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The New Alchemy making fuel from water and air

FLOATING ATOMIC PRODUCTION OF GREEN AMMONIA FOR SHIPPING AND INDUSTRY

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Executive Summary

The production of green ammonia is a key component of the decarbonisation plans for international shipping. While atomic electric propulsion will decarbonise the largest vessels, this will still leave a large number of sub-15 MW propulsion power vessels requiring a pathway to zero-emissions.

Current plans for the provision of zero-carbon ammonia rely on the unproven technology of carbon capture or the limited scalability of production from intermittent renewable electricity. The decarbonisation of other difficult to abate sectors such as chemical and steel manufacture as well as aviation will also require the manufacture of a substantial amount of these green e-fuels.

CORE POWER's concept is an offshore facility partnering marinised atomic power with an offshore ammonia production facility, which will create green ammonia from abundant seawater and air. The next generation of reactors will far exceed the safety, security, and efficiency of the pressurised water reactors (PWR) currently in widespread deployment. CORE POWER has partnered with Terrapower in the development of a specifically marinised molten salt reactor (MSR) which uses high assay low enriched uranium (HALEU) to produce heat that can then be converted to electricity. CORE POWER modelling shows that with current technology it is possible to produce 1 million tonnes of ammonia per year using 1.2 GW of electric power, reducing to 0.9 GW by 2050. This is the equivalent of 440,000 tonnes of very low sulfur fuel oil (VLFSO) and it would allow the decarbonisation of a significant number of vessels. The flexible nature of these systems will mean it will also be possible to provide a mixture of electricity, hydrogen, and ammonia for other applications, including chemical manufacturing and aviation.

The key step of the ammonia production process in terms of both the footprint of the plant as well as its overall electricity usage is the electrolysis step, where water is turned to Hydrogen and Oxygen. Current technology points towards the use of proton exchange membrane (PEM) electrolysers, however the development of high-temperature systems offers an interesting prospect. These would use a significant fraction of heat rather than electricity, improving the overall efficiency of the system. The other components of the plant are very mature, and any further improvement will have only marginal effects on overall efficiency.

The proposed facility would constitute a floating marine "atomic plug", housing the reactor and the power conversion system. The 'atomic plug' will output a mixt of electricity and heat, depending on the actual requirements. The 'atomic plug' would be sited relatively close to the offshore ammonia production facility and storage tanks. These facilities will be built on the experience of the Oil & Gas industry, which has an exceptional track record in terms of safety and cost reduction for offshore installations.

The production of green ammonia at sea using advanced atomic power is superior to both production from renewables and non-marine atomic systems. Atomic power has the highest capacity factor of any power generation method whereas intermittent renewables, wind and solar have the lowest. This reliability and dispatchability makes advanced atomic the ideal power source for e-fuel production.

Moving the reactors to sea will allow for a large reduction in costs due to the lack of a need for expensive civil engineering as well as opening the possibility of shipyard construction. By moving to the production of modular n^{th} of a kind rather than the unique first of a kind reactors ,that has kept nuclear generation prices elevated up until now, it should be able to achieve significant cost savings. From a technical perspective, it will also allow the use of the ocean as a heat sink for the reactor as well as the possibility of moving the reactors depending on the demand.

Floating atomic power is the best option for scalable, secure, and truly green ammonia production.

Introduction

Atomic electric propulsion will only be suitable for a portion of international shipping vessels those larger than 15 MW propulsion power. This this will alleviate a large share of total GHG emissions ,but it will still leave a significant number of vessels requiring a means of zero-emission power.

Currently proposed options for low-carbon fuels can be roughly broken down into three categories.

- Fossils fuels, including liquid natural gas (LNG) with carbon capture and storage (CCS)
- Biofuels
- Hydrogen-based green electro fuels.

Of these, the development of green ammonia as a green electro fuel is the most promising for decarbonisation. Carbon capture is energy-intensive, limited in its ability to capture emissions and unproven for deployment onboard ships. While trials are ongoing for the use of carbon capture on international vessels, they will still have inbuilt disadvantages. Carbon capture is often advertised as having an efficiency between 85-95% however some studies have shown that the current efficiency is around 55% which is further reduced when the extra power required to drive the carbon capture is considered.[i] There are also logistical issues concerned with the storage of the CO_2 onboard the vessels and its subsequent transport and permanent storage.

Biofuels produced from waste suffer from scalability issues, while those not from waste are highly land-intensive and must compete for space with food production. While arguably an excellent way to do low-tech carbon capture the volumes needed to adequately supply the global shipping industry are not feasible. With the added factor that the industry would have to compete with aviation and other end users as well, further constraining supply and increasing cost.

Electro fuels, especially hydrogen-based ammonia, are the only scalable option as their feedstock of water, air and electricity are abundant. They also have the added benefit that ammonia is already shipped internationally meaning that there are existing protocols in place for its storage and transfer. The major downside of ammonia is its lower energy density, far lower than VLSFO, as well as the more complex storage requirements. Ammonia must be kept refrigerated or under pressure meaning that there can be less volume available for the cargo.[ii]

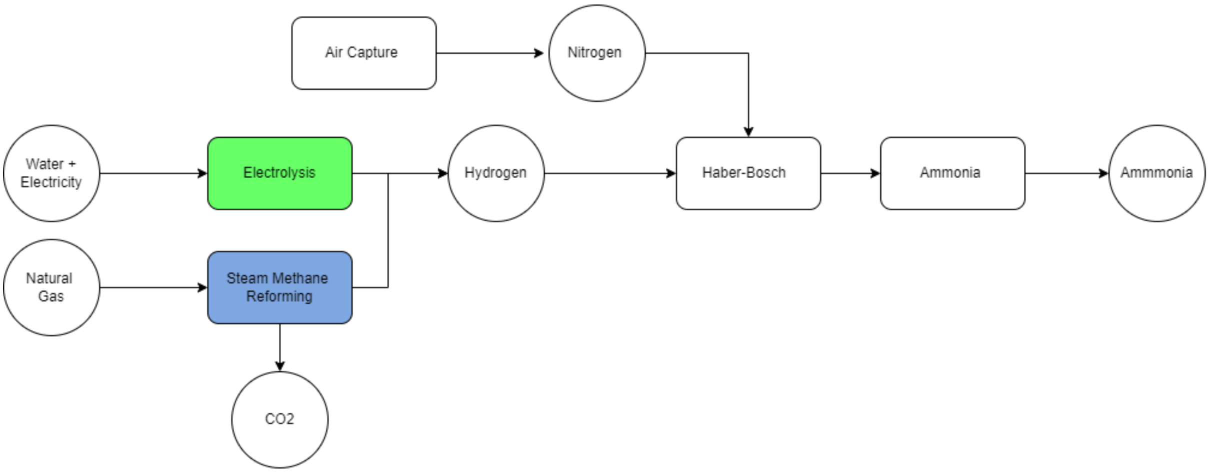

Figure 1. Potential pathways for the production of ammonia. Green hydrogen produced with atomic power provides the greenest and most scalable path towards this goal.

The most commonly proposed source of clean energy for the production of green ammonia is stranded renewable energy, which is limited as well as intermittent and therefore cannot match the demand. Furthermore, the moment that stranded energy has a market, it will be priced at the rate of grid electricity, leading to ammonia prices of 4000 $/tonne, about 6 times that of the equivalent amount of VLSFO to provide the same energy.

Others suggest producing ammonia from blue hydrogen relying on carbon capture and storage. This is yet to be developed at scale however and it would rely either on increasingly costly natural gas or highly environmentally damaging coal, even when CO_2 abatement is considered.

Currently, an intense research and development effort is being undertaken within the maritime industry to develop ammonia powered vessels, either by means of internal combustion engines or fuel cells. Major marine engine manufacturers such as DSME and MAN Energy have begun updating their engines to run on ammonia.[iii] It is therefore believed that, by the end of the decade, the uptake of ammonia as marine fuel will be significant, massively increasing the current demand. While there are significant challenges in the use of ammonia as a marine fuel, there are already well-developed protocols for its storage and transport at sea. In fact, in 2019, 17.5 million tonnes of ammonia were transported across the globe by 71 vessels, showing that ammonia can be transported safely in the maritime environment.[iv]

CORE POWER firmly believes that the only truly scalable proposition for the large-scale production of green ammonia is the use of atomically powered floating production platforms. For the production of these fuels to be viable for decarbonising hard to abate sectors the production method must be both truly green as well as scalable for industry's needs. Atomic power offers both the reliability of energy supply as well as zero emissions during operation.

The Green ammonia production process

The ammonia production process, summarised in figure 2, consists of the desalination of sea water, electrolysis to split water into hydrogen and oxygen, the extraction of nitrogen from the air, and the Haber Bosch process to produce ammonia.

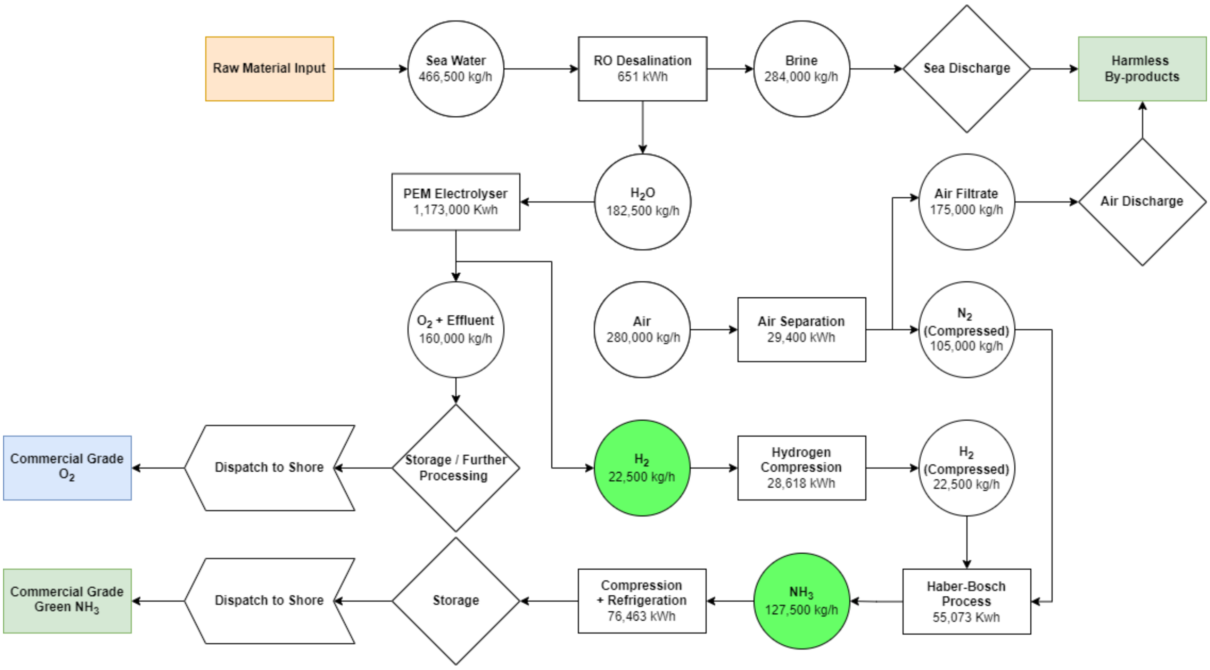

Figure 2. Flow-through of a 1 million tonne per annum ammonia production facility

Figure 2 shows the modelled flow through and power usage of a facility capable of producing 1 million tonnes of ammonia per annum, assuming a capacity factor of 95%. The model is based on data for currently available subsystems and components. While the flow-through shows the most efficient and cost-effective process with current technology we expect that within the time to deployment of these facilities there will be significant developments in the technology.

While primarily concerned with the production of ammonia the oxygen by-product of this process is also valuable with the global oxygen market currently valued at $27 billion per year and expected to grow to $37 billion by 2025. The mixture of oxygen and effluent water once processed and dried to produce commercial grade oxygen could provide additional revenue of 1.3 billion from the production of approximatley 1.2 million tonnes per annum of oxygen. The total global oxygen production as of 2019 is 380 million tonnes so the proposed facilities would become significant producers in this market.

The production process begins by pumping 466,500 Kg of seawater through the reverse osmosis desalination system producing 182,500 kg of freshwater, suitable for electrolysis, and 284,000 kg of concentrated brine, which will be pumped back into the sea. The desalinated water is then fed into the electrolyser cells producing 22,500 kg of hydrogen and 160,000 kg of oxygen mixed with residual water that will require further processing to produce commercial-grade oxygen. The hydrogen is then compressed and combined with 105,000 kg of nitrogen, which had been extracted from 280,000 kg of air, resulting in the production of 127,500 kg of ammonia. This ammonia can then be compressed and sent for storage. Assuming these facilities have a capacity factor of 95 % one such installation could produce about 1 million tonnes of green ammonia per annum.

Electrolyser technology is currently one of the major areas of technological development in the decarbonisation space. Both the EU and US have identified the manufacture of low GHG hydrogen as a key technology as they transition towards net zer.[v,vi] There are currently three types of electrolyser technologies that are deployable: alkaline, proton exchange membrane (PEM) and high-temperature systems sometimes called solid oxide electrolysers (SOEC), each having distinct advantages and disadvantages in regard to marine deployment.

Alkaline electrolysers are the most mature technology, having been used for over 50 years, however they are the most space demanding, being up to double the size of an equivalent PEM system. PEM electrolysis is arguably the technology receiving the most interest, with the Silyzer series of electrolysers from Siemens being a notable example of a developing product. Development is still required to extend the lifespan of the membranes however avoiding costly refurbishment and prolonged downtime.[vii]

High-temperature electrolysis is of great interest to CORE POWER as it replaces a large amount of electrical energy with heat, thereby, increasing the overall efficiency of the system. High-temperature electrolysis operates by changing the phase of water from liquid to superheated steam before feeding it to a solid oxide containing cell. In this way the energy required by the process goes from 100% electrical to 85% electrical and 15% thermal. The elevated temperature also increases the efficiency of the cell, Bloom energy have predicted that this could lead in an overall decrease in energy required of 45% compared to traditional electrolysis.[viii]

High temperature electrolysers are in an early development stage. The only system currently commercially available is produced by Bloom Energy, however it is uncompetitive in regards to CAPEX compared to traditional electrolysers. The expected future gains in terms of cost reductions and efficiency increases render high temperature electrolysers the most interesting technology long term , this is even more important considering the large amount of waste heat rendered available by nuclear power generation.

A price and energy efficiency comparison of the various electrolysers can be seen below in figure 3.

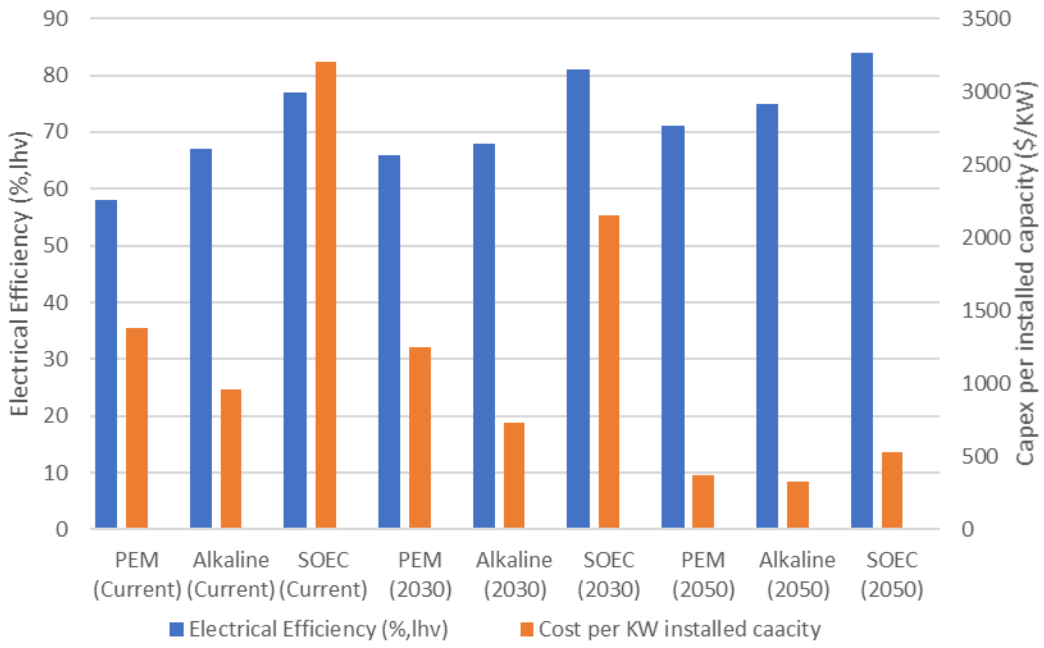

Figure 3. Comparison of electrical efficiencies and CAPEX per KW for various electrolyser technologies currently in 2030 and 2050. Data acquired from IEA[ix] and IRENA.[x]

The other technologies involved in the processes are more mature than electrolysis, in addition they have a much smaller energy footprint, as can be seen in figure 4.

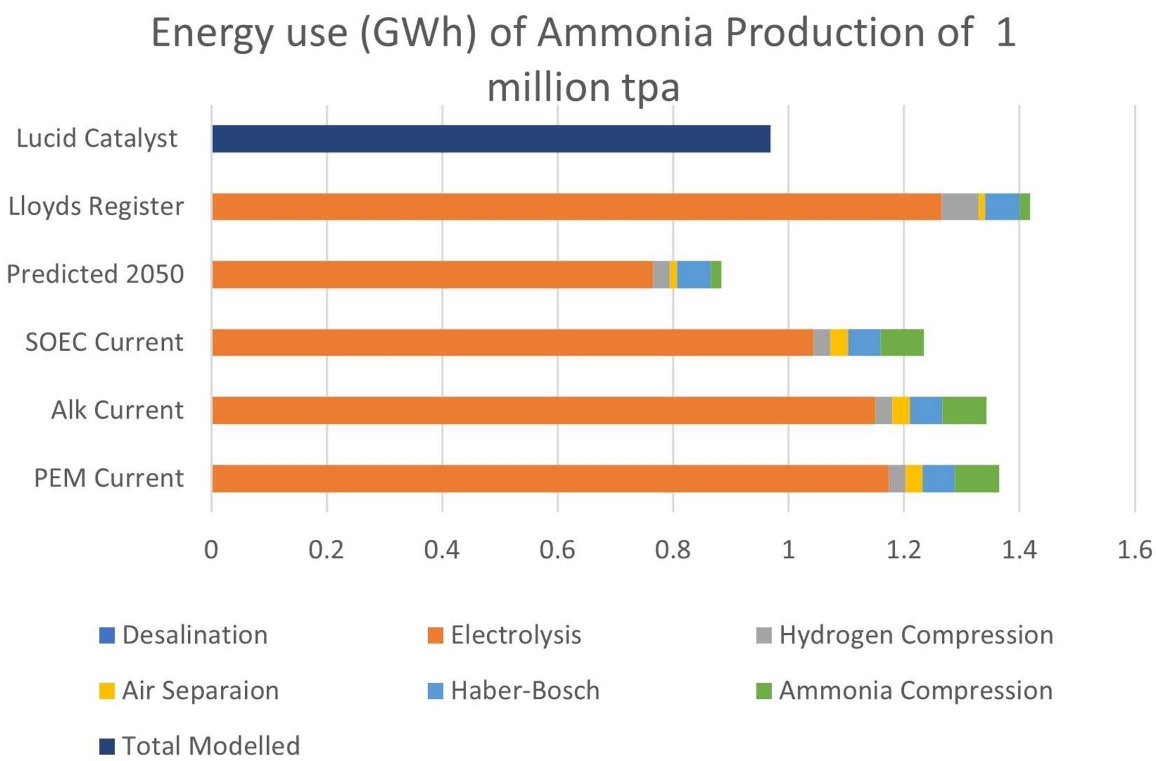

Figure 4 Comparison of modelling of a floating production facility for the production of 1 million tonnes of green Ammonia per annum by CORE POWER, Lloyds Register Decarbonisation Centre[xi] and Lucid Catalyst[xii].

Reverse Osmosis (RO) is the most widely used desalination technique worldwide, ranging from personal systems, such as the ones used on yachts, to large scale plants, such as those present in Saudi Arabia , capable of producing thousands of tonnes of fresh water per day. RO desalination operates by pumping sea water through a series of partially permeable membranes allowing water molecules to pass through but leaving behind the larger salt particles in a concentrated brine solution. The brine is them mixed with additional sea water and dispersed over a large area so as not to raise the overall salinity. The RO process is low energy compared to traditional desalination methods, as it only requires pumping the water through the membrane and the pipework, rather than the energy-intensive low pressure thermal process. In addition, the RO plant is much simpler to construct, maintain and manage.

The Haber-Bosch process has been used for over a century for the production of ammonia for various applications, in particular fertilizers. However, traditionally, it used 'grey hydrogen' obtained by means of steam methane reforming, which is highly polluting. Ammonia is synthetised by combining nitrogen and hydrogen at high temperature and pressure. The reaction process, once started, releases a large amount of heat, making it is self-sustaining and no longer requiring external heating. Haber-Bosch technology is very mature, and recent developments have allowed the size and footprint of the equipment to be reduced, allowing modularity and the feasibility of integration on marine structures and FPSOs.

Nitrogen constitutes 78% of air, making direct nitrogen capture from air a simple and effective process. The process uses either pressure swing or membrane methods these are highly mature technologies unlikely to see major future development.

The most important choice in the design of an ammonia production facility will be that of the electrolysers, as they constitute the major footprint as well as electrical and financial costs of the system. While at the moment PEM electrolysers are the most promising option, expected future developments in technology could make high-temperature electrolysis the most power and cost-efficient option. While marinising these process' will certainly require development, the experience of the oil and gas industry in moving operations offshore suggest that this can be achieved.

Potential Designs and operating procedures

CORE POWER foresees the floating production of ammonia to consist of a few separate yet interconnected installations. This ensures the highest possible safety when working with both hydrogen ammonia and nuclear power as the various risk areas will be separated preventing any adverse interactions. The final product would then be transferred to either feeder vessels or bunker barges limiting the chance and risk of collisions between assets. These facilities would be conceived to operate within the territorial waters of a host nation thereby within its national nuclear regulatory regime.

The offshore industry has seen an increasing variety of structures designed on the basis of site-specific factors including water depth and operational weather conditions. Possible structure for consideration include a gravity-based structure where a hollow concrete shell can either be floated and then tethered or sunk so they rest at the bottom of the seabed. This type of structure has already been used for floating LNG terminals in the Adriatic. Other structures that could be considered are more traditional oil rig structures as well as FPSOs and floating cylindrical structures for use in areas of more intense weather activity.

Figure 5 A variety of possible structure designs for a floating "atomic sea plug". Top Left) The Prelude LNG facility operated by Shell of the Coast of Australia is based on a traditional ship hull. Top Right) The Adriatic LNG Terminal, a concrete gravity-based structure that rests on the seabed. Bottom Left) Sevan Wisting design for floating cylindrical hull design for use in ultra-deep deployments Bottom Right) Ekofisk Field Centre operated by Phillips's petroleum in Norway a shallow water deployment <100m

The Ammonia producing portion of the facility could again draw on the experience of the oil and gas industry. Recent developments have seen LNG processing facilities being deployed on ultra large ship hulls. The most notable example of this is the FLNG Prelude built and operated by Shell off the Australian coast, while this is by far and away the biggest of these vessels several smaller vessels are in development off the African coast. One or more of these ammonia production vessels could be co-sighted near the installation housing the reactors.

These assets would be able to be deployed where there is a high demand for green ammonia, green hydrogen or desalinated water or any mixture of the three. Sites could include major shipping ports such as the area around Rotterdam and the channel ports as well as major industrial clusters where hydrogen or ammonia is required such as Antwerp which is also close to a major airport. An example of where different offtakers are present is Houston, which is discussed below in more detail.

Why intermittent renewables are not an alternative

The key benefit of the CORE POWER system compared to current suggestions that electro fuels could be made either stranded or specifically co-sighted renewables is the dispatchability, security and reliability of nuclear power. An atomically powered offshore facility could have a capacity factor of upwards of 90% far exceeding what is possible from renewables, even when considering pairing renewable assets with large scale storage. The cost of nuclear is also competitive when whole system cost of renewables is considered.

Table 1 Capacity factors of utility scale generators in the US in 2020[xiii]

Generation Method	Capacity Factor
Nuclear	93 %
Gas (Combined Cycle)	57%
Hydro	41%
Coal	40%
Wind	35%
Solar	24%

The capacity factors for dispatchable sources, like nuclear and fossil fuel plants, are dependent on the way in which the electricity is used in the grid, while for variable renewable energy sources they depend on the weather. Nuclear operates as baseload power providing constantly priced highly dispatchable power for the grid. Wind and Solar produce what they can when the weather conditions are correct. In particular the above table, shows how poor intermittent renewables are at providing reliable power, producing only at 37 and 25% of their rated capacity. This energy shortfall must therefore be made up from other energy sources.

Hydro power and gas fired plants are increasingly being used to stabilize electricity grids, ramping up and down to compensate for the variable energy output of wind and solar plants. This means that deployment of renewables does not immediately and directly translate in a reduction of pollutants and greenhouse gas emissions, as significant use of fossil fuel plants is still needed. Germany is a noticeable case in point, where after the decision to switch off nuclear power plants and focus on renewables the country remained heavily reliant on coal for its energy needs.

The second consequence is that renewables powered process cannot run at capacity, as they would be constrained to operate when renewable energy is present, and at a rate compatible with the actual quantity of renewable energy available. It is unthinkable that in the age of just in time logistics, shipping, civil aviation, and industry will simply sit and wait for wind and solar to generate enough energy to produce green fuels, the missing capacity will therefore be covered by fossil fuels making the fuels no longer green. Alternatively an atomically powered ammonia FPSO could operate continuously at rated capacity providing a reliable, secure production of green fuels.

Drawing energy from the grid will also present an uneconomically feasible prospect for the creating of e-ammonia. While much has been made of the decreasing production cost of renewable electricity over the last decades, this cost to produce does not take into account the ancillary costs these generation methods cause to grid management. Renewables need extra resources to balance the grid due to their intermittent nature as well as a requirement to ensure there is sufficient standby power when weather effects render the renewable assets non-functional. The efforts to decarbonise the worlds electricity supply are predicted to increase cost due to these factors, for instance the EIA predicted that the price to industrial users of electricity will increase 7% between 2020 and 2023.[xiv]

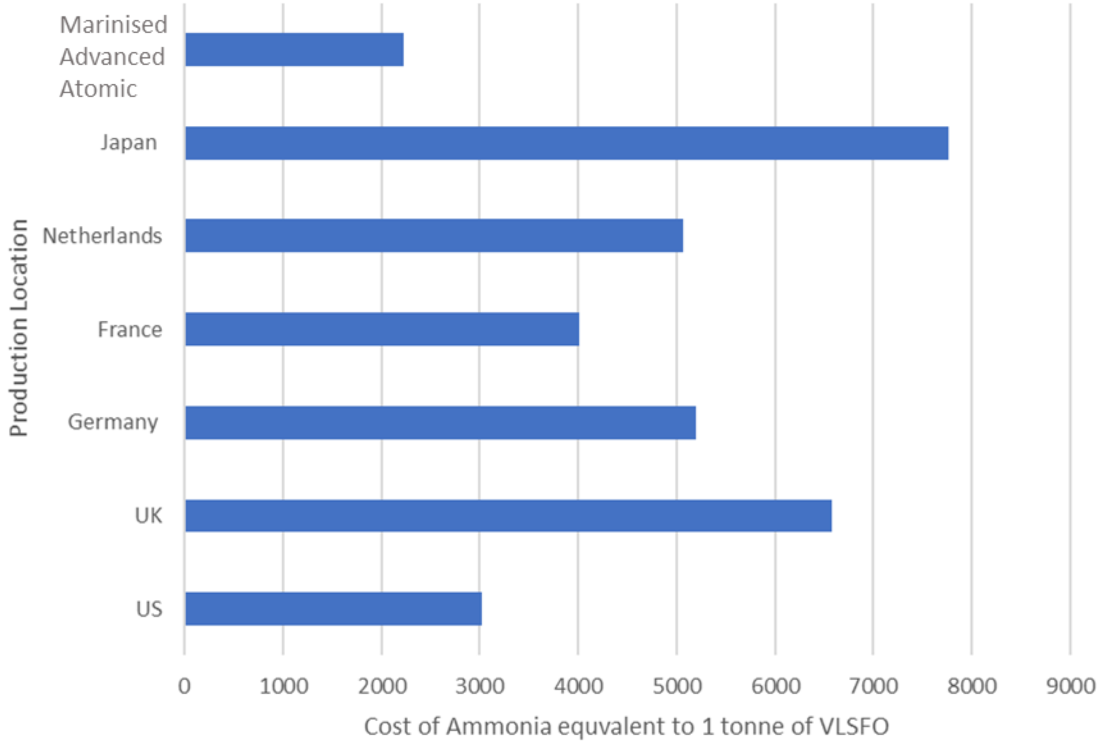

Figure 6 Price comparison for green ammonia production equivalent to 1 tonne of VLFSO using PEM electrolysis and the average electricity price for various countries and a predicted cost for marinised advance atomic of 50 $/MWh other electricity prices taken from Global Petrol Prices.com.[xv]

Figure 6 shows a cost comparison of producing ammonia equivalent to 1 tonne of VLFSO in various different nations, as well as using offshore advanced atomic.

Countries with cheaper electricity can produce cheaper "green ammonia. These countries can be broken into two categories: those with a highly polluting electricity mix based on abundant national coal and gas, such as the US, and those with a large amount of nuclear, such as France. Countries relying on intermittent renewables topped up with fossil fuels or those with high reliance on fossil fuel imports have much higher electricity costs and therefore ammonia prices.[xvi] Renewables may have a role to play when co-sighted with marinised reactors to provide extra power at peak times.

The above calculations were made using the hydrogen and ammonia price calculators now available in the client partner section of the Core Power website. These allow ammonia price comparisons based on a variety of factors, including carbon tax and electricity cost.

The case for offshore over onshore

Atomic marine facilities have several key advantages when compared to land-based installations. Deploying at sea allows nuclear power plant production to move from one of a kind on-site production to n^{th} of a kind factory manufacturing and shipyard fabrication. Shipyards are extremely efficient at fabricating large structures and assets to high safety standards in production line like setups. This offers the opportunity for modular repeated construction that will reduce the time and cost involved. The nuclear industry has traditionally suffered from high costs due to each build being a first of a kind design especially in western

Europe and America. The experience of both Korea and China of repeatedly building the same reactor type however has shown that significant cost savings can be achieved by repeated construction of the same design, the data for South Korea can be seen in figure 7.

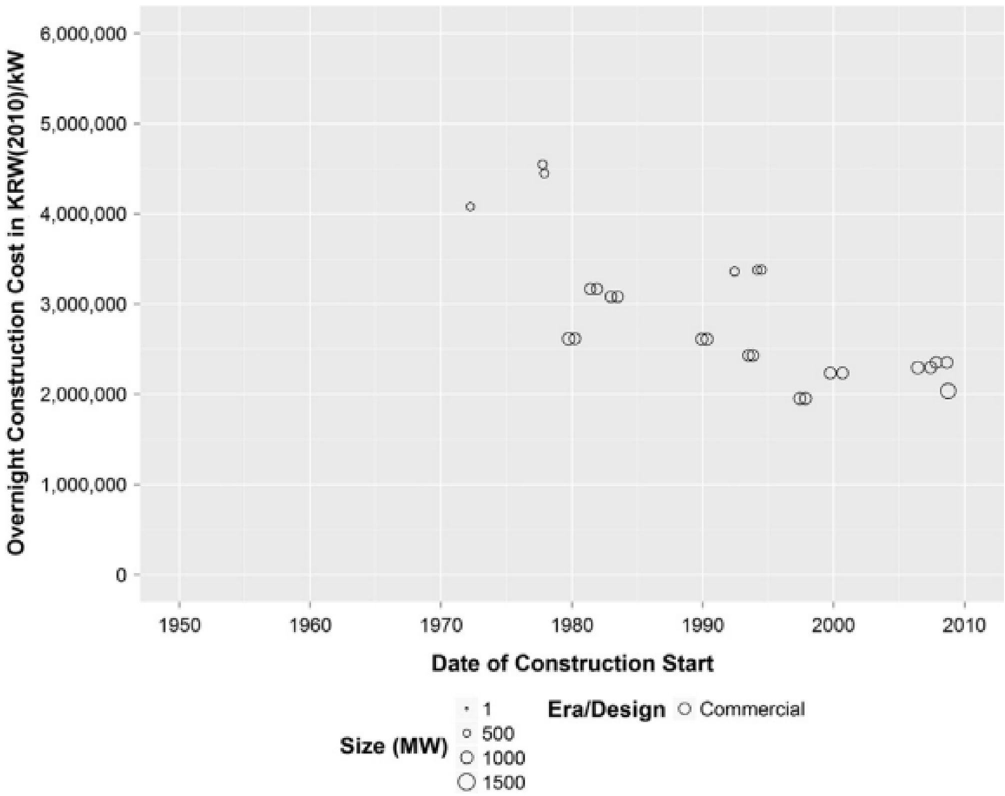

Figure 7 Graph showing the decrease in construction cost of Korean reactors per KW of installed over time showing the significant decrease in cost per KW that can be achieved with repeated builds.[xvii]

Moving to shipyard construction will allow even further reduction in costs. By reducing the size of the reactor and moving the reactor construction to specific factories, it will be possible to implement modular manufacturing methods including the increased use of automation as well simplification of the logistics of the reactor components supply chain. It will also mean improving quality assurance and quality controls.

The further benefit offered by the marine reactors is the flexibility in deployment locations. Land-based deployments are limited by factors including land cost, geological suitability, and the potential opposition of local residents. By moving offshore all these factors are significantly reduced.

They also allow the possibility of changing the assets location during its lifetime. It is conceivable to foresee a situation whereby an asset acting as a terminal for the export of mining or oil could be relocated as new areas undergo extraction and older areas are decommissioned. This would mean there would be no additional sailing requirement for vessels to bunker saving time, money, and fuel.

The next generation of reactors will still require cooling and placing the reactors at sea gives them access to the world's largest heat sink, vastly simplifying the cooling requirements for the reactors.

A final benefit of marine deployment is the ease of return to green field: it will be possible to tow the asset to a specialist nuclear site for decommissioning where the nuclear components will be removed, for recycling and disposal. Then no-longer-nuclear floating structure can be towed to a traditional scrapyard facility for final scrapping and disposal. This will allow a vast decrease in the costs associated with the decommissioning of nuclear sites. The scrapping industry for shipping and offshore facilities is already highly developed and efficient, especially when compared to the traditional nuclear industry where every site is a 1st of a kind decommissioning process.

Why floating green ammonia production is the best option

The other potential methods for the production of Ammonia that have been suggested rely on either dubious claims on carbon neutrality or from limits in scalability.

Current discussions within the hydrogen space have pointed towards blue hydrogen as the solution for the manufacture of hydrogen, whereby CO_2 is captured and stored from the existing steam methane reforming process. However, this proposal relies on both the ability to capture all the emitted carbon dioxide, which is yet to be demonstrated at scale despite significant investment from the oil and gas industry, as well as the ability to store indefinitely the captured CO_2. The carbon capture process itself is also quite energy-intensive, meaning that additional energy is needed to capture the produced carbon, reducing effectiveness even further. Carbon storage options are currently early in development and are mainly based on pumping CO_2 into oil extraction sites that will then be plugged. The leakage rate that may arise from these sites is currently unknown.[xviii]

Finally, by moving the production of ammonia offshore, the negative effects of non-climate change emissions are reduced. While the effects of emissions on atmospheric climate change are often the major area of environmental concern, there are also other emissions that have negative effects both on human health and the environment. Research suggests that moving emissions offshore can lead to a 30% reduction in negative externalities, reducing damage to both the environment and human health.[xix]

Example deployment a green corridor from Houston to Rotterdam

At Cop26, 22 countries came together to sign the Clydebank declaration which sets out an aim to provide green shipping corridors between the signatory nations. Two of these signatory nations are the USA and The Netherlands.[xx] Exports from Houston, Texas, to northern Europe account for 21% of all exports from the Houston harbour.[xxi] Ammonia FPSO's at either end of this route could allow the decarbonisation of all sub 15 MW propulsion power vessels, that will not be suitable for atomic propulsion.

Figure 8. The Route of the MSC NEUAL1 showing a transit from the Southern US to Rotterdam.

Houston is not just a major port but also a major industrial area for the oil gas and chemical industries as well as a major air transport hub offering an on the doorstep market for the energy and hydrogen by the ammonia producing FPSO facility.

Projections of benefits for Ammonia FPSO deployment

CORE POWER has modelled the potential benefits of an ammonia producing FPSO structure in Houston. Currently there are approximately 328 transits of vessels of a size not suitable for atomic propulsion between Houston and Rotterdam each year[xxii], though they may also call at other ports at either end of the journey. These vessels are mostly chemical tankers transporting crude oil derived products from the Houston industrial cluster to manufacturers in Northern Europe.

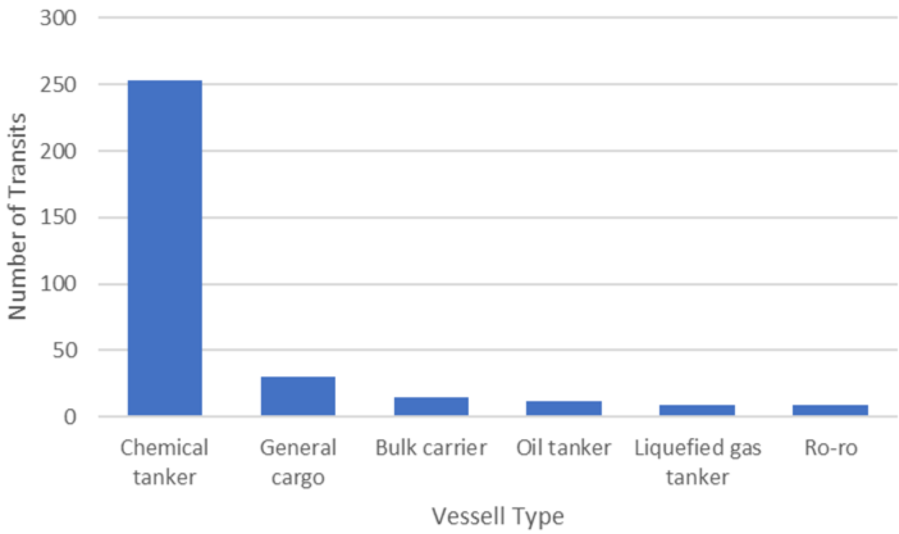

Figure 9 . Summary of sub-15MW (20,000 hp) engine power vessels transiting between the Houston and Northern European poets per annum by vessel type.

Assuming a vessel speed of 15 knots the average transit time between Houston and Rotterdam would take 17 days. These vessels are estimated to burn 25 tonnes of VLFSO per day, meaning per year these vessels use approximately 155,000 tonnes of VLFSO producing 490,000 tonnes of CO_2 .[xxiii] To replace this VLSFO would require the production of 352,000 tonnes of green ammonia, well within the operating window of the proposed FPSO facility. Current estimates of ammonia operations suggest that around 4% of the fuel weight would still be required to be VLFSO to operate as pilot fuel i.e. approximately 14,000 tonnes. This would lead to CO_2 emissions of 44,000 tonnes: a 91 % reduction, significantly exceeding the goals set by the International Maritime Organisation.[xxiv]

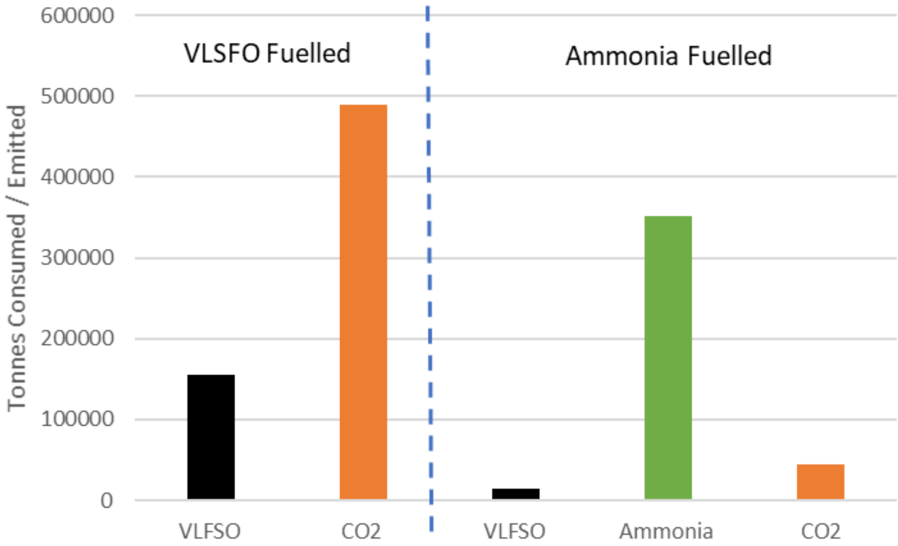

Figure 10. Comparison of emissions and fuel consumption for transits by sub 15MW propulsion power vessels between Houston and Rotterdam annually.

The proposed facility would also be able to offer both hydrogen and ammonia to industrial and aviation users in the wider Houston area providing an alternative revenue stream as well as providing ammonia for the decarbonisation of internal US shipping, which will be discussed in CORE POWER's February report.

While the current modelling only considers a facility at Houston it is possible to conceive of a network of these similar facilities deployed in strategic shipping hubs, such as Rotterdam, New York, Barcelona etc. This would allow the full decarbonisation of transatlantic trade, while also providing power and electro fuels to local industrial and aviation customers.

A CORE POWER facility, therefore, would offer a major environmental and economic benefit to the Houston area, allowing the US to meet its climate goals while ensuring the long-term economic health of the area as it transitions to net-zero. The US government is currently looking to massively increase the amount of hydrogen produced as part of its earth shots program and a Houston based facility could play an important role in this.[vi]

Conclusions

The CORE POWER design for a floating atomic ammonia producing FPSO could play a significant part in the decarbonisation of both international shipping and well as the difficult to electrify heavy industry and aviation sectors. CORE POWER is investigating a range of potential technologies for the production of hydrogen from seawater and is currently focusing on PEM and SOEC electrolysers. SOEC is especially interesting as it opens the opportunity to use heat energy rather than electricity alone. This will allow the production of cost-competitive ammonia for use in ships, although this would still exceed the cost of directly using marine molten salt reactors for larger ships.

Production modelling of these facilities shows that using a 1.2 GW of electricity it would be possible to produce 1 million tonnes of green ammonia per annum.

CORE POWER's proposal has the advantages of being truly zero-carbon, economic, and scalable to the need not only of international shipping, but also for markets such as domestic shipping and industry as well as civil aviation. In addition, it would be possible to site the assets right at the point of bunkering, thereby providing a large simplification of the logistic chain, and greatly reducing the need for transportation.

The atomic FPSO is the only effectively scalable option for the production of truly "green fuels". While the use of intermittent renewables seems like an attractive option on paper their lack of reliability makes them wholly unsuitable for the provision of fuel for such a time-sensitive industry. Renewables could integrate well with nuclear power facilities to provide power during periods of peak demand especially in deployments near to major industrial or population hubs.

Moving these facilities offshore also has considerable benefits in the ability to gain efficiencies from shipyard construction as well as no longer requiring expensive civil engineering work in either construction or decommissioning.

The deployment of atomically powered ammonia FPSO's is the best option for the production of green e-fuels being truly carbon neutral as well as scalable for the amount of fuel needed by industry.

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