
PFSA	Perfluorosulfonic acid
PM	Project Manager
PPA	Power Purchase Agreement

ppmw	Parts per million by weight
Proton	Proton Ventures BV
PV	Photovoltaic
SAF	Sustainable Aviation Fuel
SC	Supercritical Solutions
scH_2O	Water in the supercritical state (supercritical water)
TRL	Technology Readiness Level
UKLCHS	UK Low Carbon Hydrogen Standard
w%	Percentage by weight

Executive Summary

Today, ammonia is responsible for 43% of the world's grey hydrogen production and is essential for feeding the world's population through its role in synthetic fertiliser production. This market alone is responsible for ~500 million tCO_2e/annum, approximately 1.8% of global emissions and it needs to be decarbonised to achieve net zero in the sector[1]. In the near future, green ammonia has the potential to play a crucial role in facilitating the transport of renewable energy or as a zero emission fuel itself. With an energy density ~3x greater than compressed hydrogen[2] and an existing distribution network, ammonia is considered as a medium for global transportation of green energy and plays a leading role in enabling the hydrogen economy.

Phase 1 of the GreeNH_3 project, with results presented herein, concludes that commercial deployment of Supercritical's (SC) electrolysis technology for high pressure, ultra-efficient hydrogen production is feasible for green ammonia production with continued development.

SC's levelised cost of hydrogen at 200 bar ($LCOH^{200}$) is predicted to be 35% lower than current incumbent technologies at commercial scales, resulting in a 21% drop in LCOA for the modelled integrated ammonia production. Based on emissions and continued carbon, it is estimated that a reduction of 24.2 - 35.2 $MtCO_2e$/year compared to a polymer electrolyte membrane (PEM) electrolyser and 170.1 $MtCO_2e$/year compared to SMR for a given commercial plant of 43,000 kgH_2/day (0.47 TWh/annum) output could be achieved.

Considering commercial ammonia production; pressurised hydrogen delivery enables the H_2/N_2 feed compressor to be bypassed, reducing the feed compressor capital cost by a factor of 10 and its duty by a factor of 4. Heat integration between the hydrogen and ammonia plant is not considered likely to be economical at scale and has not been considered for the demonstrator.

Modelling results show that the superior performance of SC's system is closely linked to the SC electrolyser's ability to utilise heat generated through electrical inefficiencies. Optimising for electrical heat will deliver the lowest system efficiencies, delivering up to 46.9 kWh/kgH_2 for 220 bara compressed hydrogen delivery. SC has identified a Heat Transfer Fluid (HTF) that enables the heat transfer system to be operated at ~26 bar, rather than ~230 bar. This offers predicted heat exchanger CapEx savings in the range of 38-40% based on vendor engagement during feasibility.

The location of Hutchison Ports Harwich International (Freeport East) has been discussed and considered herein.

SC has ambitions to scale output of the technology to GW scale by 2030, with potential to bring 5.6 TWh/annum of new green H_2 production to market. With this, it is predicted that a minimum of 150 direct jobs will be created and an order of magnitude more in the supply chain of goods and services.

[1] Global demand for pure hydrogen, 1975-2018, IEA, accessed Aug 22
[2] Ammonia: zero-carbon fertiliser, fuel and energy store, The Royal Society, Feb 20

Overview of the Project

Today, ammonia is responsible for 43% of the world's grey hydrogen production and is essential for feeding the world's population through its role in synthetic fertiliser production. This market alone is responsible for ~500 million tCO_2e/annum, approximately 1.8% of global emissions and it needs to be decarbonised to achieve net zero in the sector[1]. Green ammonia has the potential to play a crucial role in facilitating the transport of renewable energy or as a zero emission fuel itself. With an energy density ~3x greater than compressed hydrogen[2] and an existing distribution network, ammonia could play a role in long haul transportation of green energy having the potential to ease specific challenges in the green hydrogen value chain.

The objective of Phase 1 of the GreeNH_3 "green ammonia" project was to explore the feasibility of a Supercritical (SC) system integrated into a traditional Haber-Bosch ammonia synthesis loop, at both demonstrator and commercial scales. The commercial GreeNH_3 system will be fed by air and water and powered by energy from renewable sources. Phase 1 has validated that commercial deployment of high pressure, ultra-efficient SC electrolysis is feasible and could introduce a step change reduction in the cost of green hydrogen and green ammonia by 35% and 21% respectively.

Phase 2 will see SC's electrolyser produce high purity (99.999 mol%) H_2 for its direct application in the synthesis of ammonia. Phase 2's hydrogen product purity also facilitates translational benefits to multiple sectors for green hydrogen. The purity surpasses hydrogen Grade D under ISO 14687, making it suitable for fuel cells and the majority of other applications. The location of Hutchison Ports Harwich International (Freeport East) has been discussed and considered herein.

The SC electrolyser can minimise cost and waste through its ultra-high system efficiencies. SC's high pressure operation offers benefits including complete bubble removal, accelerated kinetics and rapid mass transfer. SC's membraneless design is uniquely positioned to exploit high pressure, intermediate temperature conditions and produce hydrogen at the pressure that the ammonia industry needs; greater than 200 bar. SC has invented and filed multiple patents to protect an electrolyser cell design that removes the need for a membrane, enabling higher electrical efficiencies, with extended lifetime expected. In addition, at the end of life of an asset, SC will be the only electrolyser that is almost entirely recyclable, have no "forever chemical" usage and maximising return on valuable commodity materials.

Modelling Results and Conclusions

Phase 1 aimed to test the hypothesis that SC's intermediate temperature, high pressure operating conditions would benefit a green hydrogen to green ammonia flowsheet, by integrating heat from ammonia's exothermic reaction to benefit the SC electrolyser system and by delivering hydrogen at higher pressure to reduce the complexity and costs (capital and operating) of hydrogen compression. Other optimisation opportunities in the H_2 plant were also explored.

Ammonia integration results

High Pressure (HP) H_2 delivery to the NH_3 plant - reducing feed compressor CapEx by 10x and OpEx by 4x: A typical commercial scale ammonia plant receives both hydrogen and nitrogen at low pressure. These are mixed and compressed in the ammonia plant's H_2/N_2 feed compressor. High pressure hydrogen delivery means that the hydrogen can bypass this stage. This results in a safer, smaller, simpler and cheaper feed compressor that is only responsible for nitrogen compression. It was concluded with partner Proton Ventures (Proton) that there are minimal technical barriers in designing commercial ammonia systems for high pressure (220 bara) hydrogen delivery. This bypass of the H_2/N_2 feed compressor means that the feed compressor capital cost reduces by a factor of ten and its duty by a factor of four.

Waste heat from the NH_3 plant - found to be uneconomical: The ammonia synthesis process is exothermic and generates high grade heat. The use of this heat in the hydrogen plant was evaluated. The duty available from the ammonia plant was found to be approximately 10% of the duty required by the hydrogen plant. Whilst this would offer a reduction in energy demand in the electrolyser feed heater, the cost for the additional large surface area required for high pressure gas phase heat exchange would likely exceed the benefit. Moreover, ammonia reactors and flowsheets are highly integrated at scale with the majority (if not all) of the exothermic reaction energy used to heat streams either in the reactor or in the plant. For these reasons, heat integration between the hydrogen and ammonia plant is not considered for the demonstrator.

Hydrogen plant optimisation results

In addition to the ammonia plant integration, key design parameters within the electrolyser system were evaluated, creating a tighter envelope for optimal operation and narrowing the window of testing planned for the demonstrator phase. The following key design variables (**bold)** were considered, and the results presented below.

Electrical efficiency heat - energy demand as low as 46.9 kWh/kgH_2 for 220 bara delivery: For electrolysers, inefficiencies in electrical energy to hydrogen conversion present themselves to the system in the form of heat. Low temperature electrolysers, like Alkaline and PEM, need to design and maintain a complex cooling system to control the temperature of the electrolyser. SC, on the other hand, can use this heat to reduce any duty on its system's heat requirements.

An electrolyser's electrical efficiency is the dominant contributor to energy demand in all electrolyser plants. SC has demonstrated an electrical efficiency of 82% (LHV) in the lab and forecasts electrical efficiencies of up to 85-90% with additional development. The system efficiency, which takes into account the full balance of plant (pumps, heaters etc) is most critical however and optimisation to determine the ideal operating point to achieve maximum system efficiency is a key focus of Phase 2. The results show that the superior performance of the entire system is closely linked to the SC electrolyser's ability to utilise the electrical heat it generates through electrical inefficiencies. Optimising for electrical heat will deliver the lowest system efficiencies with the potential to deliver up to 46.9 kWh/kgH_2 for 220 bara compressed hydrogen delivery.

Heat Transfer Fluid selection - CapEx savings of up to 40% in the heat exchangers: SC's system operates with an internal heat transfer loop, maximising heat recovery in the system. SC's temperature range runs from ambient up to 425°C. An extensive study of alternative heat transfer fluids (HTFs) was conducted during feasibility.

High pressure (HP) water is used as a HTF due to its high heat capacity and an operating range that spans 0-450°C, going into the supercritical phase. It is used as a heat transfer fluid in the power sector. HP water can be very effective but the required equipment can be costly. With the SC system, there is added complexity relative to the power sector as the process side is at an equivalently high pressure. Alternatively, mineral oils are available. These are used in the chemical and energy sectors. For most commercially available options, degradation reportedly occurs at temperatures greater than 400°C. Despite this, SC has identified a mineral based HTF capable of operating up to 425°C. This HTF's lifetime is unclear at this time and its rate of degradation will be assessed in Phase 2 as its rate of replacement impacts on operational cost. With this HTF, the heat transfer system can be operated at ~26 bar, rather than ~230 bar. Apart from operational maintenance costs for HTF replacement, there are major reductions in heat exchange equipment cost due to materials savings i.e. reduced exchanger wall thicknesses, with savings predicted to be in the range of 38-40% based on vendor engagement during feasibility.

High Pressure Oxygen - power recovery capable of powering H_2 plant BOP: Oxygen compression is a complex, risky and expensive operation. Oxygen is used in processes from refineries to hospitals and storage and distribution of this gas is done at pressure. SC is the only electrolyser capable of delivering HP O_2 as a valuable byproduct from its electrolyser process without oxygen gas compression. This value can be realised through sale of the O_2 gas, with the potential to undercut existing air separation production processes (note this additional sale value of O_2 has not been included in any levelised cost models in this study). Alternatively, one can consider the HP O_2 as an energy source to generate work or power.

The HP O_2 produced in SC's system, if turbo-expanded, has the potential to power the entire H_2 balance of plant power requirements (excluding heater) with power left over. It is predicted that this excess power would exceed even the ammonia plant's recycle compressor duty, with additional power available for use in the wider system. Upon exploring the feasibility of oxygen turbo-expansion with leading vendors, it was considered feasible, building on experience in oxygen compression. O_2 turboexpanders are not currently an off-the-shelf product and would require development to scale. Whilst hugely beneficial and something that will be explored further by SC, oxygen turbo-expansion was not considered a priority for the demonstrator and was excluded from the design.

Description of Demonstration - GreeNH$_3$ Overview

Planned for a commercial port environment, the demonstration will accelerate SC's UK based technology to TRL 6, whilst transferring knowledge to industrial energy operators and end users. The SC electrolyser will deliver hydrogen at a rate of 18.4 kg/d (224 MWh/annum LHV), enabling the ammonia plant to produce 100 kg/d ammonia. The plant will be tested and monitored for up to 6 months - limited only by project lifetime.

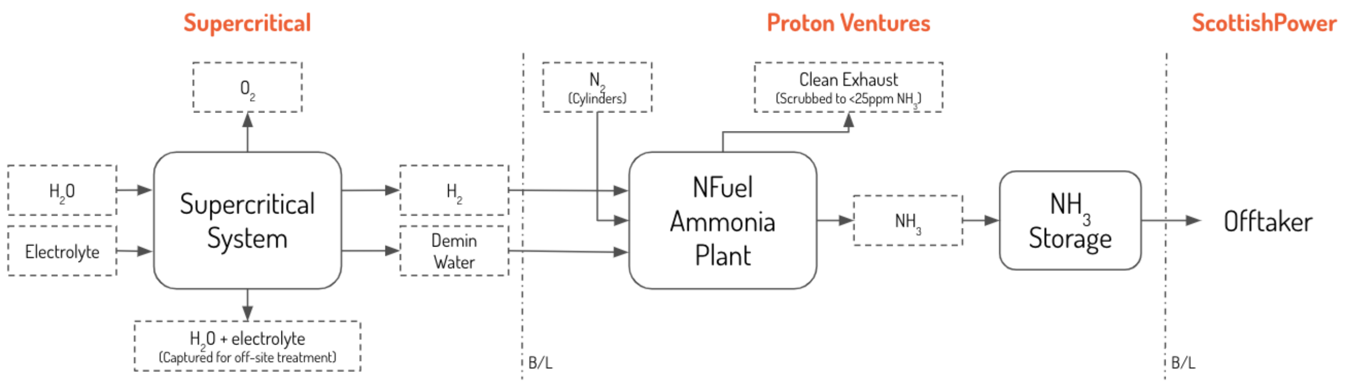

Figure 1 - High level system overview and responsibilities

Modelling predicts that the SC system is able to achieve dramatically improved levelised costs of hydrogen and ammonia (LCOH & LCOA) and that the system could already achieve the UK Low Carbon Hydrogen Standard (UKLCHS) if deployed today connected to wind or solar (based on scope 2 emissions). Demonstration of this capability will facilitate investment in SC's technology, enabling the scale up of technology which will drive job creation and manufacturing output. The demonstrated low cost of hydrogen supported by accelerated scale-up of manufacture will de-risk investment for large scale operators considering the development of utility scale hydrogen projects. SC has aspirations to deliver systems in excess of 100 MW before 2030, with output exceeding 1 GW.

Today, over 85% of suppliers to the existing SC system are UK based. SC maintains a focus on keeping this high to develop a UK supply chain, creating value and jobs in the UK and building a hydrogen economy. Green hydrogen and ammonia have the potential to be pivotal in the energy transition to net zero and SC's electrolyser technology could help accelerate it.

Design of Demonstration

SC Electrolysis Hydrogen Plant

The demonstrator is intended to qualify SC's novel water electrolyser technology on a grid connected, constant power basis. The plant has been designed to achieve steady state, on-spec delivery of hydrogen to SC's battery limit and subsequently to produce on-spec ammonia at Proton's battery limit to supply to ScottishPower. The plant's ability to operate at varying loads will be built into test plans. Hydrogen will be supplied at 220 bara, 50°C and 18.4 kg/d at the composition as in Table 1.

Table 1 - High purity Hydrogen specification - this meets the Grade D hydrogen specification in ISO 14687

Component	Value	Unit
Hydrogen	99.999	mol%
Oxygen	≤5	ppmw
Water	≤5	ppmw

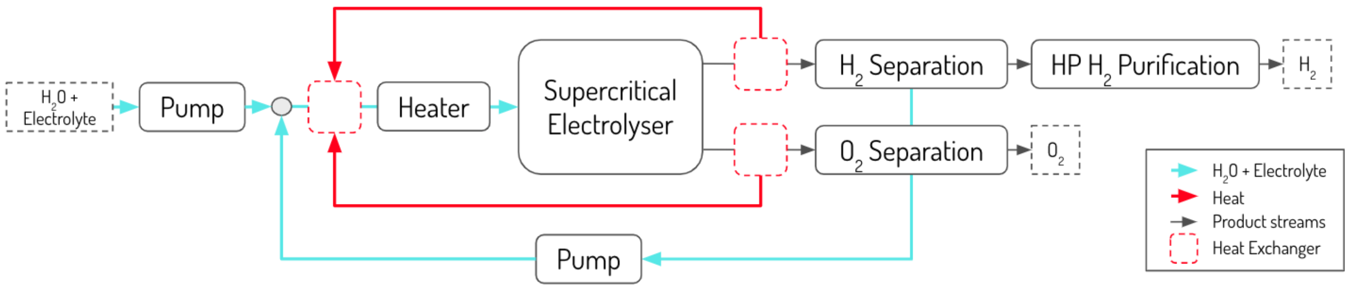

Figure 2: SC Electrolyser System - box flow diagram

A clear outcome from Phase 1 was that the optimisation of heat in the system is critical to deliver class leading system efficiencies. The demonstrator system is designed assuming the maximum electric heating will be required. The electrolyser and electric heater operation will be monitored closely and manipulated through a range of structured tests to determine a preferential operating range to minimise the overall energy demand.

NFuel Ammonia Plant

The NFuel plant design philosophy is based on modularity which offers the benefit of a large reduction in the time required to design, build and install plants. At partial load, the plant's hydrogen consumption per kg of ammonia will not increase and therefore one is not forced to overproduce and store excess product or produce at part-load with that additional expense. In addition, the modular design provides proven and reliable performance and minimal storage volumes. Minimal storage volume has a direct influence on the safety aspect of the entire installation and positively influences the permitting process. The design intent is to deliver technical grade ammonia with the specification as in Table 2.

Table 2 - Ammonia specification

Component	Value	Unit
Ammonia	≥ 99.5	w%
Water	0.2 - 0.5	w%
Oil	≤5	ppmw
Iron	≤5	ppmw
Nitrogen (in ammonia)	≥ 82	w%

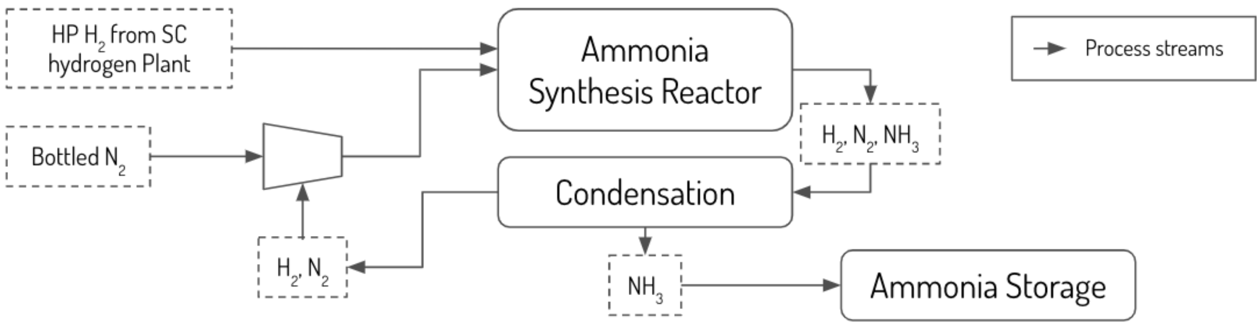

Figure 3 - Schematic of green ammonia demonstrator plant

As discussed in the results section, heat integration with the hydrogen plant was not considered economical and high pressure hydrogen delivery was deemed feasible with minimal barriers or challenges. A challenge that was identified was the ability to procure gas compressors and ammonia synthesis reactor designs at the appropriate scale to enable a demonstrator design that was the same layout as a commercial plant. Acknowledging this challenge, an alternative design was proposed for the demonstrator where the feed and recycle compressor are combined into one and where the heat integration normally found in a commercial ammonia synthesis loop is simulated through a combination of electrical heating and air cooling.

There is a very high degree of confidence in the ammonia plant operating as intended due to the number of years that this technology has been commercially operating. The overall reduction in cost of hydrogen and ammonia plant operating and capital costs relative to other electrolyser systems will be evaluated upon integration of SC's water electrolyser.

Site Plan

The preferred site for the demonstrator is in Harwich, Essex. The selection compliments ScottishPower's recently announced intent to develop a 100 MW electrolyser facility at the Port of Felixstowe. Hutchison Ports, partner to ScottishPower, has been supporting this study, considering the $GreeNH_3$ demonstrator at Hutchison Ports Harwich International, in line with their commitment to clean fuels and hydrogen. It is one of the UK's largest multi-purpose freight and passenger ports with significant transport links to the Midlands, London and the South East. Located on the North Sea it is able to serve freight and passenger traffic to and from Scandinavia and the Benelux countries, offering ro-ro, ferry, container and bulk operations as well as support services for the offshore renewable energy industry.

Hutchison Ports Harwich International is a member of Hutchison Ports, the ports and related services division of CK Hutchison Holdings Limited. Hutchison Ports operates a network of port operations in 52 ports spanning 26 countries throughout Asia, the Middle East, Africa, Europe, the Americas and Australasia. Hutchison Ports also operates other logistics and transportation-related businesses, including cruise ship terminals, distribution centres, rail services and ship repair facilities.

Felixstowe, Harwich and Gateway 14 were collectively defined as Freeport East, one of eight freeports in England selected by the HMG. This decision and commitment to support $GreeNH_3$ furthers Freeport East's ambitions to develop a green hydrogen and clean energy hub, becoming a centre of technical excellence with new production and processing capability.

Benefits and Barriers

LCOA modelling results

The LCOA model evaluates the different electrolytic options available to produce green ammonia. The model is granular to 30 min blocks over a 12 month period, to assess the carbon intensity and qualification to the UKLCHS[3]. The model assumes 'at scale' economics and 2021 reference data for modelling.

[3] UK Low Carbon Hydrogen Standard, BEIS, 2022

Table 3 - Deployment scenarios explored in the commercial model.

Deployment Scenario	Ref	Notes
Other Electrolyser - UK grid only	A0	Always on, no energy storage, grid connected
SC with UK grid only	A1	
SC with solar PPA	A2	Solar/PV PPA but with grid infill
SC with offshore wind PPA	A3	Wind PPA but with grid infill
SC with solar and offshore Wind PPA	A4	Solar/PV & Wind PPA but with grid infill
Other Electrolyser with Solar and offshore Wind PPA	A5	
SC with Battery, offshore wind and solar	B1	Wind & PV Renewables directly connected with Battery in front of electrolyser
SC with Compressed H_2, wind and solar	B2	Wind & PV Renewables are directly connected, Storing excess energy in compressed H_2 but with Grid available for Ammonia plant only if renewable energy is insufficient (consumes H_2 from storage).
Other Electrolyser with Compressed H_2 with wind and solar	B4	

Key findings of the model:

All the deployment scenarios reviewed in the model will ultimately meet the UKLCHS, based on GB grid scope 2 emissions, but the date of achieving this differs greatly as shown in Table 4.

Table 4 - Key results table: dates where deployment scenarios meet the UKLCHS and relative capital costs

Scenario	A0	A1	A2	A3	A4	A5	B1	B2	B4
Date UKLCHS met	2034	2031	2030	2021	2021	2022	2021	2021	2021
Capital outlay	Mid	Lowest				Mid	Largest	Large	Large

The lowest capital outlay is for the SC grid connected (no storage, scenarios A1-A4), requiring almost 7x less capital investment than the largest capital outlay, B1, where greater than 5.5 days of battery energy storage is required. B1, however, does represent a zero scope 2 carbon emissions, fully offgrid solution and the highest overall efficiency of 69%. The SC grid connected electrolyser scenarios (A1-A4) require 28% less capital outlay than the grid connected 'other electrolyser' scenarios (A0 & A5) and represents a 15% higher overall plant efficiency at 57% compared to 42%.

Storing renewable energy in compressed hydrogen increases the overall capital outlay by around 149% due to:

- Larger H_2 production system being required (approximately 2x larger)
- H_2 storage vessels (between 6-10 days of H_2 average production)
- Top-up compressor to uplift the stored hydrogen to 200 bar (tank will reduce in pressure as H_2 is depleted)

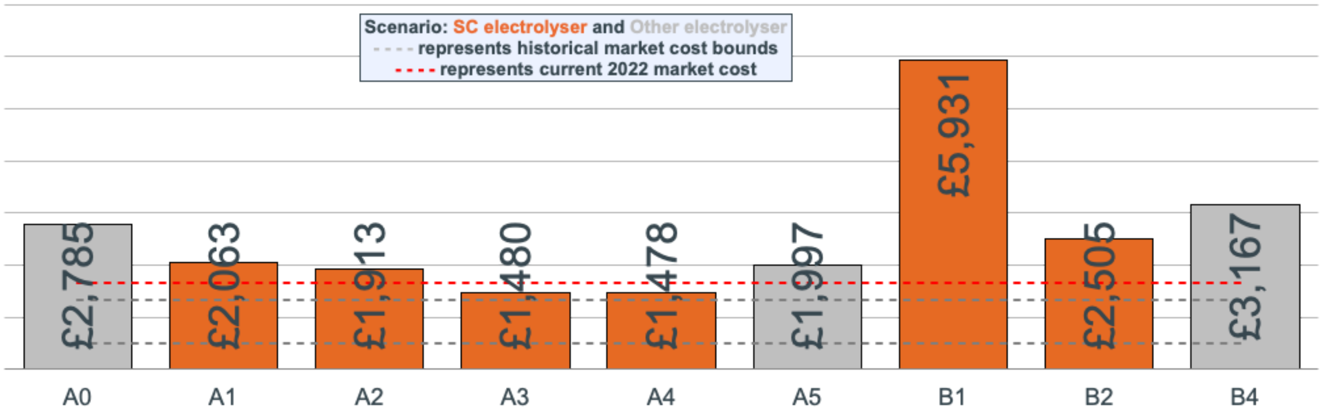

Figure 4 - Modelled economics for the levelised cost per tonne of NH_3 for each scenario (LCOA)

In all scenarios the upfront engineering is a significant capital outlay (model assumes a 3x function of scenario plant CapEx). Future business scenarios will likely treat this outlay differently from that of the plant equipment, where in this levelised model they are treated the same and depreciated linearly over 20 years.

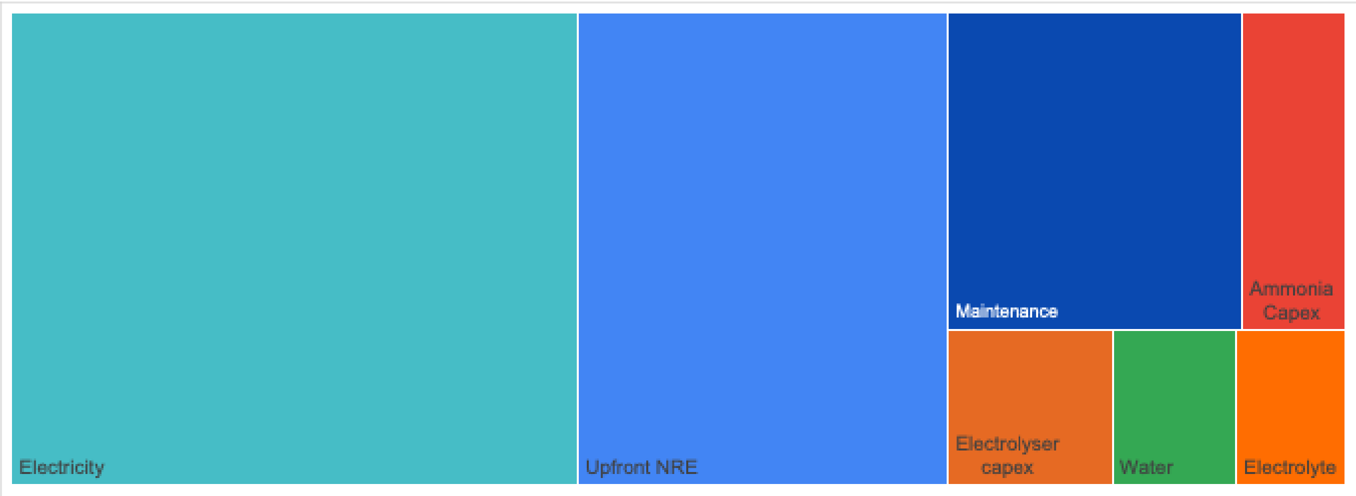

Figure 5 - Proportional representation of costs for deployment scenario A4

As shown in Figure 5, operating costs contribute significantly, mainly driven by electricity cost, at around 50% of the annual costs (including asset depreciation) for scenarios A0-A5, and lower at around 20% for B2-B4 (due to the increased CapEx in these scenarios). Water and electrolyte costs are negligible in comparison. Maintenance is the 2nd highest operating cost (between 14-48% of the annual operating cost) and third behind the depreciation of the upfront engineering (which includes deployment).

The annual operating costs are the highest for grid only scenarios (A0 and A1). The lowest operating cost scenarios are A3 and A4, closely followed by B2 (18% higher). Operating costs are 20-25% lower for the SC electrolyser scenarios when compared to the other electrolyser scenarios.

B1, requires 48% more annual operating cost than the B2 stored compressed hydrogen scenario, however it is worth noting that this is driven from the model's assumed maintenance cost, which is a function of the CapEx. Excluding maintenance, the operating costs are comparable. For B1 to be competitive with compressed hydrogen storage (B2) on a LCOA basis, the battery CapEx cost will need to be reduced to a quarter of current market value of $132/kWh.[4]

Solar in addition to wind, with grid infill (moving between scenario A3 to A4), negates 7% of the grid electricity, due to the annual profile of solar generation and how that compliments the wind profile.

Table 5 - Sensitivity analysis - effects of adjusting key input variable by 5% on the cost per tonne of NH_3

Scenario A4 - Adjusting an Input by:	Resulting change to cost per tonne of NH_3
±5% SC electrolyser efficiency (e.g. 85% to 80%)	4 - 5%
±5% Electricity unit costs	2.0%
±5% in NRE assumption	1.8%
±5% SC electrolyser cost per system kW	1.35%
±5% in Maintenance assumption	0.7%

The primary process risk across all scenarios in the model relates to the at-scale-cost per kW for the SC electrolyser which, for early technologies like SC, represents a future state with assumed challenges resolved and scaling factors applied. Storing intermittent renewable energy in compressed hydrogen form is a cost effective method to interface with an always on, constant demand process such as the ammonia synthesis Haber-Bosch process. Scenarios without grid infill, where extended periods of low to no power would be realised (longest period of 6.2 days in scenario A4 for example), a warm standby mode to maintain operation the intermediate temperature and high pressure will add to costs and reduce overall efficiency with longer periods worsening the economics. Inversely, rapid warming up and cooling down represents stress on the system and could reduce the lifetime of the system.

Technology Benefits and LCOH

The significant novel step identified through this feasibility is the breakthrough in green hydrogen production. The value of this can be realised in wider applications than just ammonia, but ammonia does have amplified value. These are presented separately for clarity:

Green Hydrogen

- SC's technology can operate at high electrical efficiencies due to its operating conditions and unique membraneless design, **minimising waste, minimising cost**
    - Intermediate temperatures improve the kinetics
    - High pressures remove bubbles
    - Membraneless design minimises ohmic resistances in the cell
- Other electrolyser's inefficiencies become SC's efficiencies - SC benefits from the heat generated through electrical inefficiencies, **minimising waste, minimising cost**
- High current densities can be achieved by exploiting the bubble-less nature and high mass transport rates of the supercritical fluids, **minimising footprint, material requirements and CapEx and maximising output**

[4] Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite, BNEF, accessed Aug 22

- SC delivers both hydrogen and oxygen across the battery limit at 220 bara - reducing the need for expensive and higher risk compressors, **minimising capital cost and increasing uptime**
- Operates with **zero scope 1, and scope 2 emissions** when exclusively supplied with renewable power
- Operating conditions drive materials of construction towards high performance nickel alloys for the electrolyser, this can result in a higher capital cost per unit mass of material needed, however this is offset by excellent anticipated in-life durability, high current densities (minimising size of unit) and high recovery of materials at end of life, resulting in a **leading levelised cost of pressurised hydrogen** (see Table 6)
- Unparalleled in life reconditioning capability and end-of-life recycling capabilities - given its no membrane, no PFAS (forever chemicals), all metal design, the SC electrolyser can be almost entirely recycled ensuring minimal negative effect on the environment in addition to its zero carbon operation capability, **putting the environment first, optimising material utilisation and minimising cost**

Table 6 - Levelised cost of hydrogen delivered at 200 bar ($LCOH^{200}$)

Type	Scenario Description	Ref	$LCOH^{200}$ £/kg	$LCOH^{200}$ £/kWh (LHV)	kg of CO_2e / kg of H_2
Grid Connected	Other Electrolyser - Grid only	A0	£ 12.44	£ 0.37	11.36
	SC with grid only	A1	£ 8.45	£ 0.25	8.43
	SC with solar PPA	A2	£ 7.55	£ 0.23	6.40
	SC with wind PPA	A3	£ 5.29	£ 0.16	2.07
	SC with Solar and Wind PPA	A4	£ 5.11	£ 0.15	1.65
	Other Electrolyser with Solar and Wind PPA	A5	£ 7.91	£ 0.24	2.42
Renewables with Storage	SC with Battery, wind and Solar	B1	£ 27.69	£ 0.83	0.00
	SC with Compressed H2, wind and Solar	B2	£ 10.52	£ 0.32	0.48
	Other Electrolyser with H2 with wind and solar	B4	£ 14.00	£ 0.42	0.50

Green Ammonia at Scale

- Preferred ‘always on’ operation fits perfectly with existing, established ammonia synthesis processes, **minimising additional development costs for the ammonia plant and maximising integration opportunities**
- **99.999% High Purity** Hydrogen delivered at 220 bara negates the need for hydrogen compression into the ammonia synthesis loop, **minimising cost and electrical duty**
- **High pressure, high value oxygen by-product** can be used
    - As a feedstock to a neighbouring facility (nitric acid for example)
    - As a supply to enable oxyfuel combustion for cleaner heat generation
    - To power equipment in the ammonia plant such as the recycle compressor through means of turbo-expansion
- SC’s heat and oxygen availability also make it well **suited for downstream nitric acid processes** where ammonia is oxidised.

Challenges

Minimising Hazards

Any electrolyser system has significant inherent hazards to contend with: hydrogen, oxygen, electricity. In addition, hazards relating to temperature and pressure are applicable to the SC system. Managing these hazards and mitigating the risk of occurrence of hazardous scenarios is a top priority.

It has been identified that the greatest risk within the plant is the risk of H_2 and O_2 coexisting in the vapour phase, at pressure, at compositions within the explosive region. The point at which this could be most catastrophic is in the piece of equipment with the largest volume, which is the separator vessel(s). The SC cell separates the hydrogen and oxygen products by design, with its performance being validated today at both cell and module scales. The risk of crossover is low, but not completely eliminated and a referenceable capability and reliability to deliver consistently safe compositions will only come with time and testing. Additional layers of safety are considered essential during the scale-up and development and will be implemented into the demonstrator system.

Perfecting Heat

Heat is a key property to understand in detail to optimise operation of the SC system. The ability to manage this heat well will facilitate the reduction of inefficiencies in the system, improve equipment design and drive down the levelised cost of hydrogen. During feasibility, a heat exchange study was conducted which highlighted a number of key findings:

- Thermophysical properties of SC product streams (H_2:H_2O and O_2:H_2O mixtures at 220 bara+) are not documented nor well understood;
- Heat exchanger design with these fluids is therefore a relatively niche territory;
- Optimal heat exchanger type selection for SC operating conditions needs to be determined through testing with SC's specific fluids; and
- Heat transfer fluids capable of operating above 400°C are not common nor well demonstrated in commercial operation.

It is also crucial to understand and quantify heat sources within the electrolyser to better manage the overall system efficiency. Researching, modelling and testing these phenomena within the SC system will be a key focus of the development plan.

Driving Down Levelised Cost

The levelised cost is critical when considering the investment case for a large scale ammonia or hydrogen plants. It takes into account all factors that influence the cost of production over the plant's lifetime. As presented in Table 6, SC's LCOH[200] is predicted to be up to 35% lower than current incumbent technologies at commercial scales (comparing scenarios A4 and A5 in the commercial model); investment in product development is required to successfully achieve this.

Technological advancements are being made to support this. For example, in SC's parallel project WhiskHy, the module design has evolved, increasing power density of the module by

36.5% and driving down cost by 25%. Through feasibility in GreeNH_3, SC has shifted designs from HP water for the heat transfer loop, to an LP mineral based HTF, a shift that is predicted to reduce the capital cost of exchangers in the BOP by 38-46%. Cell development has delivered an increase in cell size of 3.75x in surface area in just 12 months.

Even with these advances, there is still a significant task ahead for the SC team to drive down cost, demonstrate long term reliability and bring the technology to market as quickly as feasibly possible to help accelerate the UK's clean hydrogen sector. This advancement has been spearheaded by UK Government through InnovateUK and the Net Zero Innovation Portfolio and matched by a global suite of private investors, all of whom have the confidence in SC's technology and the team. With investment in Phase 2 and the delivery of the development plan, SC's technology will take a huge leap forward towards commercialisation.

Process Risks

A hazard identification (HAZID) study was undertaken for both the hydrogen and ammonia plants to determine the hazardous scenarios and identify the required measures to eliminate or reduce the risks. A summary of some key hazards identified are presented:

- Flammability of hydrogen and other streams - mitigated by the provision of appropriate ventilation, leak detection, materials, safety distances and planned maintenance procedures.
    - The dispersion effects will be considered in greater detail in Phase 2, influencing siting of the hydrogen plant relative to the ammonia plant.
    - A potential explosion scenario was identified in the separator with hydrogen and oxygen mixtures in explosive concentrations. The mitigation measures identified include hydrogen detection, composition alarms and trips, as well as elimination of the explosive atmosphere by recombination process in the electrolyser system.
- High pressure - mitigated by adequate operating procedures, safety instrumented systems and overpressure management.
- Oxidising materials - oxygen detection, materials selection, emergency shut down and appropriate operating and maintenance procedures (oxygen cleaning processes).
- Low pressure causing structural issues and freezing (Joule-Thomson effect) - structural effects can be mitigated by appropriately restraining and carrying out Acoustic Induced Vibration (AIV) Analysis on the high pressure gas lines. Freezing effects can be mitigated by designing out high risk temperature drops in the pressure drop considerations through the use of interstage heating and low temperature alarms.
- High temperatures in the electrolyser and plant heaters - mitigated by temperature alarms and trips. Based on further engagement with the product purification vendor, any hazardous effects of the heat generated during recombination on the design temperature will be considered and designed out.
- The potential supply of off-specification hydrogen product from the hydrogen plant was identified to create hazardous scenarios for the downstream ammonia plant. This will be mitigated by the use of inline oxygen and moisture analysers to trip the delivery of offspec hydrogen delivery to the ammonia process.

The process will be systematically assessed at various stages in Phase 2 to ensure that all risks are identified and appropriately designed out or mitigated.

Environmental Assessment

An environmental assessment was undertaken to consider the suitability of Hutchison Ports Harwich International and the surrounding area for the pilot, and a broader assessment of UK port sites for a commercial scale (43,000 kgH_2/day) deployment of SC electrolyser technology was also completed with key findings below.

Flood Risk and Coastal Erosion - The risk of flooding and erosion should be taken into consideration when considering larger, longer term deployments. The UK has some of the fastest eroding coastlines in Europe with 17% of coastlines affected by erosion.

Water usage and availability - Availability of water differs from region to region as does the cost /m^3. A water abstraction licence from the Environmental Agency will be required for abstractions of 20 cubic metres (20,000 litres) or more per day[6].

Protected sites and chemical runoff - Surrounding Special Protected Areas and Sites of Special Scientific Interest should be considered when selecting a site. If left unmanaged, there is potential for the plant to interfere with nearby protected sites. Electrolyte and the Heat Transfer Fluid (HTF), for example, will require dedicated storage. Good practice and measures such as bunding should also be employed to ensure no undesired run off.

Fugitive hydrogen emissions - Hydrogen gas has a very low viscosity and so leaks can often develop within a hydrogen system. A 2022 study from BEIS concluded that hydrogen has a GWP of 11±5[5]. Efforts should be made in design to avoid any potential for leakage and monitoring for leakage should be employed in operation.

Oxygen venting - High pressure O_2 by-product, in GreenNH_3, is let down to ambient pressure before being safely vented into the atmosphere. Venting of oxygen can present a number of hazards including enhanced fire risk, explosion risk and violent reactions with possible nearby materials such as oil, grease and metals. Considerations for safe venting of oxygen including weather conditions, release temperature, release angle, release velocities and concentration limits.

Ambient conditions should be considered when determining both the location of the oxygen vent and the location of the hydrogen and ammonia plant (considering fugitive emissions). High ambient temperatures in relation to the vented gas, moderately stable atmospheric conditions and low wind speed are detrimental to the safe venting and dispersion of oxygen[6].

The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) of 2002 and the Explosive Atmosphere Directive (ATEX 137) are mandatory requirements for reducing safety risk and protecting workers where flammable or explosive substances are present.

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[5] Fugitive Hydrogen Emissions in a Future Hydrogen Economy, BEIS, Mar 22
[6] Safe Location Of Oxygen And Inert Gas Vents 067/17, AIGA, accessed Aug 22

Scale and storage - Hydrogen and oxygen are named substances under control of major accident hazards (COMAH). Under the COMAH lower tier threshold the total amount on site at any one-time including storage and in process is required to be less than 5 tonnes of hydrogen and less than 200 tonnes of oxygen. Under the COMAH upper tier threshold the total amount on site at any one-time including storage and in process is required to be less than 50 tonnes of hydrogen and less than 2,000 tonnes of oxygen. Ammonia is also a COMAH substance, with a lower threshold of less than 50 tonnes and upper tier threshold of 200 tonnes.

For the Phase 2 demonstrator, water usage will be negligible and waste effluent will be captured and treated offsite. There is a risk of flooding due to the site's location that should be considered in Phase 2 given the winter period of testing that is planned. The pilot scale hydrogen plant demonstrator will produce and store hydrogen for combination with nitrogen to produce green ammonia and quantities will be well below COMAH lower tier levels. Plant layout and vent locations will be considered during detailed design to minimise risks due to planned or unplanned emissions. It is proposed that the project have a monitoring and management plan for leaks. For Phase 2, the equipment will be designed for containerisation and located to minimise risk for short term deployment. In summary, it was found that for Phase 2 of the project, there was a low risk to the environment at the site selected at Hutchison Ports Harwich International. In considering a UK port site for commercial deployment of a SC electrolyser the broader potential environmental considerations discussed above should be evaluated in greater detail.

Process Scale-up Against a Counterfactual

Today, there are no large-scale operational exclusive green ammonia facilities. There are cases of green hydrogen being partly injected into wider grey ammonia operations (YARA[7]) and there are announced intentions to develop larger scale green ammonia facilities (NEOM[8]). Larger scale projects have typically opted for alkaline electrolysis due to their existing scale and cost point. Given SC's timeline of 3 to 10 years to commercial ammonia scales, it is considered most appropriate to compare to today's incumbent grey ammonia, produced with hydrogen from steam methane reforming (SMR), and the leading fast-following electrolyser technology, polymer electrolyte membrane (PEM) electrolysis, which is likely to be deployed in this timeframe. This comparison can be found in Table 7.

'Blue' hydrogen technologies are reforming technology fed by CH_4 however CO_2 capture technology is used to reduce CO_2 emissions to the atmosphere (by 95% according to Johnson Matthey[9]). Calculations for emissions tend to exclude any fugitive emissions that may be linked to natural gas production, transport and processing. CH_4 has a global warming potential of 27-30[10]. In addition, the CO_2 captured needs to be stored where it will not find its way back into the atmosphere again. There are uncertainties around longevity of CO_2 storage, safety &

[7] Renewable hydrogen and ammonia production - YARA and ENGIE welcome a A$42.5 million ARENA grant ,YARA, accessed Aug 22
[8] Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM Powered by Renewable Energy for Production and Export of Green Hydrogen to Global Markets, Air Products, accessed Aug 22
[9] CCS-enabled (blue) hydrogen, Johnson Matthey, accessed Sept 22
[10] Understanding Global Warming Potentials, EPA, accessed Sept 22

stability relating to fracturing and leakage with industrial demonstration trials, like Chevron's gorgon project which has never delivered on targets, proving that it is extremely challenging[11].

Table 7 - Scale up comparison vs counterfactuals

	SMR[12]	PEM	SC
Lifecycle Greenhouse gas emissions ($kgCO_2e/kgH_2$)	11.9	2.6-3.3[13,14]	1.5
Approximate Efficiency kWh/kgH_2	50.8	55.5 (60% LHV in stack)	39.2 (85% LHV in stack)
Core materials	Concrete, Steel	Steel, Titanium, PFSA membrane, Pt, Ir, Concrete	Steel, Inconel, Concrete
Ease of integration with Haber-Bosch	LP H_2 Delivery	LP H_2 Delivery	HP H_2 delivery (2-4 kWh/kgH_2 benefit)
Ease of maintenance	Shutdown required but proven high reliability 90%+	Modular	Modular
Lifetime (hours)	175,000 20 years	80,000	100,000
Fugitive emission risk	Yes (CH_4 GWP of 27-30)	Yes (H_2 GWP of 11±5)	Yes (H_2 GWP of 11±5)
End of Life	Largely recyclable	Recoverable PGM however PFAS forever chemical concern	Largely recyclable ~ 30% cost recovery expected

The approach to scaling SC's technology will be modular in the electrolyser and more akin to traditional process technology in the balance of plant. SC's electrolyser development will see a progression on the cell, the module and a multi-module array enabling scaled deployment. The cell and module will be items in constant development, facilitating ever-better scaled systems. This scale up against two counterfactuals takes into consideration today's view on commercial operation for the SC electrolyser. More detail on the scale up approach can be found in the Route to Market Assessment section.

An additional significant differentiator of the SC electrolyser is that it does not use the Proton Exchange Membrane (PEM) technology. PEM technology involves the use of materials containing fluoropolymers with negative environmental consequences, as well as a high contribution per unit mass of embodied carbon.

Development Plan

Plan and cost estimates

SC's electrolyser will be built into an array for the first time within the $GreenNH_3$ project. In the SC wider system, operating conditions and fluid compositions that have never been exploited commercially will be evaluated and understood for the first time experimentally. These technical challenges, better defined during feasibility, will be tested to demonstrate the technology at a larger scale. Development, design and build work complemented by experimental tests will collectively de-risk these challenges.

[11] Chevron hit with penalty-free non compliance notice by WA govt, EnergyNews, accessed Sept 22
[12] Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming, Pamela L. Spath Margaret K. Mann, Feb 01
[13] Comparative LCA of Electrolyzers for Hydrogen Gas Production, S Lundberg, 2019
[14] Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems, Kay Bareiß, Cristina de la Rua, Maximilian Möckl, Thomas, Hamachera, Jan 19

Over the course of feasibility, 42 vendors and contractors were consulted and engaged. Expert guidance and leading technology suppliers from the UK, Europe and North America with ~57% of supply in Phase 2 (by value) anticipated to be provided from the UK. **It is deemed feasible to design, build and demonstrate the GreeNH$_3$ system with an estimated cost of £5.9M**. Economic climate, supply chain constraints and increasingly tightened timelines for Phase 2 make successful delivery on time and on budget a challenge though this has been met with an effective plan and delivery team to execute it.

Hydrogen Plant

SC, as lead technology developer in the hydrogen plant, will lead on the hydrogen plant, with support from subcontractors to facilitate the timely delivery of the plant. Time is critical in Phase 2 and early engagement is key to ensure that all bases for design are agreed and defined. Preliminary design development will lead into front end engineering design, followed by detailed design and procurement whilst adopting a rigorous hazard study approach to process safety at each stage of development. Preliminary estimates for delivery of equipment suggest that long lead items are approximately 34 weeks, subject to material availability. Early commitment to equipment purchasing will be a high priority. The plant will be containerised, designing for space and footprint and facilitating simpler construction and system integration on site, aiming for a ‘plug and play’ approach.

A competitive tender process was employed for detailed design with 60% of contractors who received the request for information submitting proposals. The primary reason for not submitting a proposal was the perceived degree of uncertainty combined with the upfront price commitment through to construction at feasibility stage. Contractors who did submit proposals also declared their concerns around cost risk due to numerous factors, for example, inflation, supply chain, technology novelty and timeline. Progressing through Phase 2, SC will employ a staged approach between FEED and detailed design allowing increased competitiveness and greater certainty through to project completion.

Ammonia Plant

The ammonia plant design and delivery will be managed wholly by Proton. Proton specialises in the entire value chain of (green) ammonia technologies. From concept to operational facilities, Proton provides consultancy support, project development management, feasibility studies and FEED study engineering services up to and including EPC work. Proton has been active in the field of modular green ammonia production and storage for 20 years.

Proton will perform the basic and detailed engineering packages, supporting the nitrogen supply system, ammonia synthesis loop (including compression), ammonia storage, and emergency, safety and utility systems. Proton will work with SC and the hydrogen plant to adhere to the site design guidance and engage in site wide hazard studies. Equipment will be selected from Best Available Technology (BAT) and from European/American vendors for the key components. The plant will be skid mounted and containerised and delivered as much as possible in finished and complete units to limit the amount of on-site works. Initial commissioning of the ammonia plant ahead of hydrogen plant on-spec product delivery will be conducted with procured hydrogen such that the plant is primed and ready for connection to the hydrogen plant.

Testing

The testing will be conducted on site, led by SC and observed by ScottishPower. Steady state operation on the hydrogen plant will be qualified independently ahead of being connected to the downstream ammonia plant. This allows for validation of the SC's electrolyser technology as a standalone, ensuring on-spec product purity, providing a greater probability of success when starting up the ammonia plant.

Minimising hazards, optimising for heat and proving capability of delivering on-spec product for extended periods of operation (at steady state and dynamic conditions) are expected to be the most enabling outcomes for Phase 2. The exact test plan, to be refined early in Phase 2, will isolate critical elements of the hydrogen plant, stressing parameters and evaluating results in order to experimentally map the capabilities of the hydrogen system. This will be done independently as a hydrogen plant and consequently with the ammonia plant to demonstrate the hydrogen delivery system as well as complete ammonia delivery.

Site

The site, agreed in principle for lease to SC for the duration of the project, will be progressed through the planning permission process. Working closely with a specialist in environmental permitting and consenting, SC will conduct the relevant site evaluation, environmental impact assessment screening, local council liaison and planning permission application to enable the project. The site will require a temporary 3-phase grid connection, water supply and waste disposal, all of which will be progressed to completion during the first half of the project.

Reporting and management

Dedicated project management resource will be recruited to oversee the project from start to finish. This Project Manager (PM) will be responsible for interfacing with key stakeholders such as the Monitoring Officer, ScottishPower, Proton Ventures, Hutchison Ports and the selected Principal Designers. Monthly updates will be provided and quarterly reports delivered. In addition to the demonstration activities, Management at Supercritical will continue to drive the business forward and will deliver an updated business plan (including capital and operating costs, process risks, environmental impact, safety, cost effectiveness and scalability vs a counterfactual), route to market assessment, rollout plan and dissemination summary throughout the project.

Business Plan

Ammonia synthesis is a mature, optimised process and available at commercial industrial scales. The successful commercialisation of the GreeNH$_3$ solution rests upon the successful commercialisation of the hydrogen technology. SC is developing its novel technology stepwise, delivering improved results and reliability at greater scales hand in hand with industry. Through SC's partner development programme of work, SC plans to confirm further small scale pilot projects for 2023/24, within our primary market sectors. In addition to the partnership with ScottishPower, SC has formalised relations with (some undisclosed):

- Industrial players, such as Beam Suntory, a key partner in SC's WhiskHy project
- Oil and gas supermajors for hydrogen delivery and refinery integration
- Heavy duty transport focussed producers and end users
- Airline operators and SAF interested parties; and
- National gas distributors and renewable energy operators

This cross sector approach to development, with the core innovation being largely transferable across sectors will accelerate SC's technology to market.

SC has evaluated and modelled three main different business models:

1. **IP'co** - IP business that licences its technology to third parties to build and operate.
2. **Hardware'co** - Electrolyser hardware company that sells hardware globally with regional sales and support teams.
3. **Gas'co** - Gas company that builds, installs and operates electrolysers, selling the gas product.

The modelling has indicated that Gas'co is the most capital intensive, highest risk but highest revenue generating, with IP'co needing the least amount of investment and delivering about the same £ in profit as the middle Hardware'co, but on lower revenues and without the investment in factories. For the next 3 years, the path is the same across the 3 business models. The product needs scaling and testing in customer locations and the product specification needs to meet the desired customer requirements. Future SC budgets have been baselined with SC as a Hardware'co but the final business model will need to be concluded (possibly on a region by region basis) by the end of demonstration towards 2025. Continued operation and greater understanding of the green ammonia market through Phase 2 will provide huge steps forward in this significant sector, but also provide demonstrable outputs for many other sectors.

Rollout Potential

The green hydrogen and ammonia market is dynamic and is in its infancy relative to a century old, established grey ammonia market. There is huge potential to decarbonise the existing ammonia use markets as well as disrupt and decarbonise markets that have not traditionally used ammonia. IRENA predicts that ammonia production will more than triple by 2050, with more than 80% coming from renewable energy sources as seen in Figure 6.

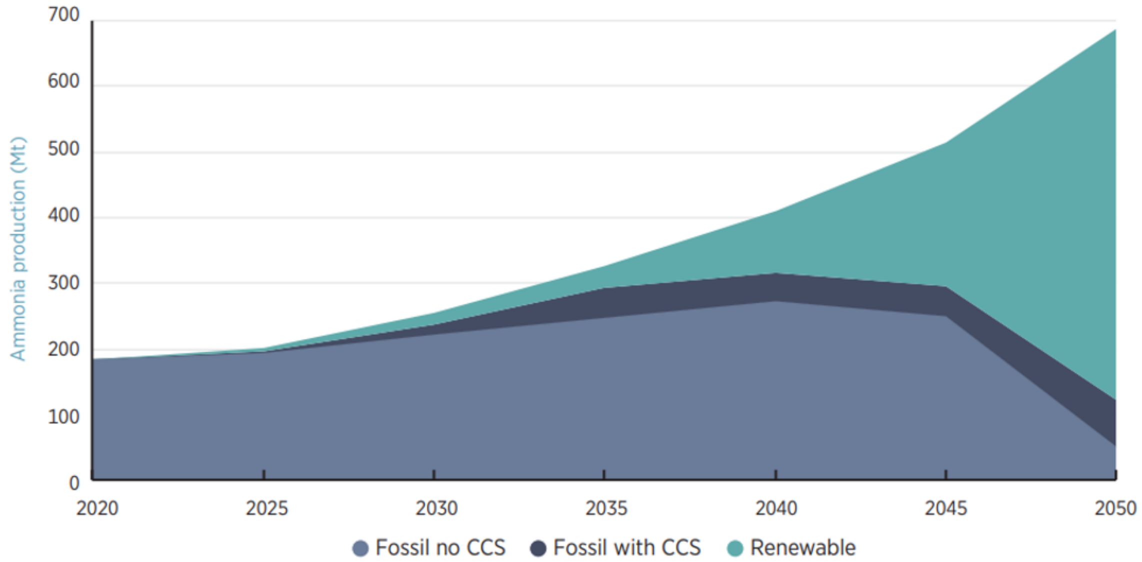

Figure 6 - Expected ammonia production capacity up to 2050 for IRENA's 1.5ºC scenario - IRENA, 2019

Green ammonia in industrial processes

Ammonia is produced and transported worldwide in huge quantities as it is the basis for many chemicals and the starting point for producing fertilisers (80% of the demand for ammonia). Ammonia production decarbonisation is a CO_2 removal opportunity as it accounts for up to 1.8% of global emissions. Moreover, urea, an ammonia derivative, which typically gets its CO_2 from the SMR of the ammonia process, could be carbon negative with direct air capture of CO_2.

The UK fertiliser and nitrogen compound manufacturing market in the UK is estimated to be worth approximately £2 billion[15]. Companies holding the largest market share in the fertiliser and nitrogen compound manufacturing in the UK include CF Fertilisers UK Ltd, Origin UK Operations Ltd and Yara UK Ltd. CF Fertilisers UK stated that it supplied up to 400,000 tonnes of this in 2021[16]. In June 2022, CF Fertilisers UK announced its intent to permanently close its Ince facility near Chester, resulting in a 39% decrease in gross ammonia production in the UK. In August 2022, it ceased ammonia production in Billingham and is importing ammonia to enable it to continue to run its ammonium nitrate (AN) and nitric acid upgrade plants.

These decisions by CF Fertiliser indicate the impact of the changing economics in ammonia production. In Figures 7 and 8, one can see a trend between the price of natural gas and the price of ammonia. Particularly over the last 12 months, with the additional stress of a significant proportion of ammonia production being in Ukraine and Russia, prices of ammonia have soared by over 400%. Increasing gas prices and greater carbon taxes are going to continue to reduce the gap in cost between grey and green ammonia, making the rollout of optimised green ammonia technology more probable. Fertilisers Europe stresses the importance of supporting the fertiliser industry to ensure food security in Europe, claiming 50% of European food production is enabled by mineral fertilisers. It points out that the gas crisis has strengthened the green agenda in the sector as it would reduce reliance on Russian energy imports[17].

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[15] Fertiliser & Nitrogen Compound Manufacturing in the UK - Market Research Report, IBIS World, accessed Mar 22
[16] CF Fertilisers UK, CF Industries, accessed Aug 22
[17] Fertilizers Europe annual overview 2021/2022, Fertilizers Europe, accessed Aug 22

Figure 7 - 25 year historical price chart of UK Natural gas futures price (year vs GBP/therm) - tradingeconomics.com

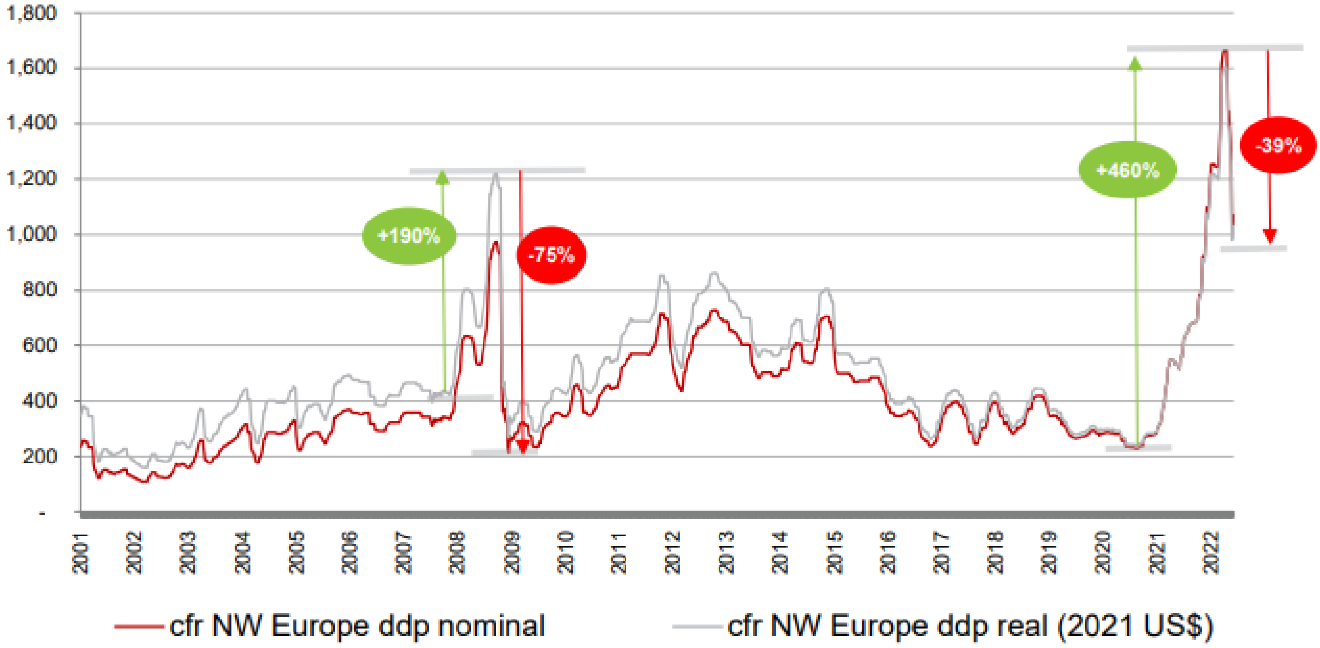

Figure 8 - 20 year historic price of ammonia - Nominal and real cfr Northwest Europe ddp, 2021-2022, ($/tonne) - IHS Markit

The price chart for ammonia shown in Figure 8 is historical and is driven by grey ammonia production processes and incumbent demand centres (fertiliser). Going forward, with green ammonia offering new value in its ability to fuel and to transport renewable energy, existing price points and accepted costs should not be taken as fixed. It is anticipated that green ammonia will have a higher value than grey in new markets.

Green ammonia as a fuel

The International Maritime Organisation (IMO) estimates that shipping accounted for 2.33% of global CO_2 emissions between 2007 and 2012[18]. The IEA concludes that there is wide variation in the different technologies' readiness for commercial application when it comes to the sector with ammonia considered in their study as a directly applied fuel and as a hydrogen carrier[19]. Projects such as ShipFC, led by Wärtsilä, with a goal to have a vessel run on ammonia powered fuel cells by 2023 for one year, provide an indication of the appetite for change in the maritime sector[20].

[18] Zero-emission Vessels 2030. How do we get there?, Lloyds Register, UMAS, 2017, accessed Aug 22
[19] IEA'S Hydrogen TCP Task 39, Hydrogen in the Maritime, IEA, Oct 21
[20] Ammonia as a Green Shipping Fuel: The Viking Energy Project, accessed Apr 22

Due to the widespread use of ammonia as a chemical feedstock, the infrastructure for storing, transporting and handling is already mature, and because it is a global commodity, standards already exist. Green ammonia as a fuel could make use of these existing facilities and procedures. The potential for ammonia use, particularly in long distance shipping, will be very significant for ports across the UK. ScottishPower has been in discussion with port owners and operators across the UK to investigate potential demand for both green hydrogen and its derivatives. There is now also interest in ammonia (or ammonia blended with hydrogen) as a fuel for gas turbine power generation use. A blend may be easier to achieve than pure hydrogen given challenges around combustion properties.

Green ammonia as a hydrogen transport vector

ScottishPower co-funded a study with Scottish Enterprise, 'Scot2Ger', which examined the emerging and substantial German demand for zero-emission hydrogen and how it could be met by green hydrogen produced in Scotland. The German market is estimated to grow rapidly over the coming years and represents the majority share of a European hydrogen import market estimated at €20 billion by 2030[21]. Germany's decarbonisation ambitions have created a drive to import green hydrogen by land and sea and a key part of the study is investigating the different vectors that could be used to transport the hydrogen. Ammonia is one of the leading options, along with liquified hydrogen, liquid organic hydrogen carriers (LOHC) and compressed hydrogen. The study is also investigating potential demand for green ammonia in Germany, which could be met by supply from the UK.

A study by Roland Berger assessed three of the hydrogen carrier technology options, including liquefied hydrogen, ammonia and liquid organic hydrogen carriers (LOHC), and analysed their costs and feasibility, with a focus on Europe[22]. This study found that each of these options have specific characteristics and requirements which may make them more suited to some applications than others. For example, due to the safety concerns, it is questionable whether authorities would permit the transportation and use of ammonia in populated areas. Major ports and seagoing vessels handling ammonia would also have to take extensive safety precautions against toxicity and explosion risks. However, ammonia emerged from this study, along with LOHC as a promising option for transporting hydrogen over longer distances. An innovation support scheme, H2 Global, also provides a good indication of the potential future demand for ammonia in the European Union[23]. The first round of funding for this scheme, with an allocation of €900 million from the German Government, is split into three lots of €300 million for green ammonia, green methanol and green jet fuel. This scheme will provide support for both the demand side and the supply side, with support for the production of green ammonia production outside of the EU, as well as for technologies using green ammonia inside the EU.

[21] Scottish - German Collaboration to Unlock €20 billion Green Hydrogen Market in the EU, ScottishPower, Nov 21
[22] Hydrogen transportation: the key to unlocking the clean hydrogen economy, Roland Berger, Nov 21
[23] https://www.h2-global.de/, H_2Global, accessed Aug 22

Route to Market Assessment

Steps to Commercialisation

GreeNH$_3$'s commercialisation relies on the scaling of SC's technology. To enable this, SC must consider the scaling of the core cell, module and system of the SC electrolyser. Given the first-of-a-kind nature of SC's innovation, the path to deliver a commercial product will occur through the application of the tacit knowledge and proficiency gained through application, aka learning by doing, in manageable steps building to commercial scale deployment. These steps to commercialisation are to be deployed in parallel with the business plan discussed in this report.

SC's Gen1 cell design was tested in early 2022 and delivered 230 bar of separated pressurised gases and operated at 82% efficiency (LHV). The first multi-cell module is 20x larger than the Gen1 cell and is due for testing at the start of 2023.

The SC strategy is to scale production of the core building block, the cell, through automation and mass production through volume manufacturing of a standard component. The all-metal design enables a highly automated, industrial and scalable solution using production processes that are established in other industries.

Current R&D is focused on two key objectives;

- Optimise and finesse production processes to deliver a high volume, high repeatability, low cost cell component
- Increase the power density of the cell through design and optimal selection of materials and operating conditions

In parallel to the core R&D, SC is building demonstration plants such as those underway in the WhiskHy project and proposed for GreeNH$_3$ Phase 2. These plants are crucial for testing of module designs and system architectures. These systems will help to identify currently unknown scaling challenges; any identified will be investigated and cost effective solutions will be sought to overcome them.

Job Creation

With the results from the testing of the first multi-cell module demonstrator, SC plans to raise further equity funding to step up its team, facilities and testing. SC expects to create 25 new skilled and administrative jobs to lead the development in core technology and the supporting system.

Objectives from the raise:

1. Demonstrate long term operability of SC module and system
2. Increase manufacturing readiness level whilst reducing the cell and module costs in advance of mass manufacturing
3. Increase the team capabilities in both resource numbers and skill diversity

4. Invest in dedicated facilities for safe testing (including multi-cell module) and ongoing cell optimisation
5. Build dedicated R&D team and project for re-application of the core technology for the production of e-fuel, technology decarbonising Jet Zero and Green Ships, supporting point 6 of HM Government's 10 point plan

Phase 2 of GreeNH$_3$ will support objectives 1-4, with the project funding forecast to directly contribute to the recruitment of 10 full time roles at SC.

SC has ambitions to scale output of the technology to GW scale by 2030, with potential to bring 5.6 TWh/annum of new green H_2 production to market. Their commitment to core R&D, larger electrolyser designs and multi-module arrays, all while reducing the cost per kW and maintaining durability will facilitate this commercialisation. The commonality of the cell building block means SC will attain buying power, even in the early years of manufacturing. Optimisation at system level of the entire solution is required to prevent the 'balance of plant' from eroding the significant efficiency gains at module level - a crucial step achieved in the delivery of GreeNH$_3$ Phase 2. By 2030, SC predicts that the development and scale up of its technology will create a minimum of 150 direct jobs with an order of magnitude more in the supply chain of goods and services.

Potential Carbon Savings

An estimate of the total emissions and embodied carbon from the hydrogen plant planned for Phase 2 of GreeNH$_3$ is around 90,000 kg CO_2e over the lifecycle (3 years) when considering UK average grid connection of 265 gCO_2e/kWh[24]. Embodied carbon for the project is estimated to be in the order of 36,800 kg CO_2e (the SC electrolyser module's contribution is estimated at 2.11% of this). Scope 1 and 2 emissions under a grid scenario account for 59% of the carbon footprint of the project. The percentage of emissions from operations is reduced to 10% when wind power is used to provide electricity to the hydrogen plant.

At commercial scales, the aspiration is the use of 100% green energy to provide electricity to produce green hydrogen and green ammonia. This can be achieved through using a green energy tariff from an energy supplier to provide 100% renewable electricity. ScottishPower uses 100% renewable energy, sourced exclusively from UK wind farms.

At a commercial scale the hydrogen plant was modelled to produce 43,000 kgH_2/day to supply the ammonia plant with an 80.5 MW electrolyser. An assumption of 100,000 hours (11.4 years) operation was used to determine the carbon assessment for the commercial scale plant. An overview of the emissions and embodied carbon is approximated to be 1.9×10^8 kgCO_2e over the lifecycle using wind power or 2.8×10^9 kgCO_2e using grid power. The largest emissions from both the grid scenario and wind power scenario are from the provision of electricity to the hydrogen project during operations, which equates to over 99% of CO_2e (88% for wind scenario). Embodied carbon is estimated to be in the order of 2.3×10^7 kgCO_2e for both power scenarios.

[24] BP Statistical Review Of World Energy, BP, 2021

There is a reduction of 24.2 - 35.2 $MtCO_2e$/year compared to a polymer electrolyte membrane (PEM) electrolyser and 170.1 $MtCO_2e$/year compared to SMR for a 43,000 kgH_2/day plant.

Table 8 - Summary of emissions and embodied carbon for representative 43,000 kgH_2/d SC hydrogen plant

	Scope 1 & 2 emissions	Embodied Carbon	Total
National grid ($kgCO_2e/kgH_2$)	15.8	0.1	15.99
Wind farm ($kgCO_2e/kgH_2$)	0.9	0.1	1.0

It should be noted that these figures are indicative order of magnitude estimates with inherent uncertainties at the concept stage. These will be refined in the detailed stages of the project, with a view to adopting potential carbon savings through material recycling where possible.

Commitment from ScottishPower

ScottishPower launched their green hydrogen business in 2021 and aims to have more than 1,000 MW of green hydrogen capacity installed in the next decade. This includes a project at their onshore wind farm at Whitelee near Glasgow, where the focus is on providing hydrogen for heavy transport and heavy industry and at Cromarty Firth (near Inverness) where the intention is to provide hydrogen for use in distilleries. More broadly, Iberdrola recently commissioned a facility in Barcelona to provide hydrogen for the city's bus fleet and a project to decarbonise fertiliser production in Puertollano, Spain, through the supply of green ammonia.

ScottishPower is already exploring the export of green hydrogen and ammonia from the UK and taking steps to identify and develop the most cost-effective ways of distributing green hydrogen. Investment of time and resources to the $GreeNH_3$ project through to the demonstration phase reinforces the commitment to the long term improvement of the hydrogen value chain.

Cross Sector Benefits

The demonstration of SC's high pressure electrolysis technology has huge potential in other sectors, predominantly as a source of heavy duty heat, fuel or chemical feedstock.

The foundation industries are vital for the manufacturing and construction sectors, they produce 75% of all the material in the UK's economy. Worth £52bn annually, they emit 50 million tonnes of CO_2 per year, contributing about 10% of the total UK CO_2[25]. This contribution needs to be net zero by 2050. They use an equivalent of 12 million tonnes of oil each year, excluding electricity, equivalent to ~12k tonnes of hydrogen a day. Green hydrogen produced at pressure for ease of onsite storage, facilitating the 'always-on' type operation that is typical to this sector, is an optimal solution for decarbonisation.

HP green hydrogen and green ammonia have a crucial role to play in transportation. Aligned with Point 4 of the UK government's 10 point plan; transport, specifically buses (3 $MtCO_2e$) and goods (21 $MtCO_2e$), would both benefit from the ultra-efficient production of green hydrogen and delivery of the gases at 220 bar, requiring a less energy intensive compression step to go from 230 bar to 300-700 bar. UK road freight is estimated to present an opportunity for the use of 6,697 tonnes of hydrogen per day.

[25] Investing in foundation industries: help to back innovators, BEIS, accessed Aug 22

Hydrogen is also crucial as a feedstock to commodities like sustainable aviation fuel (SAF). With green hydrogen delivered at pressure and carbon dioxide captured from the air, jet fuel can be generated with the capability of reducing up to 15 $MtCO_2e$ by 2050[26]. With SC's unique operating conditions, integration opportunities with processes like Fischer-Tropsch will be maximised, again taking advantage of the high pressure hydrogen delivery and storage.

SC remains focused on identifying optimal decarbonising technologies. Advanced nuclear technologies like Advanced Modular Reactors have been highlighted as optimal for cogeneration with intermediate temperature electrolysers. SC is well placed to maximise electricity and hydrogen cogeneration in the UK. This will support an existing nuclear work force and capability and enhance the UK's opportunity for export of technology and clean fuels.

Significant Barriers and Risk

There is reasonable time and cost risk given the current political and economic climate. The war between Russia and Ukraine is having a huge impact on commodity prices such as nickel and oil and gas which is being enhanced by post-COVID global surges in demand for commodities. In 2022, nickel prices doubled before more recently settling. Natural gas price data shown earlier in Figure 7 shows energy costs have increased by over 5x in the past two years. Suppliers of metals and equipment are warning of possible price increases and stretched lead times and are unwilling to commit to fixing them at this stage. Whilst high natural gas prices are beneficial to clean technologies in the long term, in the short term, they have huge effects on supply chains. For example, energy surcharges are being applied to mill produced metals. It is anticipated that manufacturing and delivery charges will see similar trends. To de-risk this, SC has spent a lot of effort building relationships with key suppliers and forecasting expected demand ahead of time.

Low TRL technologies are intrinsically high risk given the degree of unknowns associated with developing and scaling a new invention. Through application of good engineering practices and business management, Phase 2 of $GreeNH_3$ will be managed to proactively mitigate risk and drive the project to successful completion. SC has built a team experienced in technical fields such as electrochemistry, process design and mechanical engineering, taking decades of experience from similar high pressure, intermediate temperature established industries like the oil and gas sectors. In addition, SC continues to employ a highly collaborative and dynamic approach to development, engaging industry leading subcontractors in services and equipment aligned with our vision and who are committed to advancing clean technology.

Consistent policy is crucial to ensure the continued investment and adoption of clean technologies. Long term commitments like the Climate Change Act have seen follow-on commitments from the largest of companies as they prepare to continue to operate in the UK long term. Shorter term support such as the Net Zero Innovation Portfolio and the Net Zero Hydrogen Fund are going to be crucial to enabling clean hydrogen technology and maximising

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[26] The Ten Point Plan for a Green Industrial Revolution, HM Government, Nov 20

cost reduction. They help drive competition in the marketplace and position the UK as a leading export nation of both clean fuels and clean technology.

Dissemination

The GreenNH_3 consortium will disseminate their findings from the project formally on the BEIS website. In addition to this feasibility report for example, a shorter Executive Summary will also be published to facilitate the transfer of knowledge and make key findings more accessible to more audiences, supporting future net zero business models such as the decarbonisation of port operations as well as road and marine transportation.

If successful in Phase 2, a dedicated website will be launched that will detail the scope and intended deliverables of the project and act as a base for project updates which will be provided quarterly in blog format. More actively, partners SC and ScottishPower will utilise existing networks to present our ambitions and achievements. Active memberships to groups like the Renewable Energy Association (REA) and the UK Hydrogen and Fuel Cell Association (UKHFCA) will ensure sector relevant dissemination. In addition, ProtonVentures is a founding member of Europe's largest ammonia event, NH3 Europe, and a founding member of the TransHydrogen Alliance - a group dedicated to facilitating green hydrogen transport in the form of ammonia in an economically viable manner. Active participation and updates provided to these sprawling organisations will dramatically accelerate dissemination.

The GreenNH_3 consortium intends to channel news and findings through commercial, press and social channels. Iberdrola and ScottishPower with 380,000 and 100,000 followers on LinkedIn respectively will extend the reach of the project's findings globally.

Conclusion

The GreenNH_3 project represents an exciting opportunity to advance SC's electrolyser technology to TRL 6. The project itself is considered feasible, though it is noted that time for delivery is tight and that the economic climate introduces risk. Suppliers have expressed concerns around cost and time citing inflation, supply chain and technology novelty as uncertainties to overcome and deliver the project on time and budget. Short term job creation of up to 25 full time employees is expected, with a further 130 or so expected by 2030.

The long term potential benefits of commercialising the technology present themselves financially and environmentally. There is a predicted cost reduction of 35% in LCOH[200], 21% in LCOA and a potential mitigation of 24.2 - 35.2 MtCO_2e/annum versus a comparable PEM electrolyser technology at commercial scales. The advancement of the technology and demonstration in the green ammonia sector was also highlighted to offer huge cross-sector benefits with opportunities to deploy learning in more hard to decarbonise sectors in the UK such as heavy duty heat, sustainable fuels or chemical feedstock.