Sailing on Solar

Could green ammonia decarbonise international shipping?

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Environmental Defense Fund

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Ricardo

At Ricardo, our vision is to create a world where everyone can live sustainably: breathing clean air, using clean energy, travelling sustainably, accessing clean water and conserving resources. Adopting green ammonia as a shipping fuel would bring the world closer to these ideals.

Since the 1950s, Ricardo has worked to deliver improvements in air quality and pioneered the use of renewable energy technologies. We are currently working on the implementation of the Paris Agreement on climate change, helping countries to realise their plans for reducing greenhouse gas emissions.

Our founder, Sir Harry Ricardo, set out on a mission in 1915 to ‘maximise efficiency and eliminate waste’. In accordance with this mission, we aim to use our world-leading expertise to assist the maritime transport sector in facilitating global economic development sustainably.

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Foreword

Fred Krupp

President, Environmental Defense Fund

In the last decade we have seen enormous changes in energy markets around the world. Falling costs of renewable energy technologies like wind and solar have opened up vast new markets. Shipping, which accounts for 2.6 percent of global emissions and is projected to increase by 50 to 250 percent by midcentury without action, is one such potential market.

New marine fuels, derived from abundant renewable resources in countries around the world, could provide a crucial future opportunity to tackle shipping's contribution to global climate change. Such a transition would also bring potential development gains. Ports and shipping already underpin many countries' economic growth; if shipping becomes a reliable source of demand for clean solutions, it can also provide the impetus for large new investments in energy projects.

The paper explores one of those potential new fuels: "green ammonia," which can be synthesised from solar power, water and air, provided that this is additional renewable capacity and does not increase fossil fuel use. A detailed case study brings the concept to life.

Of course, there is no silver bullet; a range of solutions will be needed to effectively address the climate challenge. No group of experts can identify today, with certainty, the precise technology pathway that can achieve our climate goals. The policy challenge – and the opportunity – is to create the economic incentives that will encourage deployment of the most cost-effective solutions available today and unleash innovation in the technologies of tomorrow.

The most important contribution of this report, therefore, is to show that solutions are on the horizon. As the following pages clearly demonstrate, the technological barriers to eliminating the climate impact of shipping can be overcome and also have potential to drive investment in developing countries. What is required to make this a reality are policies that create economic incentives to unlock investment. Strong policies are also needed to ensure that the development of new energy resources is sustainable and that all emissions impacts are robustly accounted for throughout the full lifecycle in order to maintain environmental integrity.

The International Maritime Organization (IMO) has agreed to cut greenhouse gas emissions by at least 50% by 2050, and is now exploring polices that can achieve that goal. Environmental Defense Fund has commissioned this report to inform those discussions and to highlight one of the many available options to ensure a smooth transition to low carbon shipping which benefits developing countries.

We are excited about the potential to both eliminate shipping's impact on climate change and unlock green economic development around the world. Well-designed policies introduced under the IMO can deliver reductions in greenhouse gases while ensuring environmental integrity. We are committed to help bring these into being as soon as possible.

Executive summary

Introduction

‘Green ammonia,’ produced using renewable electricity, is a fuel that does not emit greenhouse gases at any point in its product lifecycle and could play an important role in achieving the International Maritime Organization’s decarbonisation goals. Until recently, there has been little motivation to explore green ammonia as a maritime fuel. However, the International Maritime Organization’s goal of reducing greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008 levels means that greenhouse gas-free fuels need to be adopted starting in the 2020s. Green ammonia is one candidate fuel that needs to be considered.

For an industry now familiar with fossil fuels, the idea of ammonia as a fuel may at first appear strange, daunting or even dangerous. This paper uses existing scientific data, basic chemistry, engineering knowledge and practical experience to show that green ammonia can – indeed should – be adopted as a greenhouse gas-free fuel more easily, quickly and safely than people may assume.

This paper explores the idea of establishing a green ammonia supply chain at the scale required for international shipping and shows how the technical and economic barriers can be overcome using existing proven technology.

Decarbonising shipping through green ammonia offers an investment opportunity for developing nations

The thesis of this paper is that widespread adoption of green ammonia will require investment in sustainable industrial infrastructure, including renewable electricity plants, to support a supply chain that is distributed around the globe. Countries around the world could benefit from this investment opportunity, especially developing countries with abundant renewable energy resources.

One of the key barriers to the development of large-scale renewable electricity plants in developing nations is uncertainty about the income from the sale of electricity due to lack of demand for electricity or the low creditworthiness of potential purchasers of bulk electricity. However, demand for green ammonia as a maritime fuel could provide a dependable long-term revenue stream – supported by long-term supply agreements – to unlock investment in renewable plants in developing nations. Morocco is presented as a hypothetical case study of how this might be achieved.

The potential benefits of green ammonia have been analysed on a lifecycle basis

The use of green ammonia in shipping can be truly emissions free on a lifecycle basis if the energy inputs used to make it are 100% emissions free with no additions from a grid supplied by fossil fuel generators. In addition, the renewable electricity should be supplied from sources that are not currently utilised due to: the absence of reliable sources of demand that can justify investment in exploiting the renewable resource at scale; or curtailment because of a generation profile that exceeds demand at different times. If neither of these criteria is met, the higher energy demand involved in converting the electricity to a storable fuel will reduce the environmental benefit that would otherwise arise from using the renewable electricity to replace existing electricity demand met with fossil fuels. Given the relatively high costs of early renewable power-to-fuel projects, its use will only be commercially feasible through dedicated policy support that expressly seeks to achieve both development and climate goals.

Ammonia is a commodity that is already produced and shipped on a global scale

Demand from the international fertiliser industry has created a global market for ammonia so that it is already produced and shipped on a global scale. Therefore, there are established standards for the safe handling, storage and transport of ammonia in bulk on ships. However, most of the ammonia on the global market is produced from fossil fuels, creating harmful greenhouse gas emissions. From a product lifecycle perspective, ammonia from fossil fuels would offer little or no environmental benefits if used as a shipping fuel.

Rather, green ammonia is produced using surplus or untapped renewable electricity sources, water and air; resulting in near-zero lifecycle greenhouse gas emissions. Commercially available technologies are used in its production, with reference plants in operation today and some dating back to the first half of the 20th century.

Green ammonia offers many advantages over other maritime fuels

Green ammonia was selected as the focus of this study over other maritime fuels (e.g. hydrogen and battery storage; acknowledging that all should be explored) because it provides the following advantages:

- It has existing global logistics infrastructure (unlike hydrogen).
- It does not require cryogenic storage (unlike hydrogen).
- It is relatively energy-dense as a liquid, providing sufficient energy storage for ship voyages lasting several weeks (unlike batteries).
- It provides flexibility as it can be used without complicated onboard processing in internal combustion engines and in future fuel cells.
- It has a risk profile that can be managed with existing standards and procedures.

Ammonia can be liquefied at a reasonable temperature (-33°C (-28°F)) or moderate pressure (1MPa (10 bar)), whereas hydrogen requires cryogenic storage at -253°C (-423.4°F). This means that ammonia requires less energy than hydrogen to liquefy, store and evaporate. In addition, liquid ammonia requires 46% less onboard storage space than hydrogen and poses a lower fire risk (it has a narrower flammability range and higher ignition temperature).

Adoption of green ammonia ideally will need to begin during the 2020s if the decarbonisation timetable is to be achieved. Given that the shipping industry is built on the use of large diesel engines, the use of green ammonia in engines is the most likely initial entry point for the fuel, with engine development for ammonia-firing ongoing. A major manufacturer has also stated that it is possible to upgrade some existing dual-fuel engines to operate on ammonia. This makes green ammonia a flexible fuel option, with further development ongoing to optimise engines to match engine performance on fossil fuels. Operation on 100% ammonia is possible, but in the short term, an additional fuel might be required to support combustion (whether hydrogen, diesel, liquefied natural gas or liquefied petroleum gas).

From a greenhouse gas emission perspective, use of hydrogen as a support fuel would be most desirable because neither fuel contains carbon. It is possible to separate hydrogen from the ammonia stream prior to mixing in the engine, so a separate hydrogen tank would not be required.

Another option is to use ammonia as a ‘hydrogen carrier’, where hydrogen is extracted from the ammonia at the point of use (e.g. in a fuel cell), to capitalise on the relative ease of storing ammonia.

When it is used in internal combustion engines, ammonia produces nitrogen oxides. Selective catalytic reduction equipment can be used to reduce these emissions, similarly to new fossil fuelled vessels in complying with Tier III requirements of Emission Control Areas. In fact, selective catalytic reduction equipment requires either ammonia or urea onboard to function, so new vessels operating in these areas would already need systems and standards to handle and store ammonia or urea anyway.

Ammonia has an achievable adoption roadmap, initially with traditional engines and later in fuel cells

There is a clear pathway to adopting green ammonia as a fuel in the next few years using engines, which are familiar to the industry. The aim in the longer term is to use fuel cells for propulsion so that even emissions of nitrogen oxides and particulate matter are eliminated. The necessary solid oxide fuel cell technology is not yet commercially available for marine applications, but with further development it is expected to be viable in the 2030s.

Transportation and storage of ammonia on ships is established primarily through existing industrial applications. Bulk ammonia transport vessels (usually liquefied petroleum gas-carriers) are designed according to the requirements of the 2014 International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). Some minor adjustments would be required to equip vessels to operate with ammonia as a fuel. Ammonia is corrosive to some substances such as copper, brass and zinc-containing alloys as well as natural rubber and some plastics. Material compatibility requirements are well understood and it is straightforward to select suitable materials to avoid damage to onboard equipment, piping, valves and other fittings.

The safety risks associated with ammonia are well understood and manageable

All fuels are hazardous in some way or another, and ammonia presents a different set of hazards to the alternatives. It is less flammable than other fuels, so poses a lower fire risk and risks from cryogenic burns are lower than for liquid hydrogen or liquefied natural gas.

As ammonia gas is toxic and corrosive, the existing safety principles and systems used throughout the global ammonia industry would also need to be deployed on ships such as gas detection systems and appropriate chemically resistant protective clothing. Ammonia has a strong odour and should be detectable if there is a leak.

In marine environments, a release of liquefied ammonia would float on the water surface, rapidly dissolving into the water body as ammonium hydroxide, and at the same time releasing gaseous ammonia. In dry air, gaseous ammonia would evaporate upwards and be dispersed by the prevailing wind conditions. The impacts on local populations (human, plant, animal) and aquatic life would depend on the quantities released.

Adopting green ammonia could stimulate investment of up to 6 trillion U.S. dollars by 2050

A high-level financial analysis estimates that a total investment value of up to 6 trillion United States dollars would be required in green ammonia plants and renewable energy plants around the world to decarbonise the international container vessel and non-coal dry bulk carrier fleets (which together represent approximately 40% of international shipping) between now and 2050. This scale of investment – underpinned by demand from a global industry – presents an opportunity for developing countries around the world to attract investment in sustainable industrial growth. This would have positive effects on economic growth through the creation of jobs and the establishment of supporting supply chains and services. It would also catalyse investment in port and bunkering infrastructure distributed around the world.

The cost of producing green ammonia is sensitive to the price of electricity. So, it can be expected to fall with continued reductions in the price of renewable electricity, as generation technologies improve in efficiency and benefit from increased economies of scale.

Considering green ammonia's potential to assist in decarbonising the maritime transport sector, shipping nations need to discuss the path of adoption and the approach to distributing the associated costs as a matter of urgency. Early adopters of zero-climate-impact fuels will be paying more per nautical mile than competitors that use fossil fuels, at least initially. Therefore, a mechanism will be required to incentivise the development and deployment of zero carbon fuels and avoid inadvertently penalising early adopters. The renewable electricity sector is an example where this has been done successfully. Clean technologies have become cost competitive with fossil fuel alternatives in a matter of years thanks to various policies.

Conclusions

Green ammonia is a technically feasible solution for decarbonising international shipping. It is a fuel that can be combusted in engines and used for fuel cells in the future. The pathway to its deployment can begin using technologies familiar to the maritime sector: diesel or dual fuel engines in new and existing vessels. To make a success of this pathway, certainty for the marine industry in building and retrofitting such vessels – and certainty for a green ammonia supply industry to manufacture at scale – needs to be provided by strategic and policy measures adopted by the International Maritime Organization. This would allow green ammonia and vessels that can accommodate it to be introduced within the timescales required to achieve the International Maritime Organization's decarbonisation targets, together with other zero and low carbon alternatives.

What is more, demand from shipping could unlock investment in the green ammonia supply chain, including low-carbon industry and renewable electricity. This represents a unique opportunity for sustainable economic development and distribution of bunkering infrastructure around the world, especially for developing economies rich in renewable energy potential.

Table of contents

CASE STUDY

Sailing on Solar: Unlocking sustainable shipping in Morocco[1]

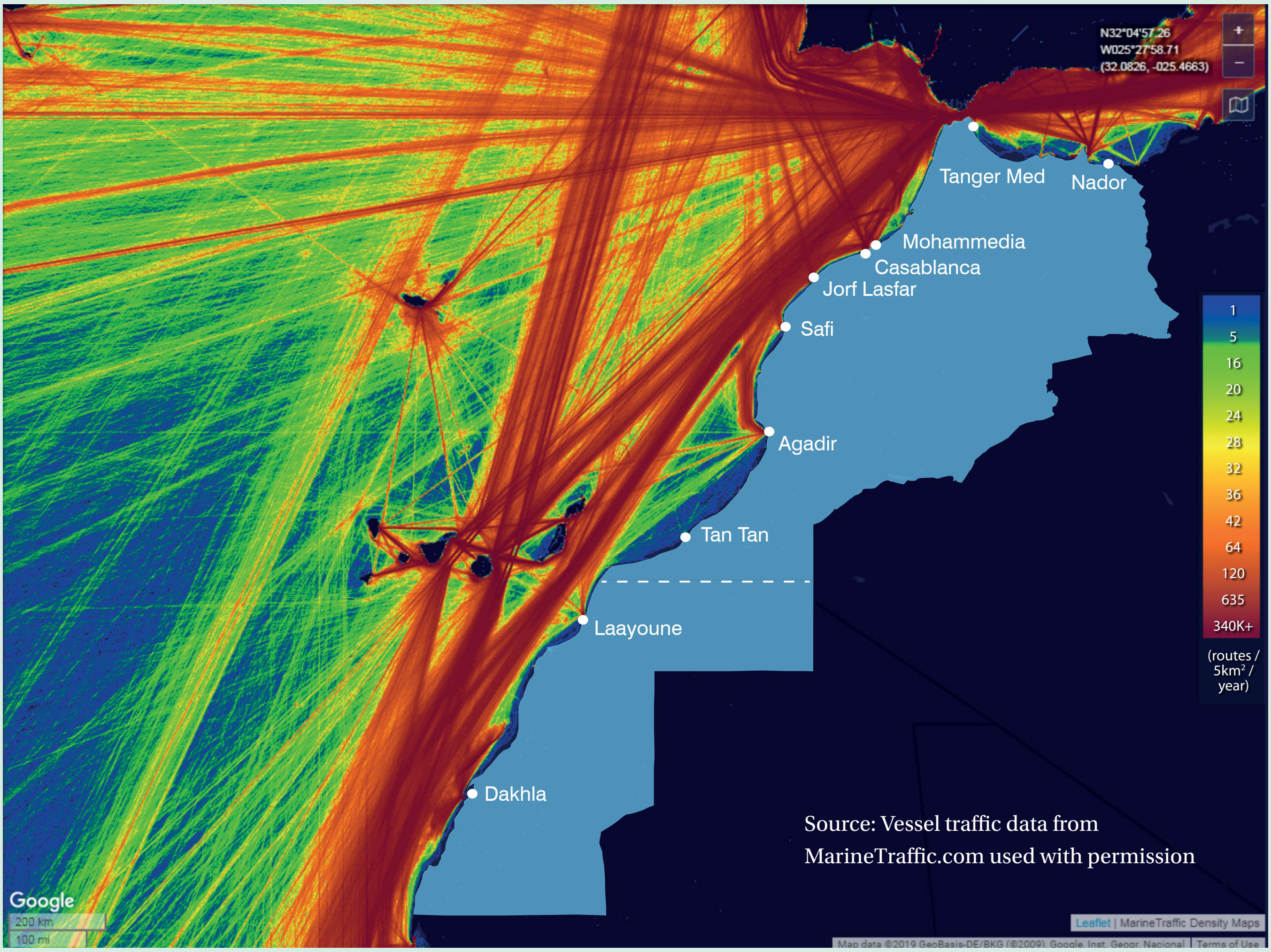
Morocco is well suited to foster a green ammonia industry

Morocco has abundant renewable energy resources and large commercial ports close to multiple key shipping routes. It is already investing in large-scale solar energy generation and has additional untapped potential. In this case study, we explore how the production and supply of green ammonia for shipping could unlock further large-scale investment in clean energy production in the country; fostering local sustainable growth while contributing to the international shipping sector's goal of at least halving its greenhouse gas emissions by 2050.

Morocco is strategically located at the Straits of Gibraltar, which is the key passage through the Mediterranean to and from the Suez Canal (see Figure 1).

FIGURE 1:

Shipping lanes past Morocco and its commercial ports



Source: Vessel traffic data from MarineTraffic.com used with permission

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[1] This paper follows the UN designation of Western Sahara as a non-self-governing territory as shown on all the maps in this report by a dashed line and expresses no position on the past, current or future governance of the area. This paper refers to the entire area as "Morocco" for ease of reference.

It is also on the routes between Europe and South America as well as West and Southern Africa. Therefore, it is at a convenient location to provide bunkering to a large number of vessels on long voyages.

Morocco was ranked 33rd in the world for total container throughput in 2017 [1]. It has 10 active commercial ports [2] with the three main international container terminals located at Tanger Med (3.31 million TEU), Casablanca (0.99 million TEU) and Agadir (0.20 million TEU) [3, 4].

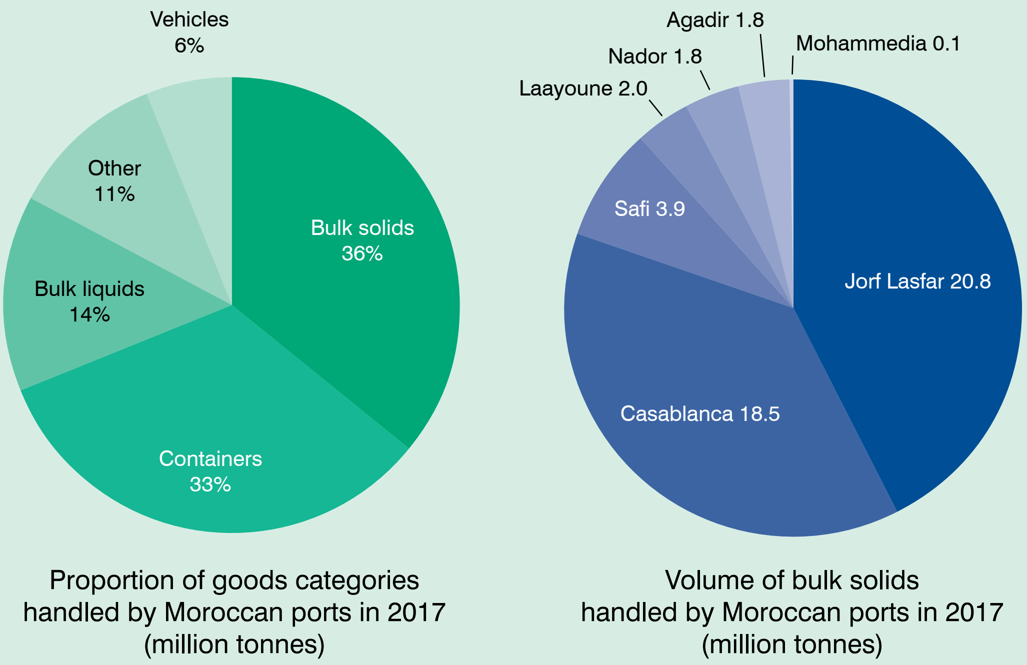
Tanger Med was ranked 46th in the world in terms of container traffic in 2017, the busiest in Africa [5] ahead of East Port Said in Egypt. Bulk solids and containers represent most of the cargo handled, as shown in Figure 2.

Renewable resources and ambitions in Morocco

Morocco is rich in renewable energy resources with a long history of generating electricity from hydro power at plants concentrated primarily in the north of the country [6, 7, 8, 9]. Although Morocco started building solar and onshore wind plants at utility scale only relatively recently, there is abundant solar potential throughout Morocco and significant wind potential, especially along the coast (where green ammonia plants would be located, see Figures 3 and 4). The maps indicate the significant potential for development of solar and wind plants in the areas around existing ports, especially Jorf Lasfar, Safi, Agadir, Tan Tan, Laayoune and Dakhle.

FIGURE 2:

Statistics of cargo handled at Moroccan ports in 2017



Sources: [3, 4]

The total potential for offshore wind along Morocco's coastline is reportedly 250GW [11], which is about 25 times the current total power plant capacity in the country and would provide enough electricity (770 terawatt-hours (TWh)) annually assuming a 35% capacity factor) to produce green ammonia for about a third of the international shipping fleet[2].

The map in Figure 4 indicates the abundant potential for solar power in Morocco.

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[2] Based on the 2012 fleet as reported in [24], the latest available data.

FIGURE 3:

Wind power density map and locations of existing and future wind farms

Sources: [6, 7, 8, 9, 10]

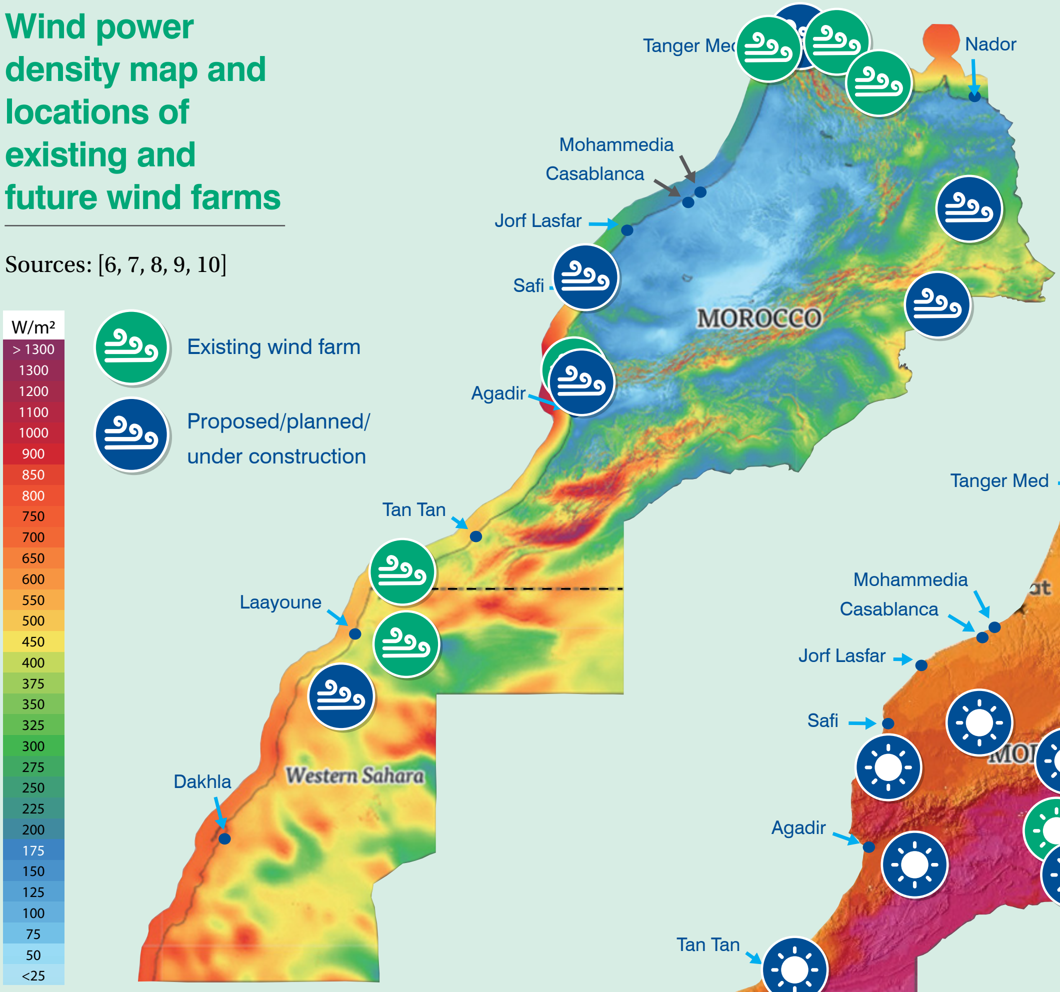
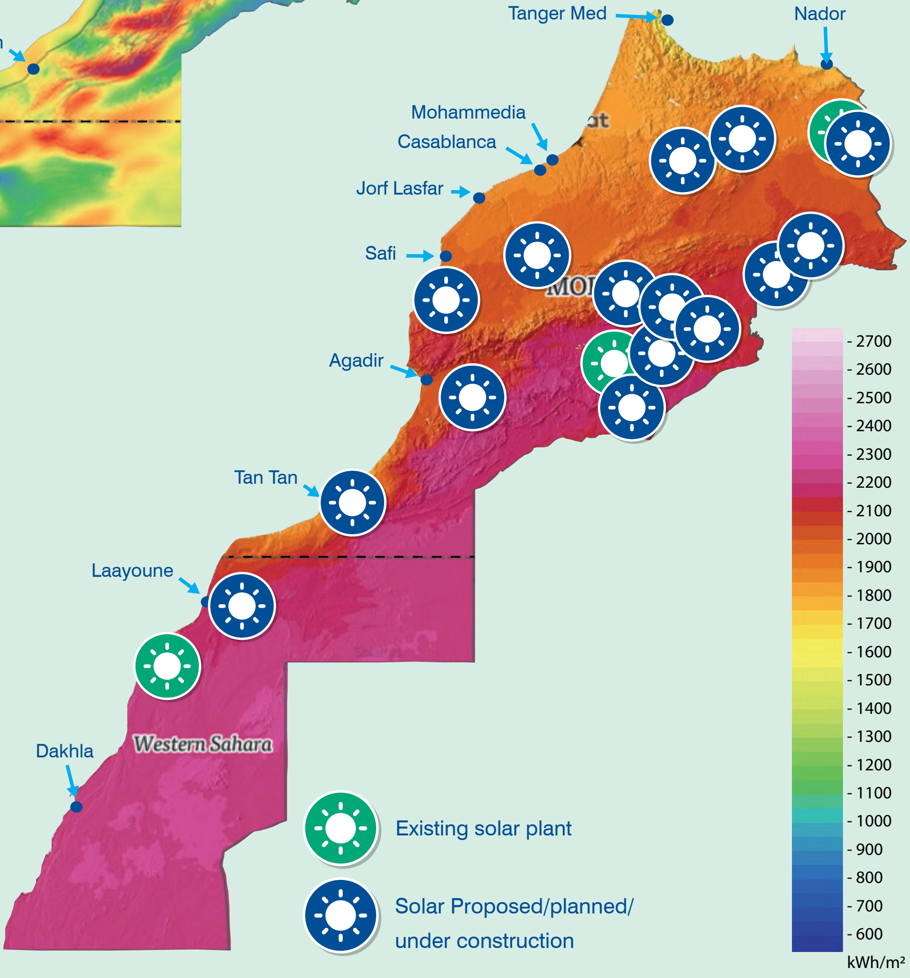


FIGURE 4:

Solar global horizontal irradiation map and locations of existing and future solar plants

Sources: [6, 7, 8, 9, 12]



The map in Figure 4 shows that there is great potential to scale up the number of solar plants to take advantage of large areas of land that have excellent solar resources close to the shore. This is especially the case in the Western Sahara region.

To capitalise on the potential for wind and solar power and reduce carbon emissions from the electricity sector, the Moroccan Government has committed to an ambitious plan to significantly increase the share of renewables in its power plant mix to at least 52% by 2030 [6, 13]. Although these plans already represent a significant change to the status quo, there is scope to significantly increase the amount of electricity generated from renewable sources beyond these figures, provided there is enough demand to justify the investment. The production of green ammonia for international shipping could provide that demand.

Possible ammonia production at Jorf Lasfar port

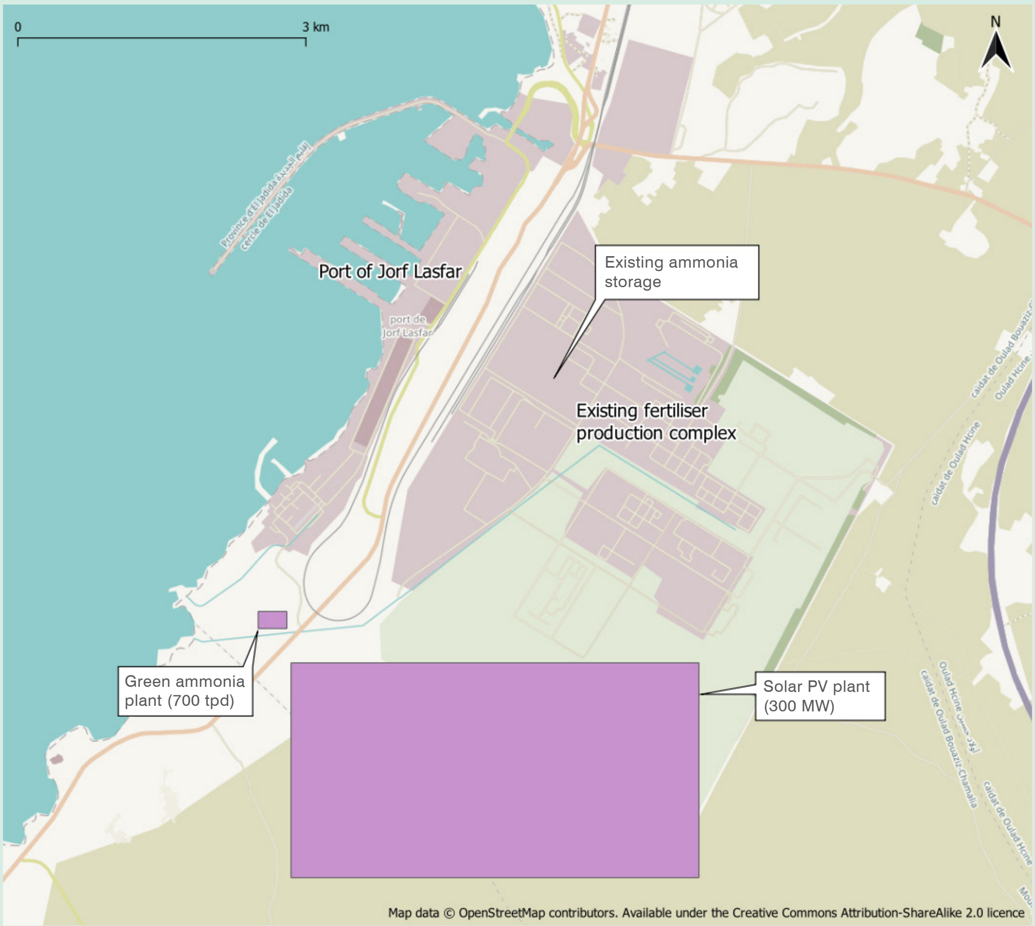
Morocco has an active and mature inorganic chemistry sector where phosphate plays a central role. Home to about 75% of the world's estimated phosphate reserves, Morocco is a leading producer and exporter of phosphorous and phosphate products [14]. The state-owned OCP Group dominates the phosphate industry in Morocco with large processing plants built near the ports of Jorf Lasfar and Safi [15]. Casablanca handles 82% of the volume of phosphates through Morocco's ports with Laayoune and Safi responsible for the balance [3].

Ammonia is imported through Morocco's ports for use in the production of ammonium phosphate fertiliser [16]. In 2017, Morocco's ports handled a total of 1.49 million tonnes of ammonia [3], which is the second-highest for a commodity shipped as a bulk liquid in the country (behind hydrocarbons).

The Jorf Lasfar port (see Figure 5) imports ammonia for use in a nearby OCP production plant. The imported ammonia is stored near the port in refrigerated tanks with a total capacity of 100,000 tonnes [17]. To give an idea of the scale in shipping terms, this is equivalent to the daily ammonia fuel consumption of about 570 post-Panamax vessels.

FIGURE 5:

Map of Jorf Lasfar port and existing adjacent chemical complex with indicative sizes of a green ammonia plant and associated solar photovoltaic (PV) plant



Map data © OpenStreetMap contributors. Available under the Creative Commons Attribution-ShareAlike 2.0 licence

Figure 5 also gives an indication of the size of the ammonia plant required to produce 700 tonnes of ammonia per day (tpd), which is equivalent to the daily fuel consumption of about 4 post-Panamax size vessels (see Figure 6). Based on the financial analysis presented in Section 6.2, a plant of this size could generate annual revenue of about U.S. dollars (USD) 194 million[3].

FIGURE 6:

A post-Panamax container vessel

There is significant land area available around the existing industrial complex for a green ammonia production facility and a solar plant. Since Jorf Lasfar is only about 100km from Casablanca, it could be an ideal location to establish a green ammonia production facility. Ships could dock at the port for refuelling or ammonia bunkering vessels could be used to transfer ammonia to Casablanca and other ports. Alternatively, ammonia bunkering vessels could refuel ships anchored offshore.

A green ammonia plant with a capacity of 700 tonnes per day consumes about 7,345 megawatt-hours (MWh) per day at an average rate of 306 megawatts (MW). As described in Section 3.2, there are many different approaches to supplying the remaining clean electricity required by the plant, so a detailed feasibility study would be necessary to determine the optimal solution. Jorf Lasfar has ample land and good solar irradiance, so a solar PV plant coupled with a concentrating solar plant with integral storage could work well. Figure 5 shows how big a 300MW solar PV plant would need to be as an example. The output from a 300MW solar PV plant will vary through the course of the day depending on the time of year because it can only generate electricity while the sun is shining, as shown in Figure 7. It would therefore be able to provide about 41% of the plant's requirements in summer and 26% in winter. This is why a concentrating solar plant with storage might be required in addition. Alternative options include importing electricity from other renewable plants through the grid or battery storage.

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[3] Based on an ammonia price of USD830/tonne, and electricity price of USD43.20/MWh, assuming that the plant operates for 8,000 hours a year.

How much green ammonia might be required?

The graph in Figure 8 gives an impression of the electricity required annually to produce green ammonia to fuel the vessels passing through Morocco's ports[4]. The graph shows how much electricity might be required to power different proportions of the container vessels and dry bulk carrier traffic serving Morocco.

FIGURE 7:

Theoretical daily production from a 300MW plant at Jorf Lasfar in the summer and winter months

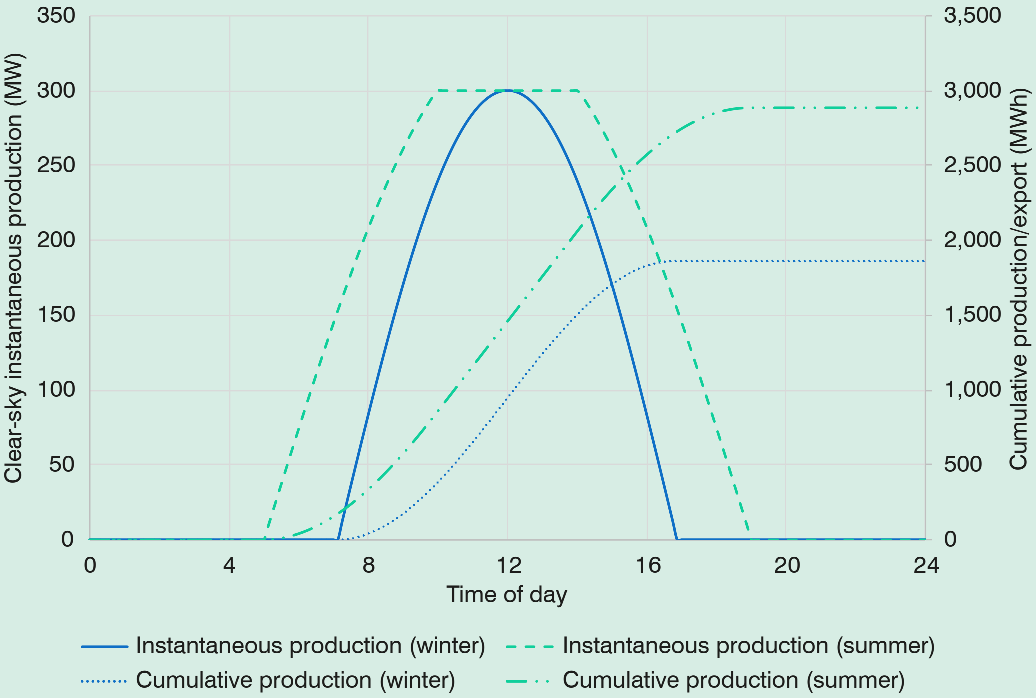
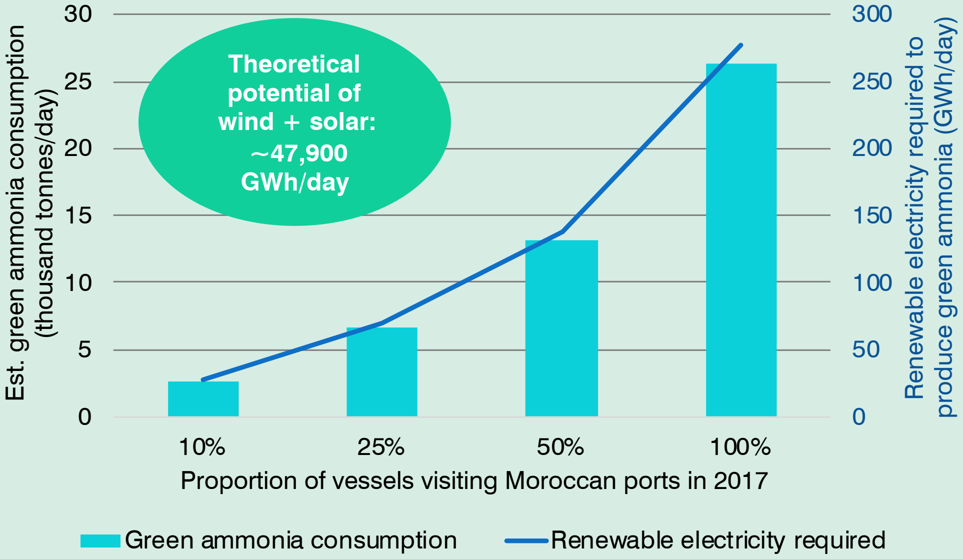


FIGURE 8:

Annual amount of electricity to produce green ammonia for container and dry bulk vessels passing through Morocco's ports



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[4] Vessel traffic is based on gross tonnage reported for Moroccan ports in 2017 [3, 4] with a representative distribution of vessel sizes similar to those reported in IMO's Third Greenhouse Gas Study [24].

For example, about 280 gigawatt-hours (GWh) per day of electricity on average would have been required to produce green ammonia fuel for all the container and dry bulk vessels passing through Morocco's ports in 2017, assuming that each took on fuel for 45 days' sailing. This is 0.6% of the theoretical potential for wind and solar sources in Morocco (about 47,900 GWh/day) [11, 18], showing Morocco's renewable energy capacity is more than large enough to cover both domestic and shipping demand sources. In 2016, Morocco's production of renewable electricity was approximately 4,740 GWh [19] (the latest year for which data is available). If any renewable energy from domestic sources is diverted to shipping, these indirect impacts should be taken into account in any lifecycle accounting and robustly accounted for internationally.

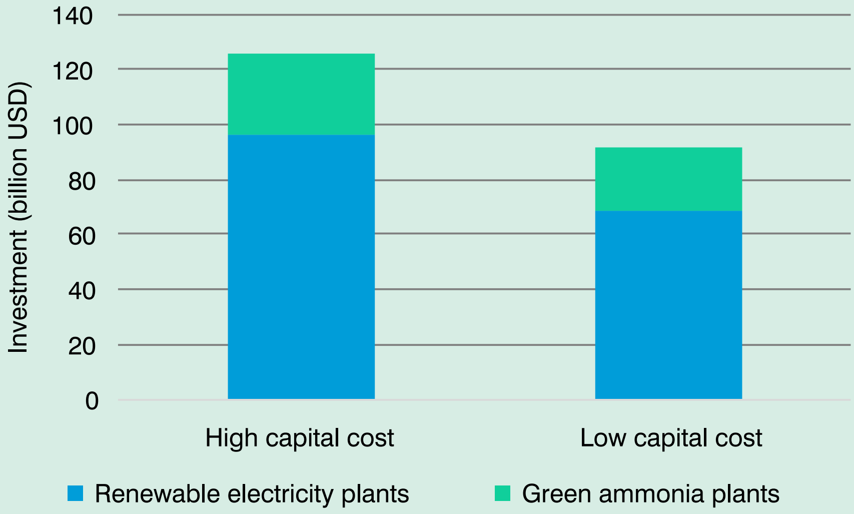
The Government's ambitions for renewable generation in 2030 have been drawn up without considering the potential additional market that shipping demand could provide. Adding shipping demand to the country's ambitions could see even more ambitious plans being unlocked in the country.

Potential level of investment in Moroccan sustainable industry

The estimated investment potential for green ammonia plants and associated renewable electricity plants to provide fuel for the ships visiting Morocco's ports (based on 2017 throughput) is given in Figure 9[5].

FIGURE 9:

Estimated investment potential for green ammonia plants and renewable electricity plants in Morocco



The potential investment value (aggregate capital costs) of green ammonia plants and associated renewable electricity facilities in Morocco is in the region of USD 100 billion. This gives an indication of the potential level of investment that could be attracted if green ammonia is adopted at scale. The renewable plants make up between 70% and 80% of the investment value, depending on the technology mix and future costs[6]. The ultimate value will depend on future cost trajectories of green ammonia and renewable electricity technologies, as well as the adoption rate of the fuel.

This brings to life the great potential for investment that the shipping sector could unlock by adopting green ammonia as a fuel.

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[5] No allowances are made for increases in vessel traffic due to changing trade patterns or increased traffic of vessels bunkering for green ammonia.

[6] For the purposes of Figure 9 it was assumed that the renewable electricity would comprise of 40% solar PV, 30% onshore wind and 15% each for concentrating solar and offshore wind. Other costs and assumptions are listed in Chapter 6 and Appendix E.

1. Why we wrote this paper

1.1 Reclaiming the renewable power of water and air

For centuries commercial ships were powered by water and air: Water to float on and wind in their sails. The sails were later replaced by steam engines and ultimately by internal combustion engines – both fed by fuels that emit greenhouse gases when combusted. This paper shows how the marine sector can 'sail on solar' by returning to the renewable power of water and air plus energy from the sun in the form of 'green ammonia'.

Produced from water and air using renewable electricity, green ammonia could play a vital role in decarbonising the marine sector. It is one of the fuel options that do not emit greenhouse gases and could be used to decarbonise the maritime transport sector – the others being hydrogen and batteries (both dependent on renewable electricity). It is anticipated that decarbonisation of the sector will require all these fuels, with selections based on the needs of each vessel type/application. The main advantages of green ammonia over other fuels that do not emit greenhouse gases[7] such as hydrogen and battery storage are that:

- It has existing global logistics infrastructure (unlike hydrogen).
- It does not require cryogenic storage (unlike hydrogen).
- It is relatively energy-dense as a liquid, providing sufficient energy storage for ship voyages lasting several weeks (unlike batteries).
- It provides flexibility as it can be used without complicated onboard processing in internal combustion engines and future fuel cells.
- It has a risk profile that can be managed with existing standards and procedures.

Ammonia can be liquefied at a reasonable temperature (-33°C (28°F)) or moderate pressure (1MPa (10 bar)), whereas hydrogen requires cryogenic storage. This means that ammonia requires less energy than hydrogen to liquefy, store and evaporate. In addition, liquid ammonia requires almost half the onboard storage space as hydrogen and poses a lower fire risk (it has a narrower flammability range and higher ignition temperature).

For an industry now familiar with fossil fuels, the idea of ammonia as a fuel may at first appear strange, daunting or even dangerous. This paper uses existing scientific data, basic chemistry, engineering knowledge and practical experience to show that green ammonia can – indeed should – be adopted as a zero-GHG-emitting fuel more easily, quickly and safely than people may assume.

This paper explores the idea of establishing a green ammonia supply chain at the scale required for international shipping and shows how the technical and economic barriers can be overcome using existing proven technology.

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[7] For simplicity this is abbreviated to "zero-GHG-emitting" in this paper. This phrase is preferred to "zero-emission" because ammonia does produce some emissions when combusted. See section 4.6 for more details.

1.2 Shipping's contribution to limiting global climate change

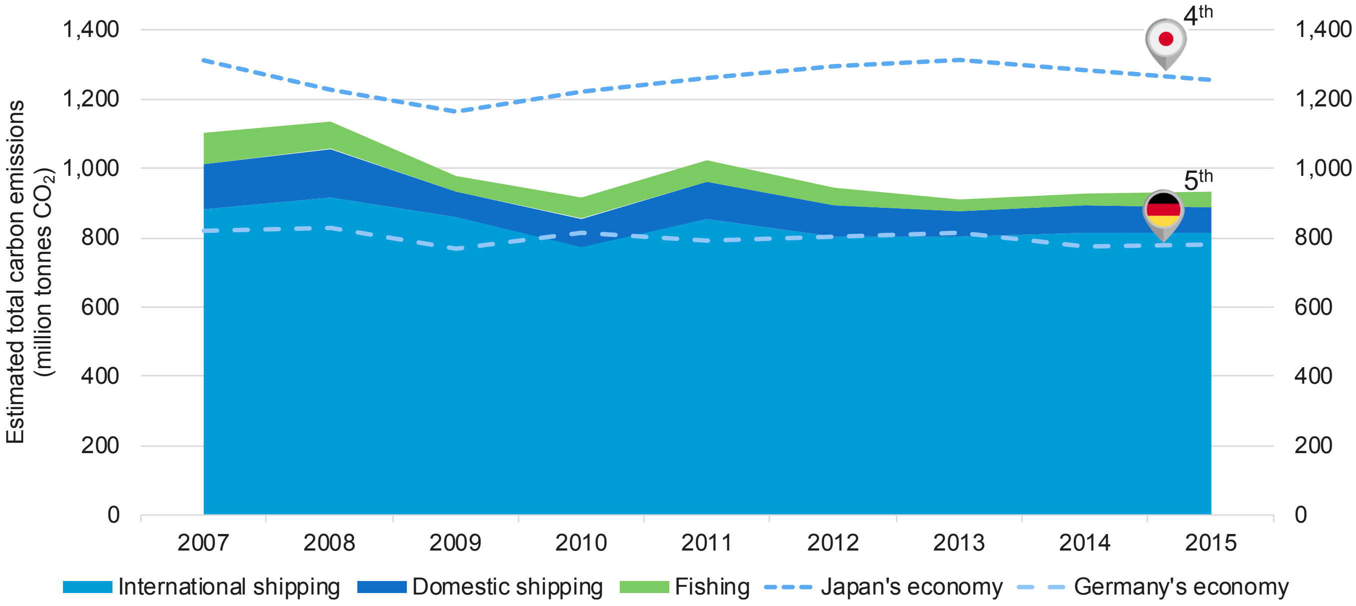
The Paris Agreement on climate change was signed in 2015 by Parties to the United Nations Framework Convention on Climate Change (UNFCCC). Its central aim is to reduce the risk of global climate change by ensuring additional manmade emissions of greenhouse gases are reduced to zero before the end of the century. This is necessary to stand a reasonable chance of keeping a global average temperature rise well below 2°C above pre-industrial levels this century and to pursue efforts to limit the temperature increase even further to 1.5°C.

The Intergovernmental Panel on Climate Change (IPCC) stated in 2018 [20] that human activities are estimated to have already caused approximately 1.0°C of global warming above pre-industrial levels and this increase is already changing our global climate, contributing to increased intensity and frequency of natural disasters, sea level rise and acidification of the oceans. The rate of accumulation of greenhouse gases in the atmosphere and the associated rate of global warming is still increasing. Every year of delay in bringing greenhouse gas emissions under control and onto a declining pathway increases the likelihood of missing our global goal to prevent dangerous levels of global climate change.

If the maritime transport sector was a country, in 2015 it would have ranked 5th in the world in terms of gross carbon emissions behind Japan and just ahead of Germany [21], as shown in Figure 10.

FIGURE 10:

Comparisons of estimated fossil carbon emissions



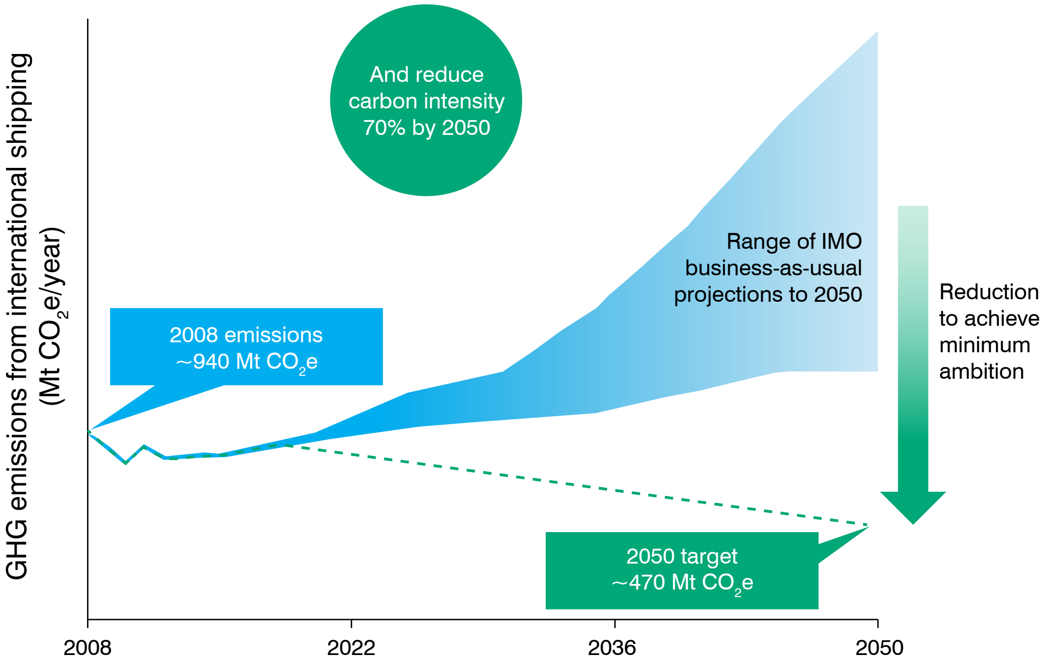
Data from [21, 22]

International shipping and aviation sit outside the UNFCCC framework of national emissions inventories and have dedicated UN bodies overseeing their operations. In April 2018 the International Maritime Organization (IMO), as the regulatory body for international shipping, adopted an initial strategy on the reduction of greenhouse gas emissions from shipping. This strategy included a vision which sets forth the IMO's commitment to reducing greenhouse gas emissions from international shipping and, as a matter of urgency, to phase them out of international shipping as soon as possible this century [23].

In its 3rd Greenhouse Gas Study [24], the IMO projected the sector's emissions to grow in a 'business-as-usual' scenario by 50% to 250% between 2012 and 2050 as shown in Figure 11. Therefore, the target to reduce absolute emissions by at least 50% by 2050 compared to 2008 levels is going to require a step change reduction in the carbon intensity of the maritime transport sector by switching away from high-carbon fossil fuels. With typical vessel lifespans of between 20 and 30 years, the international shipping industry needs to introduce vessels with low and zero greenhouse gas emissions within the next few years [25] with the intention to scale up deployment significantly.

FIGURE 11:

Reduction required to meet the IMO's absolute emissions reduction target



Data sources: [22, 24]

The shipping sector has access to established and proven technologies to achieve these targets. With innovative thinking and multilateral commitment, the most promising zero-GHG-emitting fuel solutions could be implemented at the scale required to make a difference to the climate. If the sector can expedite regulatory approvals and mobilise finance to support infrastructure investment, then it has the potential to decarbonise rapidly in the coming years.

1.3 Decarbonising shipping can unlock investment in low-carbon industrial development

Production of green ammonia for maritime transport would create demand for the development of renewable electricity plants and large-scale sustainable industry. All countries could benefit from this opportunity, especially developing countries with abundant renewable energy resources. One of the key barriers to the development of large-scale renewable electricity facilities in developing nations is uncertainty about income from the sale of electricity. There is often a lack of demand for electricity or the purchasers of bulk electricity do not have the creditworthiness to make projects viable. However, demand for green ammonia as a marine fuel could provide a dependable long-term revenue stream – supported by long-term supply agreements – to justify investment in large-scale renewable plants in developing nations.

1.4 What you will find in this paper

This paper aims to show that it is realistic and achievable to adopt green ammonia as a maritime fuel. It does this by looking at the aspects of supply (production plants) and demand (the vessels themselves). The concept has been brought to life throughout the paper using hypothetical case studies for various countries, with a focus on Morocco at the beginning. These case studies seek to demonstrate how countries with untapped renewable energy could benefit by establishing a green ammonia supply chain for the marine sector.

2. Why green ammonia is proposed as a fuel	Describes the characteristics of ammonia as a fuel and compares it with other low- and zero-GHG-emitting fuel options. It also shows how ammonia is already an established commodity that is traded and shipped on a global scale.
3. Green ammonia production process	Gives an overview of the green ammonia production process, which is powered by clean electricity.
4. Vessel propulsion, onboard storage and emissions	Discusses the propulsion options for ammonia-powered vessels. It describes the challenges associated with using ammonia in combustion engines and the requirements to store and handle ammonia onboard safely. It also gives an overview of the greenhouse gas emissions and implications for air quality.
5. Ammonia's risk profile and transport options	Presents the risk profile of ammonia and mitigations that would be required in the fuel supply chain. It also gives an overview of the transport options.
6. Estimated level of investment	Gives an impression of the level of investment required to establish a sustainable green ammonia supply chain to serve the shipping sector.
7. Conclusions	Summarises the main points presented in this paper.

2. Why green ammonia is proposed as a fuel

To meet the IMO's targets and ultimately decarbonise the sector, vessels using zero-GHG-emitting fuels need to start entering the international shipping fleet in the 2020s.

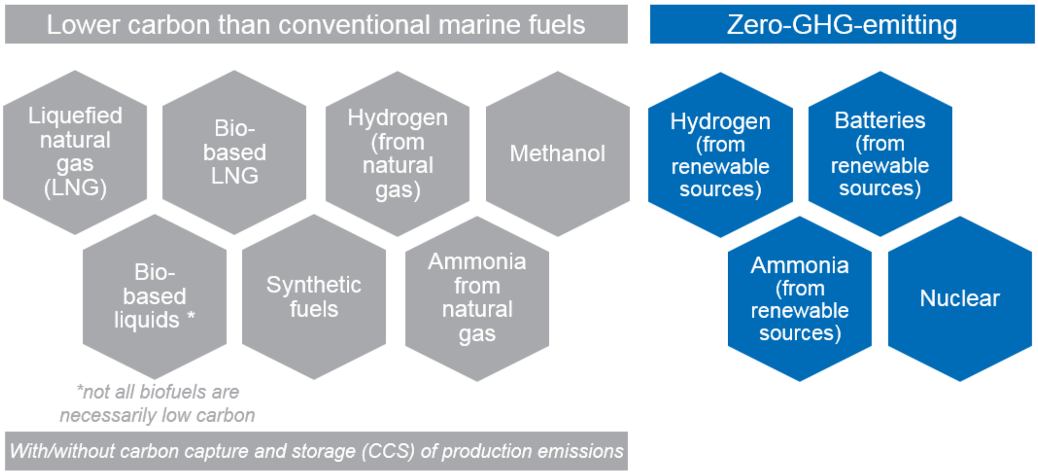
2.1 Vessels that emit zero greenhouse gases are required to meet IMO targets

Achieving the IMO's greenhouse gas emissions targets will require a decisive intervention to alter current fuel trends in the sector. At present, marine fuels contain carbon which is released into the atmosphere as carbon dioxide (CO_2) when the fuels are burned, remaining there for up to 1,000 years. Additionally, the production of fossil fuels emits greenhouse gases throughout the lifecycle: in the exploration, production, processing, and transport stages. The maritime transport sector will need to be decarbonised across the full lifecycles of its various fuels.

Part of the challenge is related to the typical lifetimes of the vessels in the fleet. Ships quite typically remain in the fleet for between 20 and 30 years before being scrapped. With one of the key targets set at 2050 and considering the multi-year lead time for designing and building a vessel, imminent action is required to make a transition towards implementing lower- and zero-GHG-emitting fuels in the maritime fleet. The shorter-term transition might include fuels with lower carbon content, but it should quickly make way for zero-GHG-emitting fuels.

The range of fuels available for the industry – those that are potentially lower-carbon and those that are zero-GHG-emitting over their lifecycle, including indirect impacts – are listed in Figure 12 (without judgement on their relative merits):

FIGURE 12:
The range of low- and zero-GHG emitting fuel options for maritime transport



Liquefied natural gas (LNG) is considered by many in the industry as a means to reduce sulphur oxides (SO_X) and particulate matter emissions from ships, as well as carbon emissions. It is being explored by several ship operators and bunker fuel providers. However, even assuming all new ships use it, due to the growth forecast for the global fleet, there would still be an increase in overall CO_2 emissions. With LNG there is also the need to reduce leaks of methane throughout the production, liquefaction and transport phases of the lifecycle to achieve a saving in emissions (even a small degree of so-called 'methane slip' can fully erode the carbon savings offered by LNG over higher-carbon options like heavy fuel oil (HFO)). Compared with HFO, LNG can only achieve reductions in greenhouse gas emissions of up to 10% [26, 27].

To meet the IMO's targets and ultimately decarbonise the sector, vessels using zero-GHG-emitting fuels need to start entering the international shipping fleet in the 2020s. Indeed, the industry recognises this itself: in 2018, the International Chamber of Shipping [28] wrote 'a 50% total cut by 2050 can realistically only be achieved with the development and widespread use, by a large proportion of the fleet, of zero CO_2 fuels.'

Green ammonia is one of the potential fuel options that has been identified to meet this need although it will not be suitable for all end uses. Therefore, green ammonia could be part of a multi-pronged strategy where low- and zero-GHG-emitting fuels are selected based on the needs of each vessel type/application[8]. Initial modelling for the United Kingdom's Department for Transport's Clean Maritime Plan (anticipated in 2019) predicts that consumption of green ammonia for UK international shipping should exceed all other fuels by 2041 for the sector to achieve a 50% reduction in greenhouse gas emissions by 2050 [29].

The renewable production of ammonia holds promise beyond the shipping sector as well. The most obvious and immediate benefit is decarbonisation of fertiliser production [30]. Applications that are being considered in other sectors include long-term energy storage [31] and use in power generation [32, 33].

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[8] For example, batteries charged with renewable electricity are unsuited to long range vessel movements such as large container, cruise, bulk carriers, because they have relatively limited energy capacity and weight-to-energy trade-offs. However, batteries are already proving appropriate for some domestic shipping or short ferry applications. Nuclear-powered vessels are limited to military use; the future use in civilian vessels offers lower emissions traded off against the risks of human exposure to radioactivity during vessel construction and disposal, as well as risks to the environment in case of accidents.

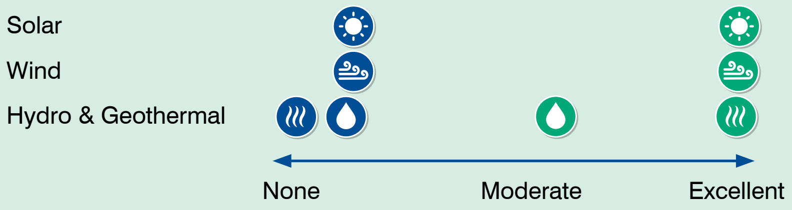
Chile

MINI CASE STUDY

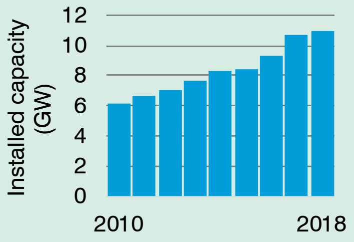
Total container volume through ports in 2017: 4.2 million TEU

Renewable resources

(blue icons: existing; green icons: potential)

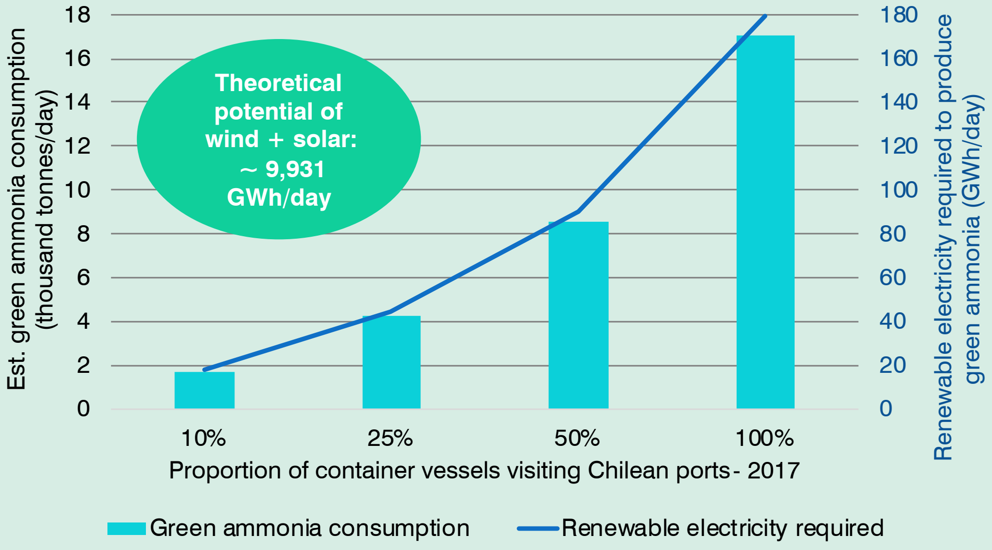


Recent growth in renewables



Hypothetical green ammonia consumption & required electricity for container vessels in 2017

The mini case studies in this paper focus on container ships due to data availability and because they are the vessel type with the largest contribution to maritime GHG emissions. Globally, in 2012, the IMO estimated that the container fleet consumed 22% of the total fuel consumption of all shipping [24].



Note: Container vessel traffic for 2017 from the UNCTAD database [1]

Sources: [19] [100] [101]

2.2 Green ammonia offers many advantages over other fuels

Ammonia offers several potential advantages over the conventional fuels used in the marine industry – HFO and marine distillates – as well as LNG, which are summarised in Figure 13. Green ammonia also offers advantages compared to other zero-GHG-emitting fuel options, as listed in Figure 14.

FIGURE 13:

Advantages and aspects to consider for green ammonia compared to carbon-based maritime fuels

Advantages

- Zero carbon emissions when combusted
- Lower toxic emissions (SO_2, metals, particulate matter, polycyclic aromatic hydrocarbons)
- Lower fire risk
- Can be used in engines and fuel cells
- Zero NO_X in low temperature fuel cells

Aspects to consider

- Storage volume: ammonia requires 4.1 times as much space as fossil fuels
- Corrosiveness: some materials should be avoided
- Safety and environmental risk due to toxicity
- Similar NO_X performance (also needs to be controlled)

FIGURE 14:

Advantages and aspects to consider for green ammonia compared to other zero-GHG-emitting fuels

Advantages

- Abundant commodity with existing infrastructure for production, storage and transport
- Higher volumetric density than hydrogen: allows longer international journeys without refuelling
- Can be stored as a liquid at reasonable temperatures and pressures
- Lower fire risk than hydrogen (narrower flammable range; higher ignition temperature)
- Can be used in engines and fuel cells

Aspects to consider

- Might require a pilot fuel when used in combustion engines
- Corrosiveness: some materials should be avoided
- Safety and environmental risk due to toxicity
- Higher NO_X emissions that need to be controlled (e.g. with selective catalytic reduction)

This paper seeks to demonstrate that the perceived challenges of using ammonia as a fuel – listed in the blue boxes in these figures – are surmountable. An important advantage that could help with a transition from current fuels to ammonia is that ammonia can be used in existing adapted dual-fuel engines in the shorter term as well as in fuel cells in the longer term (for more on this, see Chapter 4).

Ammonia can also be a ‘hydrogen carrier’ where it is used to store hydrogen, which can be used in hydrogen fuel cells to generate electricity for propulsion by electric motor. Ammonia is attractive as a hydrogen carrier because it can be transported as a liquid relatively easily with significantly higher energy density than as a gas. In contrast, hydrogen must be cooled to -253°C or pressurised to between 35MPa to 70MPa (350 bar to 700 bar) to be stored as a liquid [34]. The process of liquefying, storing and evaporating hydrogen for use on a vessel also involves energy losses.

Table 1 provides comparisons for the various candidate low- or zero-GHG-emitting marine fuel options, against marine gas oil (MGO; grade DMA/DMZ).

TABLE 1:
Comparison of fuel characteristics

	Marine gas oil	**Liquefied natural gas**	**Methanol**	**Green ammonia**	**Green hydrogen**
Type	🟥 Fossil fuel, high carbon	🟥 Fossil fuel, high carbon	🟧 Low-carbon	🟩 Zero GHG emitting	🟩 Zero GHG emitting
Temperature for liquid storage	🟩 Ambient	🟧 -162°C	🟩 Ambient	🟧 -34°C (or pressurised)	🟥 -253°C
Tank volume for 1,000 nautical mile range of Handymax carrier	🟩 73m^3	🟧 164m^3 (2.3 x MGO)	🟧 169m^3 (2.3 x MGO)	🟧 299m^3 (4.1 x MGO)	🟥 555m^3 (7.6 x MGO)
Suitable application	🟩 Short and long voyages	🟩 Short and long voyages	🟩 Short and long voyages	🟩 Short and long voyages	🟧 Short voyages

🟩 Best performing 🟧 Acceptable 🟥 Problematic

Sources: [35, 36]

Ammonia contains about one third of the energy per cubic metre of HFO or MGO, so vessels would need larger fuel storage tanks or to refuel more often. Given the need for the sector to decarbonise through switching to zero-GHG-emitting fuels, green ammonia should be compared to other zero-GHG-emitting fuels rather than retrospectively to the fossil-fuelled status quo. From this perspective, liquid ammonia requires 46% less storage volume than cryogenically stored hydrogen when the volume of the tank insulation is included[9]. This highlights ammonia’s potential as a fuel and as a convenient hydrogen carrier for hydrogen-based propulsion technologies.

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[9] A “system-level” density of liquid hydrogen of 40 kg/m^3 is assumed in this paper to account for the extra space required for insulated fuel tanks as per Minnehan and Pratt [114] and Comer [115]. The authors of this paper calculate that accounting for the insulation of the fuel tanks results in a corresponding system-level density of 48kg/m^3 for liquid ammonia.

2.3 Developing nations stand to benefit from green ammonia production

The development of renewable electricity capacity has the potential to provide countries that are dependent on imported fuels with a higher degree of energy independence. As costs for technologies such as wind and solar fall, their ability to make rapid contributions to decarbonising the global energy sector increases.

It is a happy coincidence that some of the most abundant renewable electricity resources are found in developing countries, where they could be used to facilitate sustainable development. However, a large capital outlay is usually required to construct renewable electricity plants before they begin to earn an income. Funding this upfront cost can be risky for investors and lenders, so they usually require some assurance that the plant will be able to provide a reasonable return on their investment over its operational lifetime.

It is often difficult to find credit-worthy purchasers of electricity in developing countries to give investors and lenders comfort that the renewable plant will be able to earn a reasonable and predictable income. This is especially true for countries that have low electricity demand due to low levels of industrial and commercial activity, and/or low electricity connection rates.

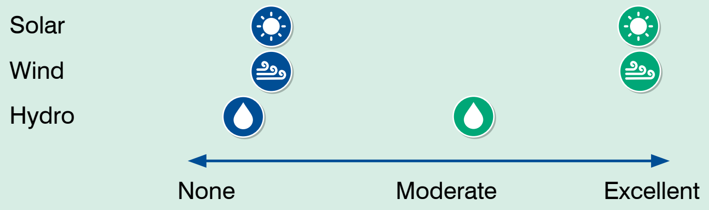
China

MINI CASE STUDY

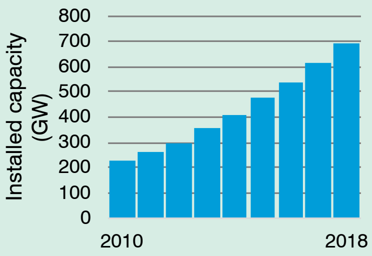
Total container volume through ports in 2017: 214 million TEU

Renewable resources*

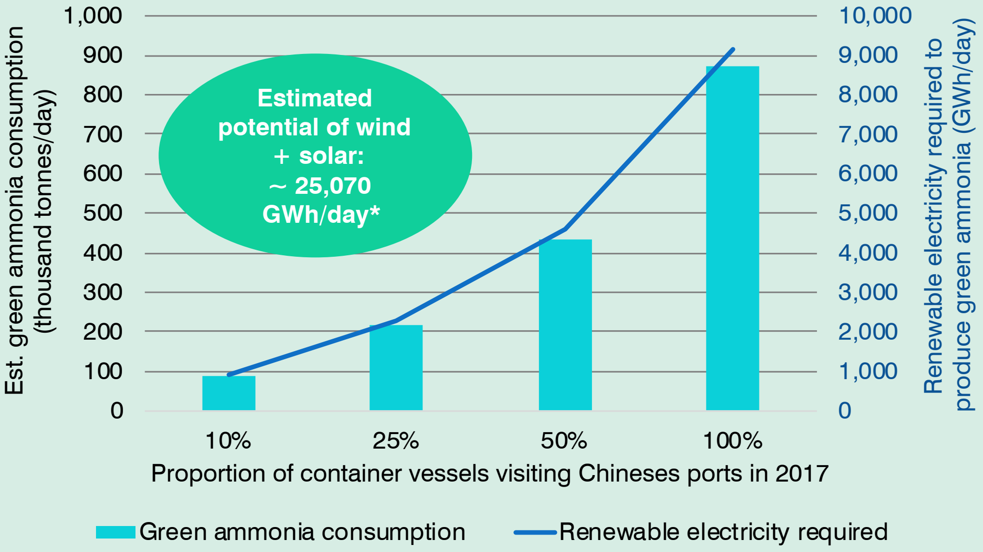
(blue icons: existing; green icons: potential)



Recent growth in renewables



Hypothetical green ammonia consumption & required electricity for container vessels in 2017



*China's size means it covers multiple climate regions. Reliable estimates of renewable energy potential for the country as a whole are difficult to find in the English literature.

Note: Container vessel traffic for 2017 from the UNCTAD database [1]

Sources: [19] [102] [103]

Power purchase agreements with reputable buyers are therefore extremely valuable for investors and lenders, especially if they guarantee that a significant proportion of the electricity will be purchased for several years. The adoption by the international shipping industry of green ammonia as a fuel would create a dependable long-term demand for it. Therefore, green ammonia plants could facilitate the expansion of renewable electricity supply in developing and developed countries alike.

2.4 Ammonia is a commodity that is already traded on a global scale

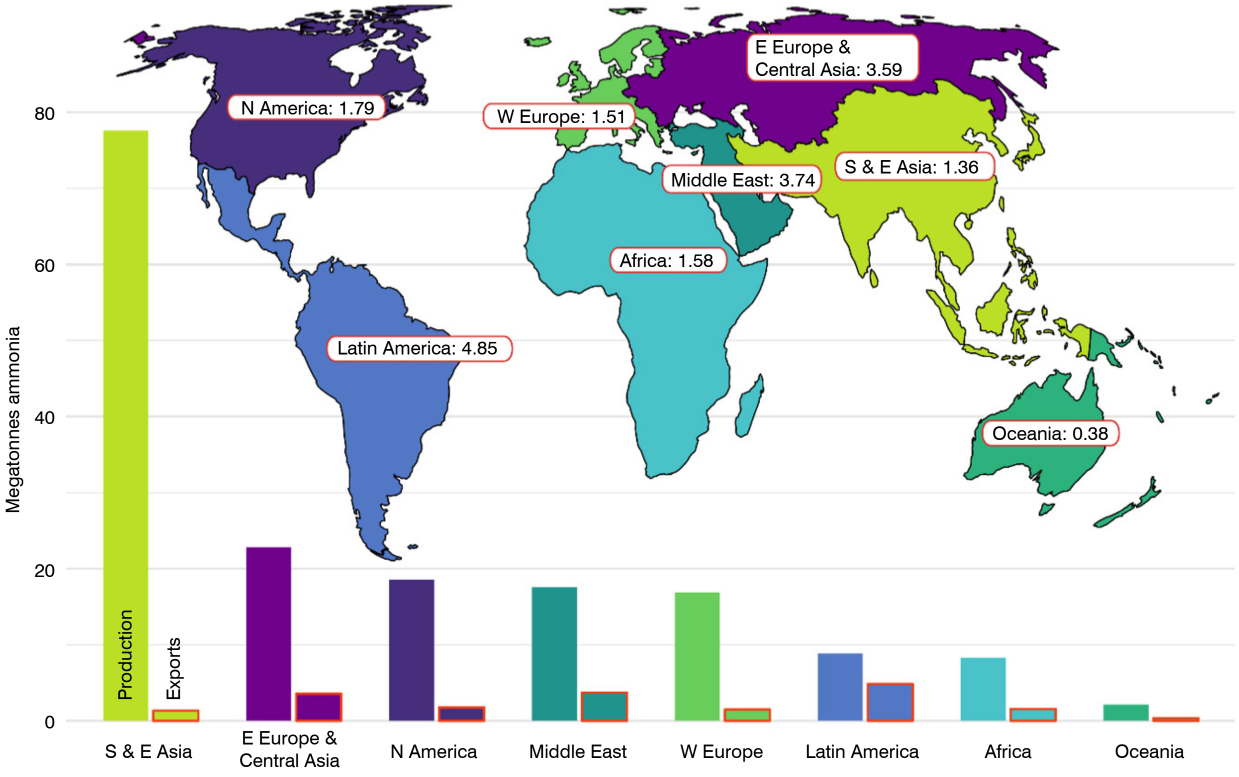
The global production and trade of ammonia is principally driven by the fertiliser industry because ammonia is an important nitrogen-rich ingredient. According to the International Fertilizer Association [37], an average of about 175 million tonnes of ammonia per year was produced globally from 2015 to 2017. Of this, about 18.8 million tonnes was exported. Most of this ammonia was produced using the traditional method from fossil fuels, which is greenhouse-gas intensive [38]. To put this into the context of this paper, this level of annual production is already more than is needed to fuel the entire international fleet of container vessels for a year[10]. Three and a half times the current global ammonia production – but from clean electricity – would power the entire international shipping fleet.

Ammonia is not only a globally produced commodity, but is also exported around the world, as shown in Figure 15. Therefore, ammonia is a well-understood, globally traded commodity, which has been transported by international vessels for many years. This not only alleviates concerns about safety onboard vessels, but also indicates that there is an existing supply chain and regulatory framework for ammonia that could support its adoption as a maritime fuel while green ammonia plants are developed around the world. This helps to de-risk the transition process since existing infrastructure already exists on a global scale.

There is an existing supply chain and regulatory framework for ammonia that could support its adoption as a maritime fuel while green ammonia plants are developed around the world.

FIGURE 15:

Regional ammonia production (graph) and exports (map and graph) in 2017



Data source: [37]

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[10] By comparing the energy content of ammonia and HFO, and based on the 2012 container fleet fuel consumption data presented in [24] resulting in a daily fleet consumption of about 329,000 tonnes of ammonia.

2.5 Amount of green ammonia required for international shipping

Considering the potential that green ammonia holds for decarbonisation of shipping as well as encouraging investment in production plants and renewable electricity, it is natural to ask how much of it might be required. This section uses the growth projections for the international fleet of container and non-coal dry bulk vessels to 2050 within the Third IMO Greenhouse Gas Study [24] to estimate the amount of green ammonia required to achieve a meaningful reduction of the sector's greenhouse gas emissions by then. IMO considered five different 'shared socioeconomic pathways' (SSPs) towards economic growth in 2050 [39]. Two of these scenarios – SSP1 'Sustainability' and SSP3 'Fragmentation' – were used for the projections in this section, which represent a range of outcomes but exclude the fossil-fuel reliant SSP5 'Conventional development' scenario. For simplicity in this paper, SSP1 and SSP2 are referred to as the "high case" and the "low case".

The estimated green ammonia consumption values for the two scenarios in 2050 are shown in Figure 16 assuming 10%, 25%, 50% or 100% of the international fleet will use the fuel. This shows that the fuel consumption of all the non-coal dry bulk and container vessels in the global fleet in 2050 under the 2050 High Case (approx. 1.35 million tonnes/day; 493 million tonnes/year) would be about 2.8 times the global ammonia production in 2017, which was 173 million tonnes.

Figure 17 shows the associated consumption of electricity required to supply the theoretical demand for green ammonia in aggregate for the international fleet in 2050. Further detail is given in Appendix D about the expected consumption of various vessel types.

FIGURE 16:

Green ammonia consumption in 2050 for the two scenarios

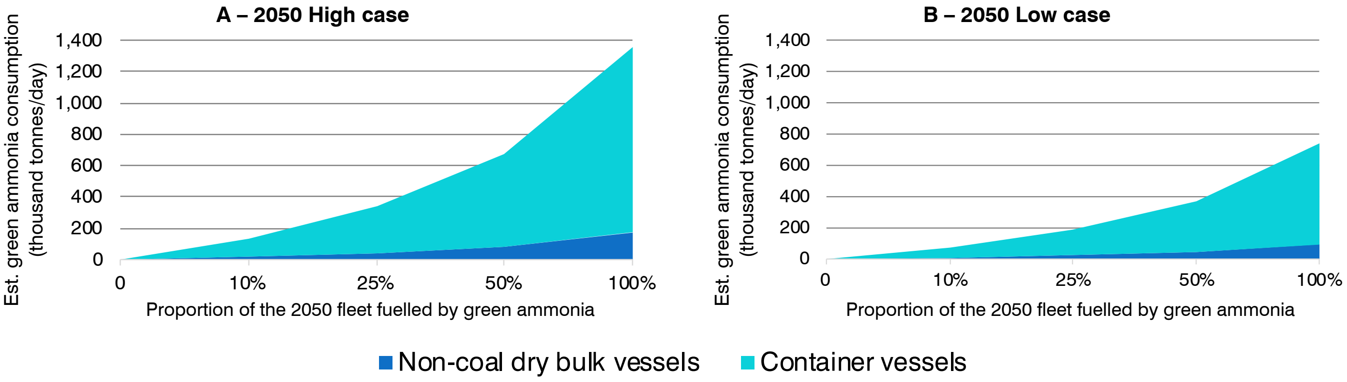
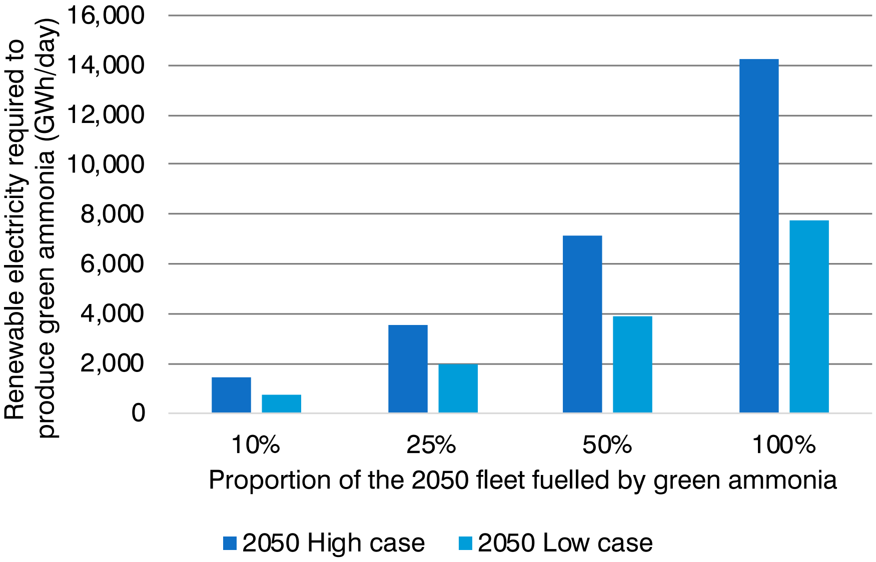


FIGURE 17:

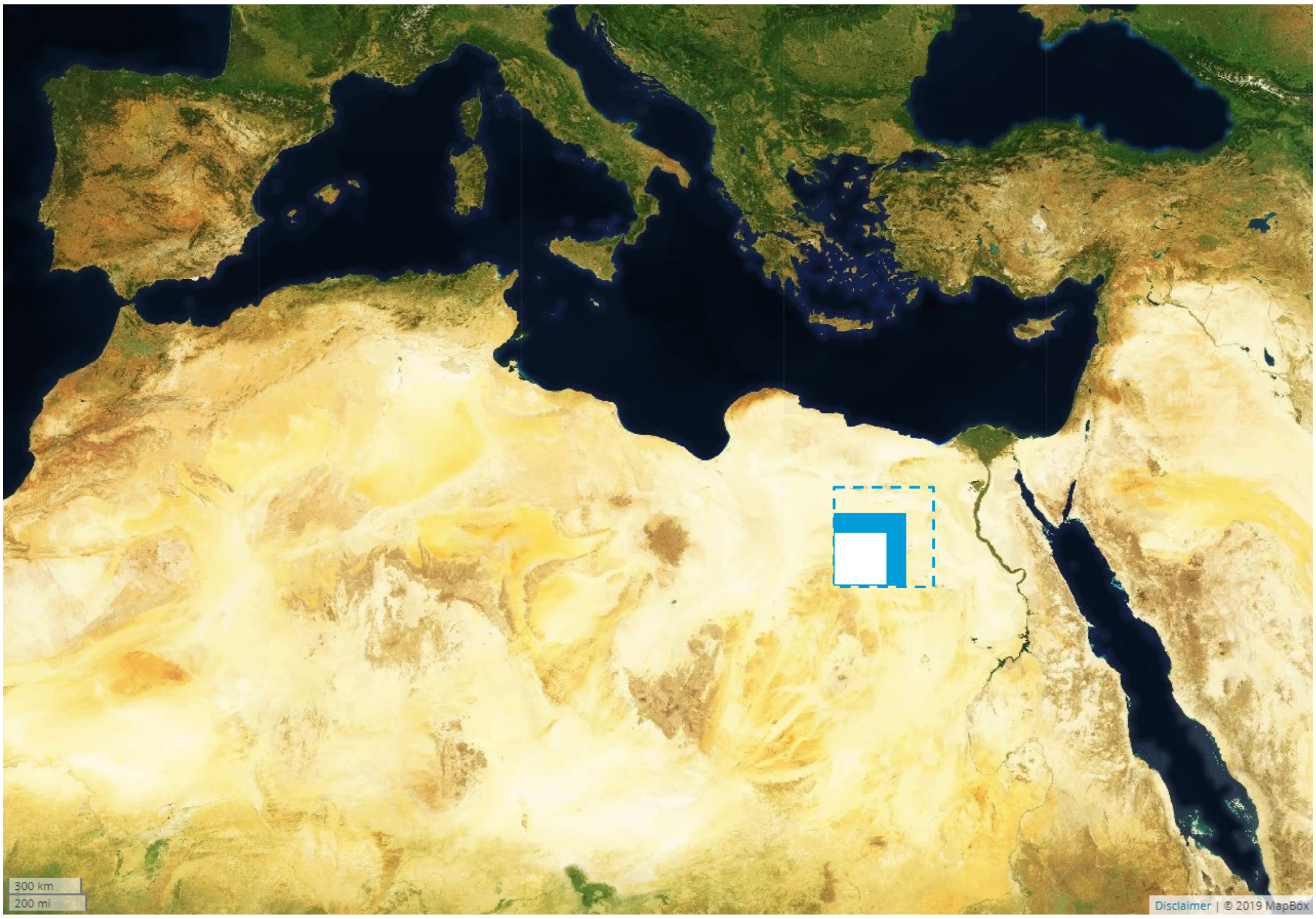
Renewable electricity required to produce green ammonia for the international shipping fleet in 2050



To provide some context, the electricity required to produce the daily fuel consumption of the post-Panamax vessel in Figure 6 (1.9 GWh) is equivalent to the average daily consumption of about 117,000 people in the European Union [40]. Figure 18 gives an indication of the land required for solar PV to generate the electricity required to produce green ammonia for the international fleet of container vessels and non-coal dry bulk carriers in 2050.

FIGURE 18:

Map showing land area required for solar electricity to produce green ammonia for the international shipping fleet in 2050



Satellite image from [12]

The larger blue square (with sides of 296km) represents the area required under the 2050 High case, while the smaller white square (with sides of 218km) is for the 2050 Low case[11]. The square with the dashed lines represents the entire international fleet in 2050, assuming that carriers and dry bulk vessels make up 40%, as they did in 2012 [24]. The calculated average annual capacity factor at the indicated location is about 22% according to the Global Solar Atlas [12], whereas the global average value is about 17% [19].

These areas are relatively small when one considers that it would be provided by a range of renewable sources (not only solar PV) and the plants would be dispersed around the world to provide green ammonia capability on a global scale.

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[11] Size is based on calculated consumption values of 4,680 TWh/year (installed capacity of 2.4 TW) for SSP1 and 2,555 TWh/year installed capacity of 1.3 TW) for SSP2 in 2050. An area of 0.032 square kilometres per MW installed capacity was used [116].

3. Green ammonia production process

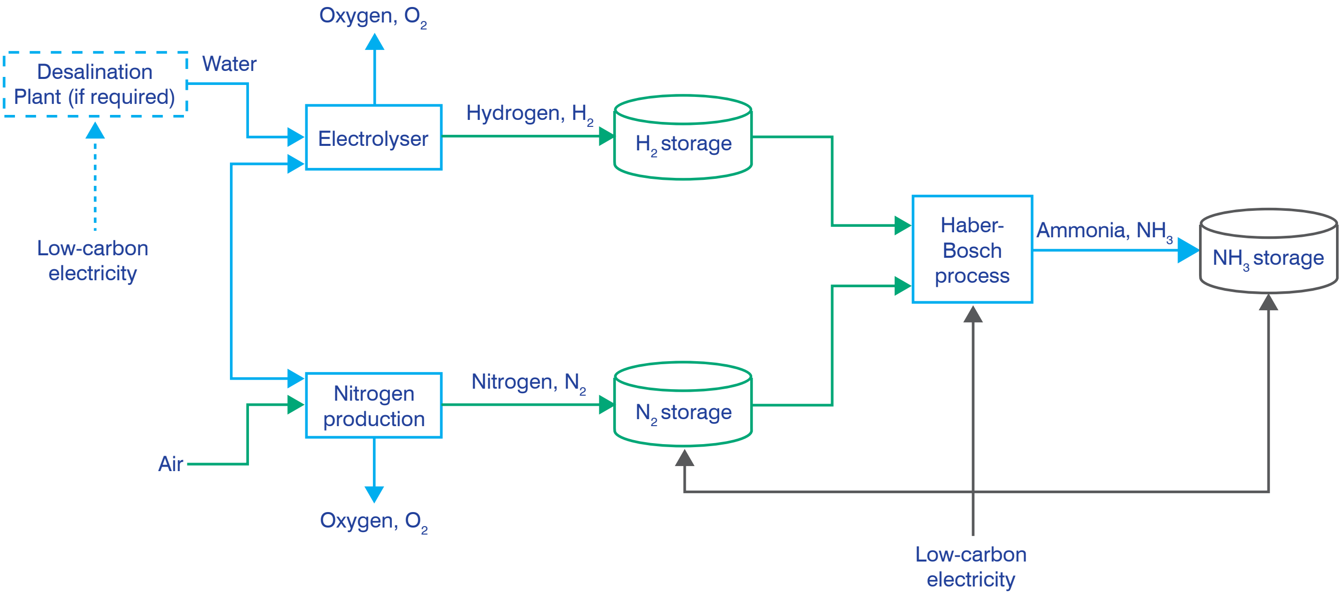
3.1 Overview of the production process

The most common method of producing ammonia involves producing hydrogen from fossil fuels. It is possible to incorporate carbon capture and storage equipment to remove most of carbon emissions from the traditional method, but the technology is still in its infancy at the industrial scale and yet to be demonstrated to be commercially viable. There are also challenges associated with finding a place to securely store the CO_2 after it is captured.

Green ammonia is manufactured with commercially proven equipment, but it does not involve any greenhouse gas emissions, using water, air and renewable electricity as the primary inputs, as shown in Figure 19. The financial aspects of the plant are described in Chapter 6.

FIGURE 19:

Diagram of the green ammonia production process



Green ammonia is manufactured with commercially proven equipment, but it does not involve any greenhouse gas emissions, using water, air and renewable electricity as the primary inputs.

The main difference between the traditional process and the green ammonia process is the method for producing hydrogen. In the traditional method, hydrogen is 'reformed' from carbon-based feedstocks like natural gas, oil or coal. However, the green ammonia process uses equipment called electrolysers to separate hydrogen atoms from oxygen atoms within water. Electrolysers are already in extensive commercial use. The electrolyser plants for green ammonia production are made up of multiple modular units that can operate low loads and can be stopped or started easily. These characteristics give them high operational flexibility, which is well suited to renewable electricity with fluctuating output.

Figure 19 shows that a desalination plant can be incorporated, which is useful for the marine fuel application because the ammonia plants are likely to be located close to seawater ports. The interested reader is referred to Appendix B for more technical details.

Nitrogen is usually harvested from air using an air separation unit, which is also an established technology that is used in the traditional and green ammonia production techniques. Technical details are also provided in Appendix B.

The Haber-Bosch process is the most common method for producing ammonia from hydrogen and nitrogen on an industrial scale and is well understood. It is used in the traditional (fossil-fuelled) and the green ammonia production processes. The Haber-Bosch process involves an exothermic reaction (i.e. it creates heat) that works best when it continues uninterrupted, so it is not amenable to frequent stopping and starting. In a fossil-based ammonia plant, the Haber-Bosch process is designed to maximise throughput, but it is consequently relatively inflexible to operate at part loads. However, it is possible to design the Haber-Bosch plant with the ability to operate more flexibly and reduce the load at times of lower electricity output from intermittent renewable sources.

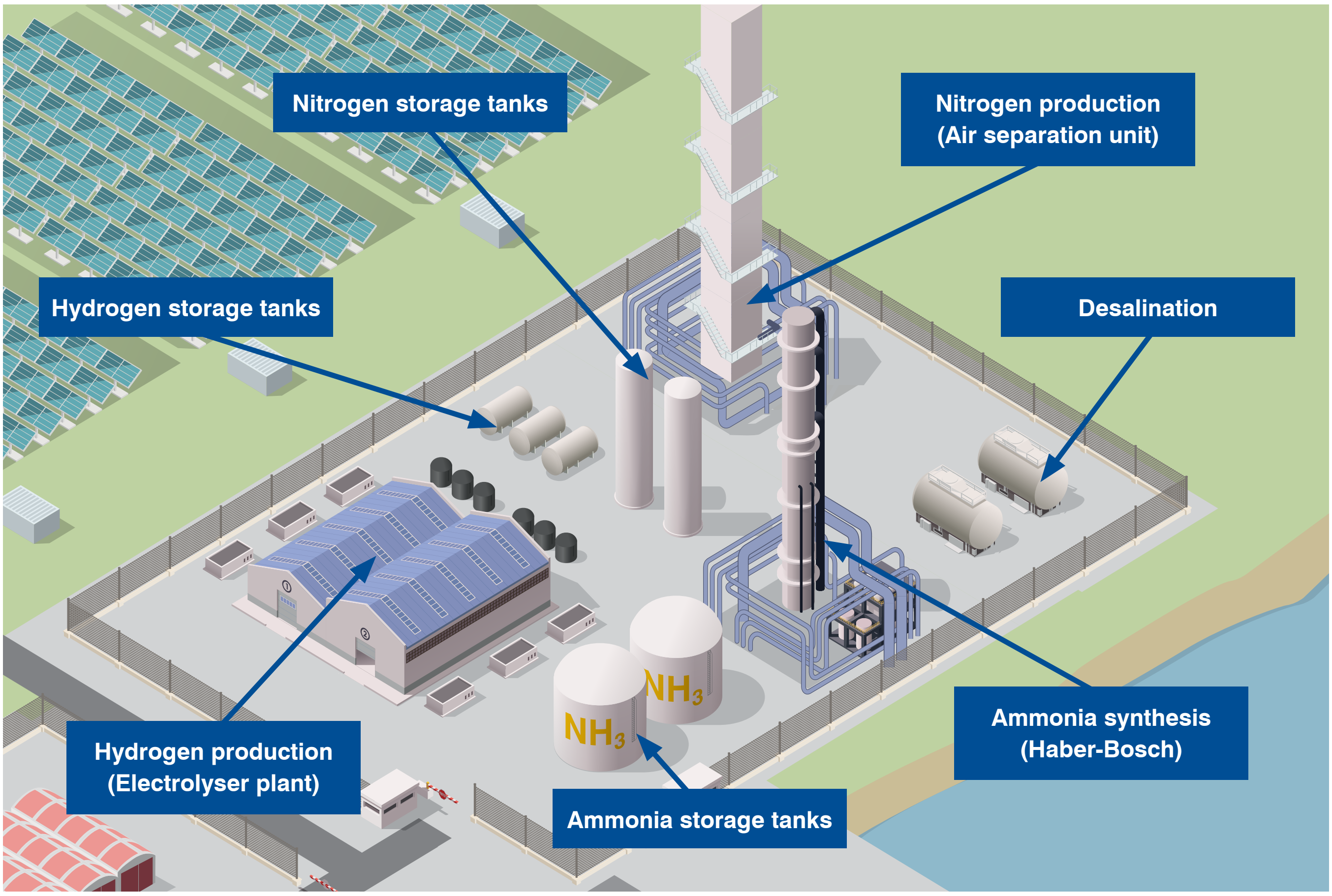
The Haber-Bosch process only represents about 6% of the electricity demand of a typical green ammonia plant, while the electrolysers consume about 92%. There is also scope to include energy and gas storage facilities within the design to provide buffers within the plant to allow the Haber-Bosch process to operate continuously even if the supply of electricity is intermittent. Therefore, with the flexibility of the electrolysers and the storage buffers, the electricity supply could drop by more than 92% and the Haber-Bosch process could continue operation near full load.

There are many storage options depending on the types of the low-carbon generation used. For example, excess energy might be stored (e.g. in batteries or other device) to supplement electricity supply when output is low. In addition, hydrogen and nitrogen buffer tanks can be used to store the gases if there are fluctuations or minor interruptions to the gas production processes. The multiplicity of storage options provides the flexibility to design plants to be financially optimal for the local conditions.

A conceptual diagram is shown in Figure 20 of the various components in a hypothetical green ammonia plant.

FIGURE 20:

Conceptual layout of a hypothetical green ammonia plant



3.2 Low-carbon electricity options

There are many options available for low-carbon electricity generation with the optimal choice of technology depending on the design of the green ammonia plant and the local conditions (including weather, topology, proximity to suitable rivers, availability of geothermal resources, etc.). The options are discussed in Appendix C.

The costs of renewable electricity systems have been falling in recent years, leading to increases in installed capacity and further reductions in manufacturing cost. This trend is most pronounced for solar PV, which has been increasing as a share of the electricity mix in countries around the world.

Energy storage technologies can be used in combination with the generation technologies to make output more consistent and/or predictable by absorbing energy in times of excess and releasing energy at times of deficit. A good example of an integrated energy storage solution is a concentrated solar plant where the molten salt, which is heated and used to generate power, can be stored for hours. This allows the salt to be heated during the day and stored so that it can be used to generate electricity at night.

It is also possible to connect renewable plants to electricity storage equipment like batteries. Historically, the cost of electricity storage has been relatively high, so adoption at grid scale has been limited. However, the falling cost of battery systems coupled with the need to balance increased production from intermittent renewable sources, have led to an increase in adoption in recent years. This trend is likely to continue.

It is also possible to combine multiple intermittent sources (different technologies and/or locations) – possibly with storage – so that the combined output is less intermittent. Ultimately, the optimum solution for each green ammonia plant would depend on the energy resources available locally.

Power lines can transfer electricity relatively easily and efficiently for up to hundreds of kilometres from a location that is optimal for generation (e.g. in the desert for solar plants) to the point of use (e.g. a green ammonia plant located near a seaport).

The availability of zero-climate-impact electricity – taking into account direct and indirect impacts – is crucial to the development of green ammonia. Ammonia production requires significant amounts of energy - roughly two units' worth of energy (electric power) to produce one unit of ammonia. Therefore, when calculating the lifecycle climate benefits of using green ammonia as a fuel, the opportunity costs vis à vis the overall low-carbon energy transition, and the resulting potential indirect emissions, must be considered. These means that, unless it is produced with a stable supply of renewable electricity that is actually surplus (taking into account the intermittency of wind and solar, the overall demand for renewable infrastructure, and the overall demand for electricity), using ammonia to power ships could potentially increase emissions. But if in the future there is sufficient zero-climate-impact electricity, producing ammonia could generate benefits as a mechanism to store excess electricity production in a significant way. Moreover, each of these considerations can affect costs.

4. Vessel propulsion, onboard storage and emissions

4.1 There are multiple options for ammonia to be used to propel ships

There are potentially four propulsion options that could use green ammonia as a fuel:

1. Direct combustion in an internal combustion engine.
2. Direct combustion in a gas turbine.
3. Indirectly as a 'hydrogen carrier' for a hydrogen fuel cell system.
4. Chemical reaction of ammonia in a solid oxide fuel cell system.

Given that the shipping industry is built on the use of large diesel engines, the use of green ammonia-fuelled modified diesel engines is the most likely initial entry point for green ammonia as a marine fuel and will need to begin during the 2020s if the decarbonisation timetable is to be achieved

Options 1 and 2 involve direct combustion of ammonia. Combustion of ammonia in internal combustion engines dates to at least the Second World War, when ammonia was used to fuel buses in Belgium [41]. However, further development is required before ammonia could be used in modern engines or turbines, especially at the scale of ship propulsion. As described in Section 4.2, conventional internal combustion engines need to be modified to operate on ammonia and initially a second support fuel might be required.

Combustion Engines

The available research on the direct use of ammonia is somewhat limited but the potential is shown by the commitment of leading engine and turbine manufactures to invest in developing ammonia-fuelled options [42, 43]. For example, MAN Energy Solutions is working with Kyushu University in Japan to conduct ammonia combustion tests for the MAN ME-LGIP engine [44]; and Siemens has established an ammonia production, storage and combustion demonstration facility in Oxfordshire [31]. The Siemens facility includes a small off-the-shelf engine, which has been demonstrated to operate on ammonia without any modifications. Siemens staff have reported anecdotally that the engine has operated successfully on a mix of ammonia and hydrogen, but that the fuel supply system would require re-design to allow the engine to reach the rated output [45]. These early results are encouraging, but further research and testing is required to modify larger marine engines to achieve optimal efficiency on ammonia.

Gas Turbines

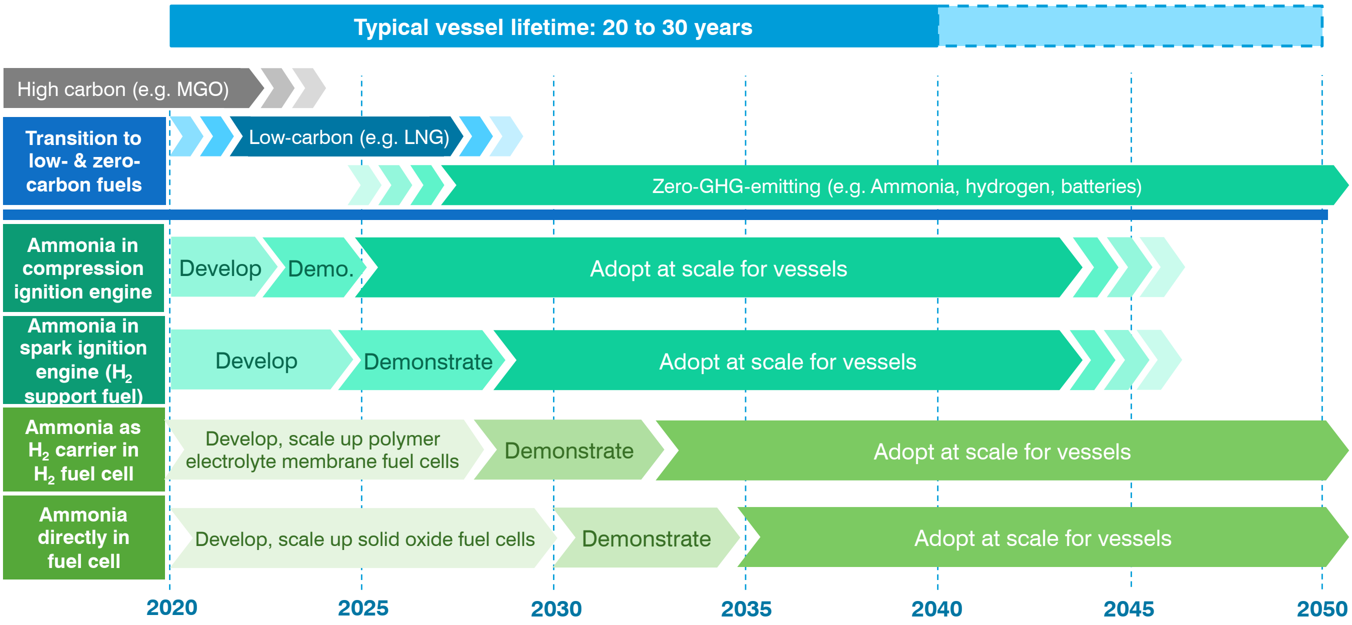
Although gas turbines (option 2 in the list above) are well established as prime movers in naval vessels, the relatively higher costs of the high-quality fuels have traditionally hindered their adoption in civilian vessels [46]. Gas turbines also generally operate at lower efficiencies than similar reciprocating engines, meaning that more fuel is required to travel the same distance. Demonstration projects have shown that it is possible to burn ammonia in a gas turbine together with a support fuel [47] and NASA has demonstrated a supersonic jet fuelled by ammonia [48]. However, further research and development is required for a commercially ready ammonia-fuelled turbine for ships. Although it is conceivable that ammonia-fuelled gas turbines could be suitable for some vessel applications in the future, they are not considered further in this paper.

Technology roadmap

This paper focusses on ammonia in combustion engines (Section 4.2) and fuel cells (Section 4.3). A possible roadmap for development and adoption of these technologies is shown in Figure 21.

FIGURE 21:

Technology roadmap for ammonia propulsion technologies



Given that the shipping industry is built on the use of large diesel engines, the use of green ammonia-fuelled modified diesel engines is the most likely initial entry point for green ammonia as a marine fuel and will need to begin during the 2020s if the decarbonisation timetable is to be achieved. Spark-ignition engines are also included in the possible roadmap in order to combust ammonia with hydrogen. During the 2020s, further development is required in the use of green ammonia in fuel cells to allow for their roll out in the 2030s. With the current state of development, the initial fuel cells will likely be the proton exchange membrane type, and this may over time give way to solid oxide fuel cells. Having a staggered multi-technology roadmap also allows to pave the way for supporting green ammonia infrastructure to be expanded at a suitable rate.

4.2 Ammonia can be used in internal combustion engines that are common in the maritime sector

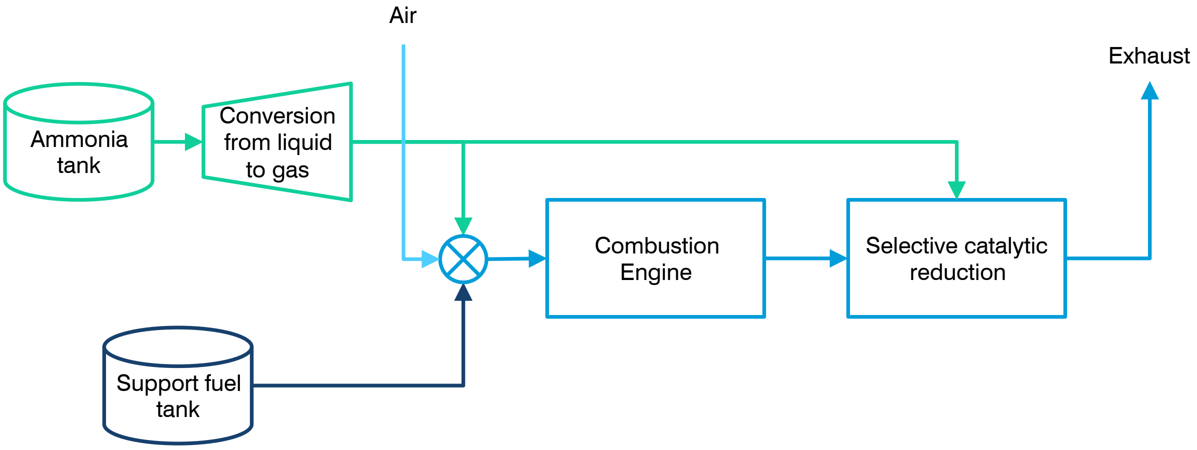
The flame characteristics of the combustion of ammonia have implications for the use of ammonia in engines. As well as a relatively narrow flammability range (15-25%), the flame produced has a relatively low propagation speed [49]. This means that the combustion conditions are unstable at very low and high very high engine speeds. To mitigate this instability, and for ignition, it is typically foreseen that ammonia will be supplemented with a support fuel in a dual-fuel engine.

For conventional large marine 2-stroke compression-ignition engines, this support fuel may be diesel, biodiesel or a synthetic diesel. Research is also underway investigating using ammonia in spark ignition engines. The use of a support fuel is also helpful to sustain stable combustion conditions. Suitable support fuels include carbon-based fuels such as petrol (gasoline), biogas, methanol or liquefied petroleum gas (LPG) [50] and carbon-free fuels such as hydrogen [51]. Further testing is required to explore some of the technical challenges and limitations, including on minimising the proportion of support fuel. However, early-stage testing by Iowa State University [52] has suggested that 100% ammonia combustion could be feasible.

A schematic diagram of an ammonia combustion engine with a support fuel is shown in Figure 22. This diagram includes 'selective catalytic reduction' as an after treatment system to reduce NO_X emissions from ammonia combustion, similarly to new fossil fuelled vessels in complying with Tier III requirements of Emission Control Areas. In fact, selective catalytic reduction equipment requires either ammonia or urea onboard to function, so new vessels operating in these areas would already need systems and standards to handle and store ammonia or urea anyway (see Section 4.6).

FIGURE 22:

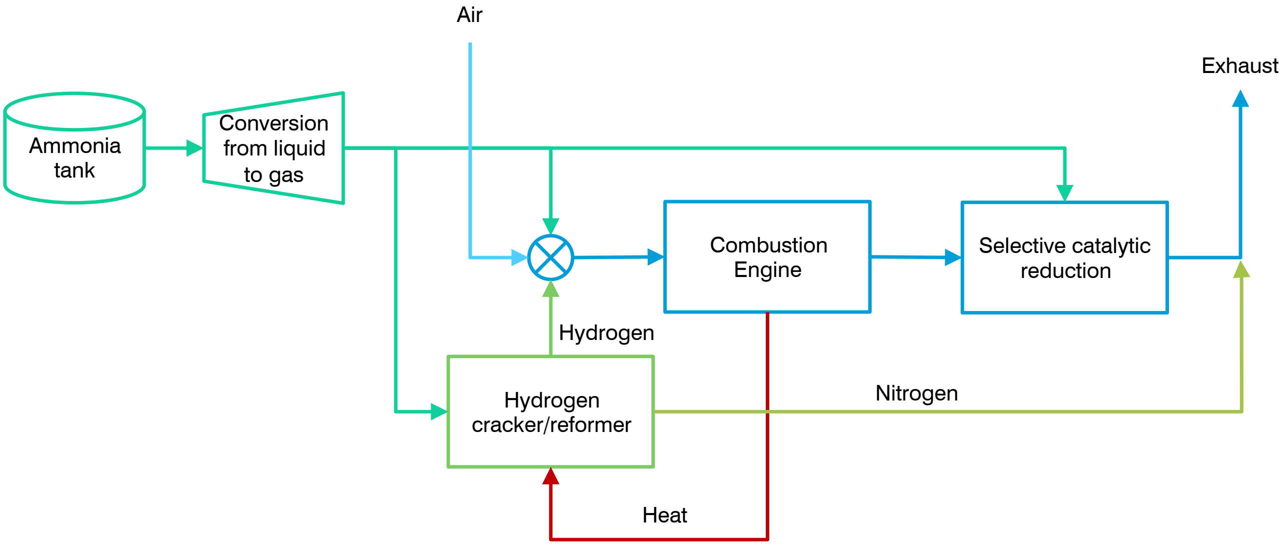
Process diagram of an ammonia combustion engine



Hydrogen itself can also be used to provide combustion stability as a mixture with ammonia in a spark ignition engine[12] [47, 53, 45]. Mixtures of approximately 30% hydrogen and 70% ammonia (by volume) have been reported [45, 54]. However, a separate fuel tank for hydrogen may not be a necessity because an on-board reformer sited between the ammonia fuel tank and the engine could be set up to crack a proportion of the ammonia into hydrogen (and nitrogen) to support combustion [49], as shown in Figure 23. Approximately 5% of the ammonia (in mass terms) would need to be sent to the cracker [52]. The cracking process itself is relatively simple, but further research and development is required to calibrate the rate of hydrogen cracking to support stable combustion conditions at variable engine loads and speeds.

FIGURE 23:

Process diagram of an ammonia combustion engine with hydrogen cracking system



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[12] The majority of research undertaken on the use of ammonia has been on spark ignition engines. However, some limited reporting on the use of compression-ignition engines running on ammonia have also been described.

Dual fuel engines are increasingly used in the marine industry. The additional fuel to complement the conventional liquid HFO/distillate fuel in ships delivered to date has been LNG, methanol, ethane or LPG. An increasing proportion of new engines installed in the maritime sector are dual fuel-capable, and the latest engines do not compromise on efficiency when running on alternative fuels [42]. This provides fuel flexibility to allow for compliance with a range of regulations and has the benefit of reduced CO_2 emissions from using lower-carbon fuels. Such engines are available for a wide range of marine applications from 5MW to 85MW, covering the full ship size range up to the largest vessels.

Therefore, it is encouraging that MAN, a leading manufacturer of marine engines, is planning to develop one of its engine models to run on ammonia with efficiencies in the region of 50% [55]. Furthermore, MAN also indicated that up to 3,000 existing engines could be retrofitted to run on ammonia [42].

MAN anticipates that a relatively short timeframe of 2.5 years would be required to develop and test its engine for ammonia-firing, which indicates that it is technically achievable to have new and retrofitted existing vessels with ammonia-fired engines in the 2020s (regulatory matters would need be considered quickly to avoid holding deployment up). It appears that the LPG storage is anticipated on deck for tankers and bulkers, which would allow for the accommodation of larger tank sizes for storing ammonia.

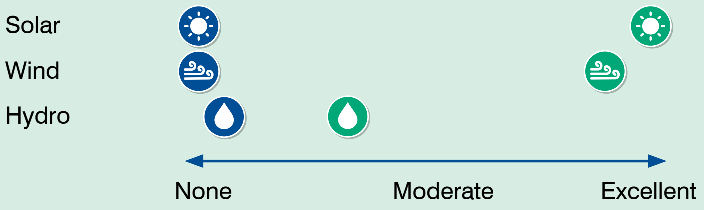
Greece

MINI CASE STUDY

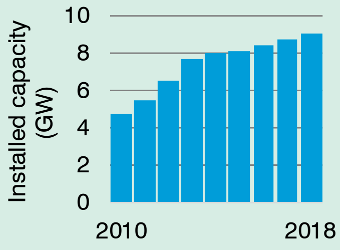
Total container volume through ports in 2017: 4.5 million TEU

Renewable resources

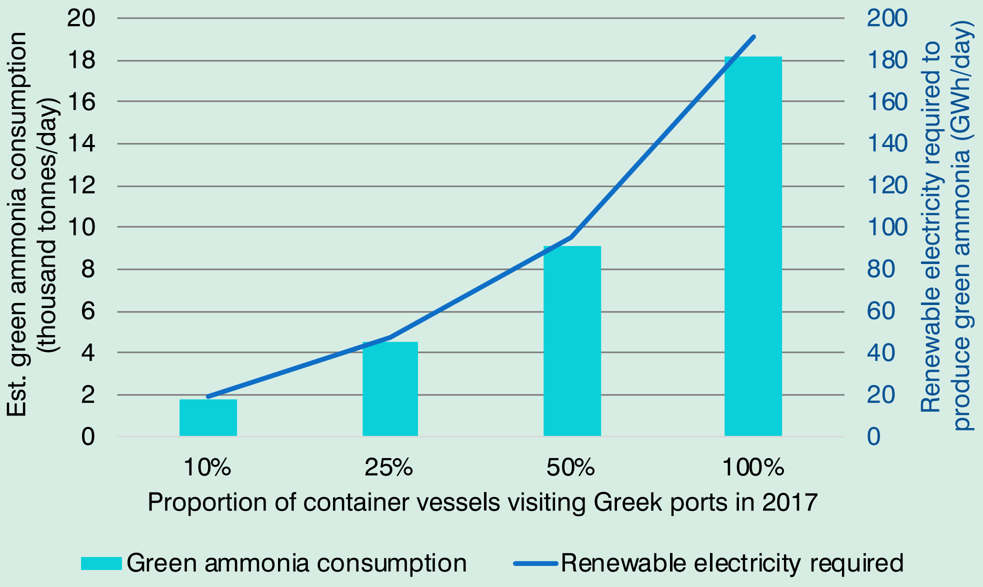
(blue icons: existing; green icons: potential)



Recent growth in renewables



Hypothetical green ammonia consumption & required electricity for container vessels in 2017



Note: Container vessel traffic for 2017 from the UNCTAD database [1]

Sources: [19] [104]

4.3 Ammonia could also be used within a fuel cell system

A fuel cell system could be used to generate the power on the vessel rather than a conventional engine. Fuel cells offer advantages over combustion engines of:

- The potential for higher efficiencies.
- Quieter and vibration-free operation.
- Negligible pollutant emissions.

Ammonia can be used directly in some fuel cell types, or hydrogen can be split from ammonia and used in other types of fuel cell.

The fuel cells most widely developed use highly purified hydrogen as a fuel in proton-exchange membrane fuel cells or polymer electrolyte membrane fuel cells (PEMFC) [56]. However, as discussed earlier, hydrogen has drawbacks when needing to be transported on a ship: low volumetric density and the need for cryogenics.

This is where ammonia can offer advantages as a hydrogen carrier. Ammonia is a promising hydrogen carrier due to its high hydrogen density and ease of liquefaction [57]. To store the same energy as a quantity of liquid hydrogen, ammonia takes up 46% less space because the stronger nitrogen-hydrogen bonds make it denser.

Ammonia can be used as a hydrogen carrier for hydrogen fuel cells

Hydrogen fuel cells are a mature technology that are already being tested in the shipping industry [58, 59]. An onboard plant would be necessary to crack the hydrogen from the nitrogen of the ammonia before use in a hydrogen fuel cell. The fuel cells identified as most promising for the maritime sector are proton exchange membrane fuel cells and solid oxide fuel cells [60]. For use in a proton exchange membrane fuel cell, hydrogen treatment equipment would be necessary onboard to reach the high purity levels required. This would involve additional costs as well as larger mass, volume and energy demand onboard. However, solid oxide fuel cells are earlier in the development cycle and can also be fed by ammonia directly, as described below.

Ammonia can be used directly in some fuel cells

Fuel cell systems operating on ammonia directly, instead of separating the hydrogen first, could offer higher efficiencies. This is because it would avoid the need for hydrogen cracking equipment [61]. The proton-exchange membrane fuel cells that are suitable for hydrogen as a fuel are not suitable for using ammonia directly. However, there are alternative fuel cell technologies available; the most promising option for ammonia is solid oxide fuel cells.

The high temperatures within solid oxide fuel cells (up to 1,000°C) encourage the rapid decomposition of the ammonia into hydrogen and nitrogen at a rate high enough to provide performance similar to hydrogen fuel cells [62]. Solid oxide fuel cells hold much promise for the future, but research and development is needed in the next few years before they can be rolled-out at scale. Areas of attention include optimisation of operation and determining suitable materials to handle the thermal stresses and so increase the system lifetime [63].

Ammonia is compatible with many common materials including carbon and stainless steels (in liquid and anhydrous states). This means that most standard pipes, fittings and valves can be used with ammonia.

4.4 Onboard storage and handling of ammonia

Transportation and storage of ammonia is established primarily through existing industrial applications. Ammonia is generally transported in its liquid state to avoid undetectable leakage and to occupy less volume. There are two methods to storing ammonia and maintaining its liquid form. The first is to store it in pressurised containers at a minimum pressure of 1.72MPa (17.2 bar). The second is to cool it to -33°C at atmospheric pressure [64]. The most suitable solution (refrigerated vs pressurised vs semi-refrigerated) for onboard ammonia fuel storage tanks is still to be determined.

Ammonia is compatible with many common materials including carbon and stainless steels (in liquid and anhydrous[13] states). This means that most standard pipes, fittings and valves can be used with ammonia [65]. However, ammonia corrodes copper, brass and zinc containing alloys [32] as well as natural rubber and some plastics.

Existing bulk ammonia transport vessels are designed to be explosion proof and have pressure relief valves [66]. They are designed according to the prescribed requirements of the 2014 International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). While the storage of ammonia represents a cost increase from storage of conventional liquid fossil fuels such as gas oil, it is not a burdensome requirement when compared with cryogenic storage of hydrogen.

As ammonia gas is toxic and harmful to human health (see Section 5.1), gas detection systems are required around the vessel near any ammonia fluid handling equipment that have a significant leak probability. Sensors need to be positioned at human breathing height or directly above the potential sources of leakage because ammonia is lighter than air [67]. Ammonia handlers must wear the appropriate chemically resistant protective clothing. Eye cleaning stations and safety showers should be provided within the vicinity of the onboard storage units [68].

As a matter of course for compliance with Tier III NO_X standards in NO_X ECAs, many vessels built from 2021 may use selective catalytic reduction (SCR) systems to control NO_X. SCR systems rely on ammonia to reduce the NO_X to form nitrogen and water in the presence of a catalyst. Therefore, these vessels and their crews will already be set up for the safe storage and handling of ammonia or urea onboard.

FIGURE 24:

Ammonia can be safely used on board ships using established materials and safety processes

4.5 Green ammonia can deliver at least a 95% reduction in lifecycle greenhouse gas emissions

Ammonia does not contain carbon, so it produces zero CO_2 emissions at the point of use (similarly for the other zero-GHG-emitting marine propulsion options of renewable energy-derived hydrogen and batteries). Other greenhouse gases are not a concern – neither methane nor nitrous oxide (N_2O).[14]

Analysis from a lifecycle perspective is the most rigorous approach to comparing greenhouse gas emissions of green ammonia with conventional fossil fuels (i.e. taking into account the emissions associated with the production and transport of the fuel as well as its consumption). On its own, the use of green ammonia (or renewably produced hydrogen) is reported to offer nearly a 95% reduction in lifecycle greenhouse gas emissions compared with HFO, desulphurised HFO or marine distillates [69]. With the appropriate renewable-powered operations during the production, transport, storage and refuelling stages prior to use in the ship, the lifecycle greenhouse gas emissions of green ammonia ought to approach zero.

---

[13] As a gas at atmospheric pressure and ambient temperature, it is referred to as ‘anhydrous ammonia’.

[14] No monitored evidence has been identified to suggest that N_2O emissions would be higher than from conventional diesel engines. In fact, some theoretical results suggest N_2O emissions from ammonia combustion would be expected to be lower than from combustion of fossil fuels [54].

With the appropriate renewable-powered operations during the production, transport, storage and refuelling stages prior to use in the ship, the lifecycle greenhouse gas emissions of green ammonia ought to approach zero.

As identified in Section 4.1 and Figure 21, the most likely initial step in the use of ammonia fuel will be in conventional diesel engines together with a supporting fuel, which could contain carbon. Therefore, the greenhouse gas emission reductions from the use of ammonia in diesel engines in combination with another fuel will have the greenhouse gas emissions associated with that fuel. The options for operating slow speed diesel compression-ignition engines with ammonia together with other fuels include HFO and distillates (MDO/MGO). It has been shown that the power density and efficiency of engines operating on a mix of ammonia and diesel (where diesel provides less than 5% of the total fuel energy) are similar to those of pure-diesel operation [70]. MAN Energy Systems confirmed that it expects after development, ammonia-firing in its dual-fuel LPIG engine will match the performance on 100% diesel [43].

A likely parallel development pathway sees ammonia combusted in spark-ignition engines together with hydrogen (e.g. cracked from ammonia) [51, 71], LPG or petrol for example.

The proportion of support fuel in the mix will affect the direct greenhouse gas saving offered by ammonia. For example, a mixture of 50% HFO and 50% ammonia will offer a saving of 47.5% in greenhouse gas emissions from running solely on HFO (based on the 95% saving quoted above). And a mixture of 5% marine distillate pilot fuel and 95% ammonia would offer 90% greenhouse gas emission savings compared to running solely on marine distillates. Tests conducted at Iowa State University on a diesel engine rig with ammonia injection achieved stable engine power output with a 5% diesel support fuel [72].

4.6 Ammonia use leads to significant reductions in air pollutants

The exhaust pollutants from ships combusting fossil fuels impact on human health and on the environment apart from greenhouse gas impacts. Pollutants of particular concern from the combustion of fossil fuels are SO_2, NO_X, particulate matter, as well as toxic heavy metals, hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) which (together with unburnt fuel) manifest as particulate matter. The impacts can have effects locally (e.g. in ports) and regionally as air pollution is blown in-land by the wind. Chemical reactions in the atmosphere involving pollutants such as NO_X and SO_2 (as well as NH_3 from other sources) lead to the formation of components of secondary inorganic particulate matter, thus increasing the overall contribution to particulate matter at a regional level. At a very local level, emissions of pollutants can have direct health impacts on the ships' crew and passengers (if applicable) through either workplace exposure or on the upper-deck downwind of the funnel on passenger vessels.

Combustion of ammonia in engines eliminates most of these toxic pollutants. Sulphur dioxide, carbon monoxide, heavy metals, hydrocarbons and PAHs should be eliminated completely and particulate matter should drop substantially. The use of ammonia in fuel cells eliminates these further by avoiding combustion products altogether. Unintentional releases of ammonia (as leaks or unburned ammonia) would need to be avoided because ammonia is an aerosol precursor which contributes to particulate matter concentrations.

A key air quality pollutant that is not eliminated when combusting ammonia is NO_X. Control methods for reducing NO_X emissions are already widely in place in land-based industrial installations and in the transport sector. One of the most prevalent techniques is SCR technology, which is an end-of-exhaust pipe technique that uses ammonia as a reductant to reduce the NO_X to nitrogen and water vapour in the presence of a catalyst [73]. Urea is often used as the dosing reagent (forming ammonia when heating with exhaust gases), but ammonia would already be present on the ship in the case of an ammonia-fuelled ship. While the IMO's Tier II requirements on NO_X emissions from new marine engines produced since 2010 do not need SCR to be fitted to meet the limits, the IMO Tier III requirements that are applicable in designated NO_X Emission Control Areas (such as the North Sea and English Channel and Baltic Sea from 2021) would need SCR or other similar NO_X-controlling techniques or lower-NO_X fuels to meet them. Therefore, there are likely to be plans for fitting SCR equipment to new vessels produced from 2021 that are going to be sailing in NO_X Emission Control Areas. N_2O emissions can also be generated by SCR systems, so the calibration of SCR systems to minimise N_2O emissions will be important to avoid greenhouse gas penalties [74].

Releases of gaseous ammonia (e.g. leaks, or incomplete combustion) directly into the air would contribute to acid deposition and eutrophication, which in turn, can lead to potential changes occurring in soil and water quality. It would be expected that any emissions of unburnt NH_3 should be possible to minimise through correct engine calibration and controlled combustion conditions by the manufacturers, or through the use of ammonia slip catalysts that are already well developed for land-based and road transport-based SCR solutions. Further research is required into the combustion products of ammonia from well-calibrated engines designed to burn ammonia.

In addition to not producing greenhouse gases, ammonia does not contain any sulphur. This means, compared with the conventional fossil fuel options used by the marine industry (HFO and distillates), the use of ammonia would inherently comply with the IMO's fuel sulphur content standards.

The particulate matter emissions from the combustion of fossil fuels comprise unburnt fuel, sulphate and nitrate particles. Combustion of ammonia should decrease emissions of particulate matter compared to conventional liquid fuels due to the lack of metals, sulphur and other impurities but these would not be eliminated completely – some particles of unburned fuel would remain. The NO_X emissions may form secondary nitrate aerosols in the atmosphere, and potentially also ammonium nitrate. Further analysis is required on the particle size fraction distribution from combustion of ammonia. LNG for example leads to lower total particulate emissions than conventional marine fuels, but a higher quantity of ultrafine particles [75] and methane is a precursor to ozone in the troposphere, a harmful local pollutant. Table 2 provides a summary of the air pollutant impacts of ammonia when combusted in engines.

TABLE 2:

Summary of air pollutants from combustion of ammonia compared to other marine fuels

Pollutant	Fuel		
	Heavy fuel oil (HFO), Marine gas oil (MGO)	**Liquefied natural gas (LNG)**	**Ammonia (combusted in engines)**
SO_2 and metals	🟥 Present	🟩 Not present	🟩 Not present
Carbon monoxide and hydrocarbons	🟥 Present	🟥 Present or increased	🟩 Not present
VOCs and PAHs	🟥 Present	🟧 Reduced	🟩 Not present
NO_X	🟧 Needs SCR for Emission Control Area	🟩 Meets Emission Control Area without SCR	🟧 Needs SCR for Emission Control Area
Direct particulate matter	🟥 Present	🟩 Reduced	🟩 Reduced
Ammonia (NH_3)	🟧 NH_3 slip catalyst required with SCR	🟩 Not present	🟧 NH_3 slip catalyst required

🟩 Best performing 🟧 Acceptable 🟥 Problematic

Sources: [52, 76, 77]

5. Ammonia’s risk profile and transport options

5.1 The safety risks associated with ammonia are well understood and manageable

Anhydrous ammonia is a colourless but pungent inorganic gas at atmospheric pressure and ambient temperature. Except in particularly humid environments, it is lighter than air and so will rise if released. It readily dissolves in water to form ammonium hydroxide [78]. Its boiling point is -33°C, and hence it can be stored as a liquid below this temperature at atmospheric pressure; the liquid is not considered to be cryogenic but can still cause frostbite if applied to the skin.

From a flammability perspective, ammonia is safer than other fuels – it is not very flammable, having a slow flame speed and narrow flammability range in air of between 15% and 25%. Under the European Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures (Classification Labelling and Packaging Regulation), liquid anhydrous ammonia is classified as a category 2 flammable gas [79] and under the US system for identifying materials’ hazards (NFPA704) as flammability category 1 (‘non-flammable gas’: must be preheated before ignition can occur) [80]. This means that ammonia does not require a hazard pictogram for flammability, whereas flammable gases (e.g. LNG) and liquid fossil fuels (e.g. HFO and MGO) do require one.

However, ammonia is corrosive and toxic via inhalation with a classification under the European Union’s Classification Labelling and Packaging Regulation of Acute Toxicity 3 (with 1 being the highest level of risk). This corrosive effect can cause severe skin burns and eye damage as well as acute respiratory symptoms. Consequently, the ammonia industry has well-specified safety processes to avoid exposure. In the United Kingdom, for example, workplace exposure limits for ammonia are 25 parts per million (ppm) over 8 hours, and 35ppm over 15 minutes [81]. Areas where workers are regularly carrying out activities need to be monitored to ensure that these limits are not exceeded. The immediately dangerous to life and health level for ammonia is 300ppm [82], which is substantially lower than the lower explosive limit (150,000ppm). However, its odour can be detected by humans at concentrations below 1.5ppm, significantly lower than concentrations that produce eye, nose or throat irritation. Although ammonia has a strong odour, it should not be detectable unless there is a leak.

Personal protective equipment is required for personnel who are directly handling ammonia: a gas-tight suit and self-contained breathing apparatus [83]. Additionally, for handling refrigerated ammonia, thermal protection may also be necessary. In low hazard areas, as a precaution, ammonia can be filtered from the air using a mask. An appropriate minimum level of protection can be achieved by wearing chemical protective splash suits, boots, protective goggles and gloves. As ammonia is water-soluble, decontamination of equipment and personnel can be carried out using water. In the event of a release, water curtains can also be used to ‘knock down’ ammonia vapour.

As with all gases stored as liquids, there is also a risk of gas expansion: in the event of a release of liquid ammonia, a large volume of air could quickly be displaced by expanding ammonia gas, particularly in confined spaces.

In marine environments, a release of liquefied ammonia would float on the water surface, rapidly dissolving into the water body as ammonium hydroxide, and at the same time releasing gaseous ammonia. In dry air, the gaseous ammonia would evaporate upwards and be dispersed by the prevailing wind conditions, with impacts on local populations (human, plant, animal) due to its toxicity varying based on the quantities released. The toxic hazard at ground level will be smaller at lower wind speeds. For aquatic life, the potential impacts will vary according to the water temperature, pH and salinity. Spills would lead to mortality for aquatic life, and the extent of the range affected would depend on the quantities released.

Appendix A provides a summary of hazards associated with ammonia and compares them with other current and future marine fuels (with summary using the US NFPA system, and specific hazards classification according to EU Regulation 1272/2008 as amended).

A pathway for developing rules and regulations governing new marine fuels is well established and has been demonstrated by recent development of rules for methanol and ethanol:

- 2013: DNV-GL: Tentative Rules for Low Flashpoint Liquid Fuelled Ship Installations.
- 2016: Lloyd's Register: Provisional Rules for the Classification of Methanol Fuelled Ships.
- 2018: IGF Code - International Code of Safety for Ships Using Gases or Other Low Flashpoint Fuels (draft interim guidelines).

A similar pathway would be followed for ammonia and has already been started. In an interview [43], a representative of MAN Energy Solutions said that MAN is already working with DNV-GL and Navigator Gas on an early-stage risk assessment to use ammonia as a maritime fuel.

5.2 There are established methods of transporting ammonia on water and on land

There are many different options for transporting ammonia, considering that it can be transported as a liquid or a gas, depending on the volume and distance. LPG vessels are generally used for maritime transport of bulk ammonia [84, 85], as shown in Figure 25.

Vessels with pressurised tanks are typically used for small scale applications up to about 3,000 tonnes of ammonia. Pressurised storage involves higher up-front cost, but lower operating costs than refrigerated tanks. Refrigerated tanks become more economical at larger storage volumes [87]. Semi-refrigeration provides an intermediate solution for medium sized vessels around the 3,000 tonne mark, where a combination of pressure and cooling is used [88]. Thus, for the quantities to be transported as a marine fuel, refrigeration is the most likely option. Barges can also be used to transport large volumes of ammonia along inland waterways [86].

FIGURE 25:

LPG carriers can be used to transport ammonia in bulk

Similarly, as shown in Figure 26, there are multiple options for transporting liquid ammonia on land. For land transport, individual tanks are smaller than for vessels, so liquid ammonia is generally transported as a pressurised liquid rather than refrigerated. Similarly, for pipelines, pressurisation is preferred to avoid the need for excessive insulation. However, if the transport option involves the use of fuels that emit greenhouse gases, then this would increase the lifecycle emissions of green ammonia.

FIGURE 26:

Options for transporting ammonia on land

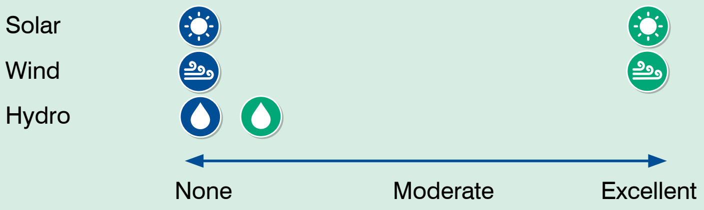
South Africa

MINI CASE STUDY

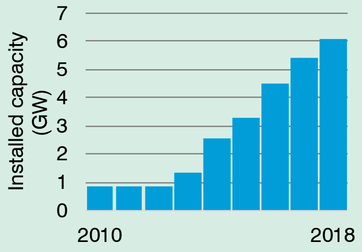
Total container volume through ports in 2017: 4.6 million TEU

Renewable resources

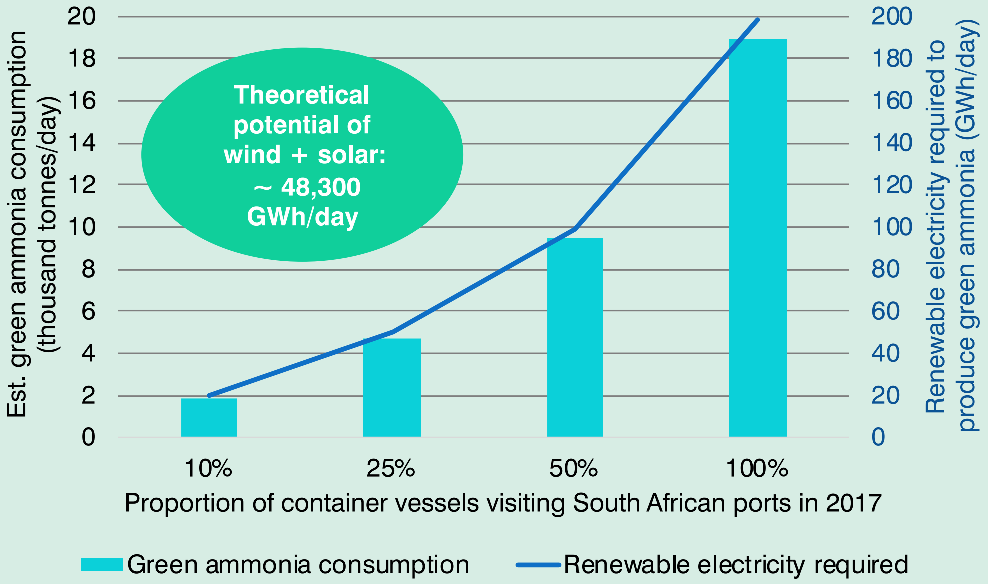
(blue icons: existing; green icons: potential)



Recent growth in renewables



Hypothetical green ammonia consumption & required electricity for container vessels in 2017



Only areas with a wind turbine capacity factor of 0.3 and above (in [18]) are included in the quoted potential.

Note: Container vessel traffic for 2017 from the UNCTAD database [1]

Sources: [19] [18] [105]

6. Estimated level of investment

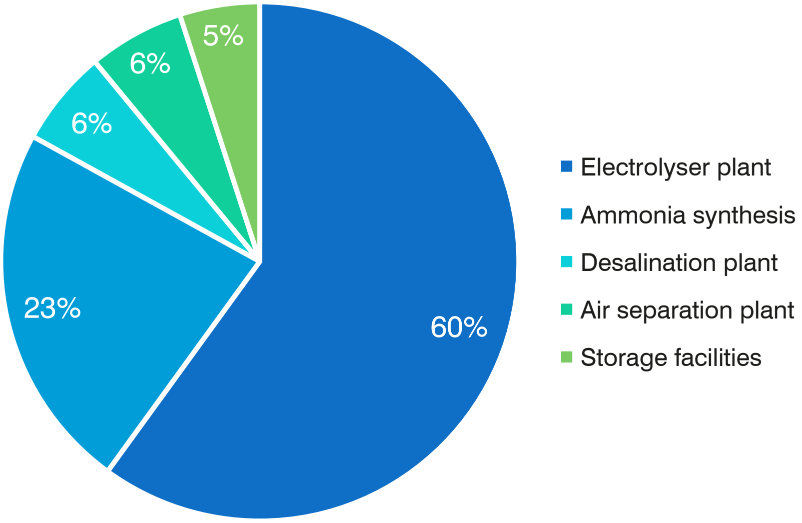
6.1 Green ammonia is a great investment opportunity in sustainable infrastructure

The cost of building a green ammonia plant with a capacity of 700 tonnes per day (tpd)[15] was estimated to be between USD620 and USD791 million. This excludes the cost of the renewable energy facilities required to supply the green ammonia plant with electricity[16]. A 700 tpd plant is approximately equivalent in energy terms to the daily fuel consumption of 4 post-Panamax size vessels.

Figure 27 provides a breakdown of the capital cost contributions for each part of the green ammonia plant. The electrolyser plant represents 60% of the overall capital costs. The values used in this analysis are for multiple modular alkaline electrolysers obtained from an industry survey [91]. However, a feasibility study by Morgan [92] suggests that there is potential to combine and share elements of the electrolyser common plant, which could reduce capital costs. Morgan estimated that theoretical capital cost savings of up to 50% for the electrolyser plant could be achieved in this way. There is also opportunity to design the ammonia synthesis (Haber-Bosch) process to capitalise on economies of scale. Further investigation is required to examine the potential for further capital cost reductions.

FIGURE 27:

Proportion of capital costs for a green ammonia plant



The references provide differing views about whether the costs of components are likely to fall in the future. Since the plant is comprised of well-established technologies manufactured primarily from commonly available materials, it is unlikely that the prices of individual components will fall significantly in the future. However, as the industry designs, builds and operates more plants at this scale, it is likely that increases in efficiency will be achieved through innovation and improvements in process design.

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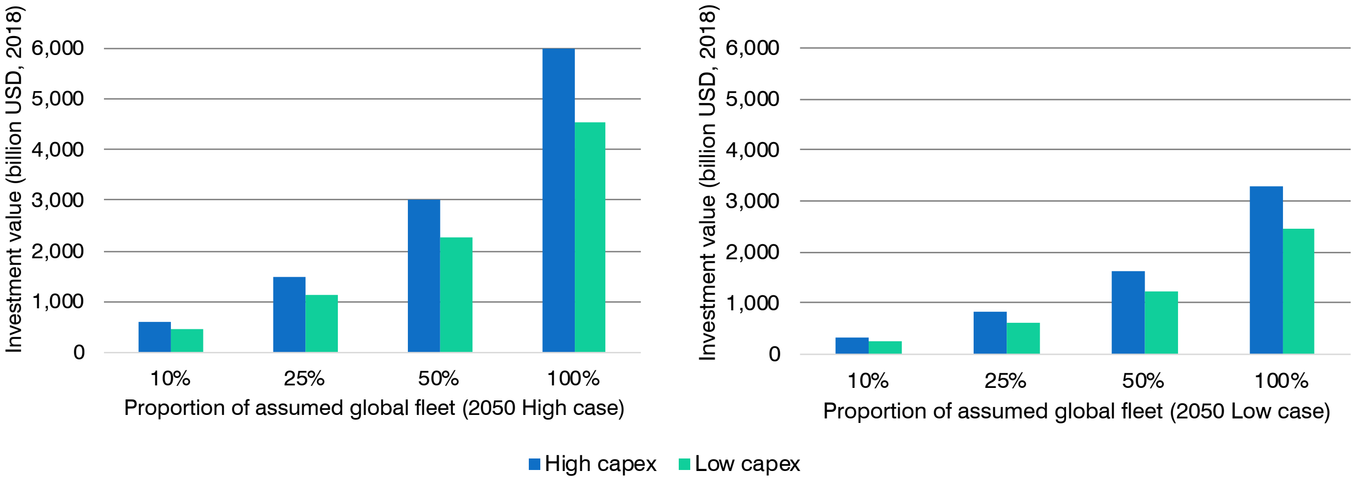
[15] This chapter provides an initial partial analysis of the investment required to realise some of the vision of this paper. A fuller assessment would be required for definitive figures. See Appendix E for details about methodology and input assumptions for the financial analysis.

[16] As noted in the Morocco case study, the renewable plants make up between 70% and 80% of the total investment value (i.e. the capital cost of the green ammonia plant plus the capital cost of the renewable energy plants), depending on the technology mix and future costs.

The graphs in Figure 28 show the range of aggregate investment potential under the High case and Low case development scenarios for the 2050 fleet (see Section 2.5 for an explanation of the scenarios).

FIGURE 28:

Potential investment value in green ammonia plants and supporting renewable energy facilities to 2050



The assumptions for the costs of renewable energy plants (included in the investment values in Figure 28) are described in Appendix E, which are made up of 40% solar PV, 40% onshore wind, 10% concentrated solar and 10% offshore wind. With these assumptions, the renewable plants make up approximately three quarters of the total investment cost in both scenarios.

Figure 28 shows the wide range of potential investment value, depending on the development of international trade between now and 2050 and the adoption rate of green ammonia. The graphs indicate that a total investment value of up to 6 trillion United States dollars would be required in green ammonia plants and associated renewable energy plants around the world to decarbonise the international container vessel and non-coal dry bulk carrier fleets between now and 2050.

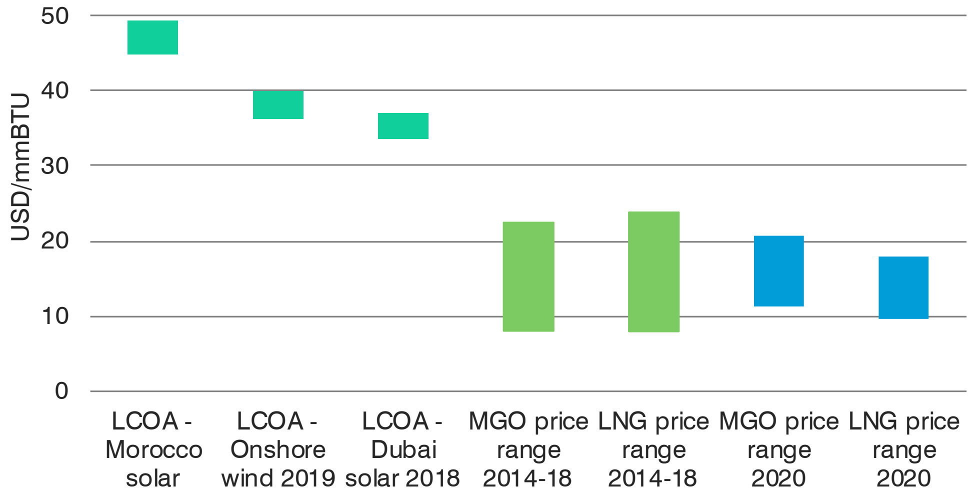
6.2 Adoption of green ammonia will require coordinated policy and regulatory incentives

The financial analysis used the cash flow for the construction and operation of the hypothetical 700 tpd plant to generate 'levelised cost of ammonia' (LCOA) estimates. The levelised cost methodology, which is commonly used for infrastructure projects, calculates the net present value to give the discounted cost per unit of ammonia produced based on the construction costs (capital costs) and the costs of operation and maintenance. Therefore, the LCOA indicates the price of ammonia required for the plant to break-even financially over its lifetime. Consequently, it can be used as a proxy for the price of ammonia and compared against the prices of other fuels in the market.

The results of the LCOA analysis with a discount rate of 7.5% are presented in Figure 29.

FIGURE 29:

Levelised cost of ammonia compared with other marine fuels[17]



Three cases were considered for the LCOA calculation to investigate the effect of electricity price on the results (potential costs of using the network and costs associated with mitigating indirect effects were not considered):

1. Calculated with an electricity price equal to the tariff awarded to the Noor PV 1 project in Morocco in 2016 (USD43.20/MWh) [93] with a 10% reduction to account for reductions in solar PV prices since then. The plant started production in 2018.
2. Calculated with an electricity price equal to the levelised cost of electricity for onshore wind in 2018 published by Lazard (USD29/MWh) [94].
3. Calculated with an electricity price equal to USD24/MWh in 2018, which is the tariff for the Mohammed bin Rashid Maktoum Solar Park in Dubai (the lowest published tariff for solar PV) [95].

Four other reference prices are given for comparison:

1. The historical price range of marine gas oil between 2014 and 2018 [96].
2. The historical price range of liquefied natural gas between 2014 and 2018 [96][18].
3. Predicted price of marine gas oil in 2020 based on an average of estimates by EnSys and Navigant [97] and CE Delft [98] and a ± 30% range added.
4. Predicted price of marine gas oil in 2020 based on UMAS estimates in 2018 [27] with a ± 30% range added.

Figure 29 indicates that, initially at least, green ammonia would not be able to compete directly with fossil fuels if the social costs of greenhouse gas emissions are not internalised. To encourage early adopters, a mechanism should be developed to incentivise the development and deployment of zero carbon fuels and avoid inadvertently penalising early adopters. This has been done successfully in other sectors that have embraced greenhouse-gas free technologies that were initially more expensive than traditional fossil fuels. Examples include renewable electricity generation, where various policy support mechanisms encouraged technologies such as solar and wind to enter the market. There are now established global markets for solar PV and onshore wind technologies, which has reduced costs significantly in recent years such that they are now competitive with fossil fuel alternatives in some jurisdictions [99].

To encourage early adopters, a mechanism should be developed to incentivise the development and deployment of zero carbon fuels and avoid inadvertently penalising early adopters. This has been done successfully in other sectors that have embraced greenhouse-gas free technologies that were initially more expensive than traditional fossil fuels.

Furthermore, the LCOA results summarised in Figure 29 indicate that the price of ammonia is relatively sensitive to electricity prices. The cost of electricity represents 45%, 30% and 25% of the total levelised cost for the Moroccan solar, onshore wind and Dubai solar cases respectively. Therefore the cost of producing green ammonia will reduce as the price of renewable electricity continues to decrease in the coming years in accordance with recent trends and expectations of the electricity industry.

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[17] The ammonia costs might be higher if batteries are added to balance the intermittency of renewables.

[18] An additional USD6 per million British thermal units (mmBTU) was added for liquefaction, storage and onboard gasification.

7. Conclusions

Of the fuels available to decarbonise the maritime transport sector, green ammonia is one of the most technically feasible in the short term. The financial analysis indicates that for green ammonia to be able to compete with MGO, LNG and other fossil fuels on a financial basis the externalities associated with these fuels in terms of greenhouse gas emissions and local air pollution would need to internalised. Even then, for the early stages of deployment, policies to incentivise deployment will be required to underpin investment. These may be justified for a number of reasons, not least their contribution to development in poorer regions. Policy options to bring forward investment need to be discussed as a matter of urgency so that they can be implemented within the timescales required to achieve the IMO's decarbonisation targets.

The immediate focus should be on establishing policy that will drive the uptake of fuels that have zero climate impact on a lifecycle basis, taking into account consequences for direct and indirect emissions. Green ammonia should be considered in that fuel mix. Such policies should include regulatory requirements for the safety and environmental effectiveness of these fuels.

Internal combustion engines are being further developed so that they are optimised for use with ammonia, achieving acceptable efficiency levels. This should be further encouraged.

Although adoption in the 2020s will be driven by internal combustion engines, significant investment should be directed towards solid oxide fuel cell technologies with the aim of using them for vessel propulsion from the 2030s onwards.

Likewise, planning and preparation should begin immediately for the development of infrastructure to produce zero-climate-impact fuels, which could include green ammonia plants in locations with as yet untapped and surplus renewable power and water supplies, preferably near ports that could provide bunkering facilities. The plants should be designed with the aim of optimising equipment to capitalise on economies of scale and operate effectively with electricity supplied by renewable sources. Other areas identified for further research and development are summarised in Appendix E.

Green ammonia has the potential to be a vital part of the International Maritime Organization's strategy to meet and even exceed its decarbonisation targets. Moreover, demand from shipping could unlock investment in the supply chain for low carbon fuels such as green ammonia, and that supply chain investment can in turn help unleash greater investment in low-carbon industry and renewable electricity. This represents a unique opportunity for sustainable economic development and distribution of bunkering infrastructure.

Abbreviations

AEM	Anion exchange membrane
CO_2	Carbon dioxide
GHG	Greenhouse gas
HFO	Heavy fuel oil
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
km	Kilometres
LCOA	Levelised cost of ammonia
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MGO	Marine gas oil
mmBTU	British thermal units
MW	Megawatts
N_2O	Nitrous oxide
NO_X	Nitrogen oxides
PAH	Polycyclic aromatic hydrocarbons
PEMFC	Polymer electrolyte membrane fuel cells
PEM	Proton exchange membrane
PV	Photovoltaic
SCR	Selective catalytic reduction
SO_X	Sulphur oxides
SSP	Shared socioeconomic pathways
TEU	Twenty-foot equivalent units
tpd	Tonnes per day
TWh	Terawatt-hours
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar

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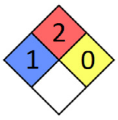
Appendix A: Comparison of safety and environmental hazards for selected marine fuels

	Marine Gas Oil	Liquefied Natural Gas	Methanol	Hydrogen (Liquid)	Ammonia (Liquid)
Physical Hazards					
Flammability	Cat. 3 H226 Flammable liquid and vapour	Cat. 1 H220 Extremely flammable gas	Cat. 2 H225 Highly flammable liquid and gas	Cat. 1 H220 Extremely flammable gas	Cat. 2 H221 Flammable gas
Gas under pressure	Not classified	H281 Contains refrigerated gas; may cause cryogenic burns or injury	Not classified	H281 Contains refrigerated gas; may cause cryogenic burns or injury	H280 Contains gas under pressure; may explode if heated
Health Hazards					
Acute toxicity	Cat. 4 H332 Harmful if inhaled	Not classified	Cat. 3 H301 H311 H331 Toxic if swallowed, in contact with skin, or inhaled	Not classified	Cat. 3 H331 Toxic if inhaled
Aspiration hazard	Cat. 1 H304 May be fatal if swallowed and enters airways	Not classified	Not classified	Not classified	Not classified
Skin corrosion	Cat. 2 H315 Causes skin irritation	Not classified	Not classified	Not classified	Cat 1/1B H314 H318 Causes severe skin burns and serious eye damage
Carcinogenicity	Cat. 2 H350 May cause cancer	Not classified	Not classified	Not classified	Not classified
Specific target organ toxicity	Cat. 2 H373 May cause damage to organs through prolonged or repeated exposure	Not classified	Cat. 1 H370 Causes damage to organs (single exposure)	Not classified	Not classified
Environmental Hazards					
Hazards to the aquatic environment	Category 2 (chronic): Toxic to aquatic life with long lasting effect (H411)	Not classified	Not classified	Not classified	Category 1 (Acute): Very toxic to aquatic life with long lasting effects (H400)
Summary					
Summary (US NFPA704)					

Appendix B: Technical information about green ammonia production

Electrolysis and hydrogen storage

The electrolysis of water is its decomposition into hydrogen and oxygen due to the passage of a direct electric current. It has been used to produce hydrogen industrially for well over a century. However, its share of current global hydrogen production is only 4% [107] with the traditional method being favoured. With a greater focus on reducing greenhouse gas emissions in recent years, interest in electrolysis has increased due to its ability to produce low- or zero-carbon hydrogen when coupled with renewably generated electricity.

There are three key electrolyser technologies on the market: alkaline, proton exchange membrane (PEM) and anion exchange membrane (AEM). Alkaline electrolysers have been successfully built at the scale of hundreds of megawatts (the sort of scale required for green ammonia production) since the 1920s and they account for nearly all the installed water electrolysis capacity today. PEM electrolysers have been commercially available for approximately 15 years, whereas AEM has only appeared more recently. While PEM technology offers some advantages in terms of dynamic system performance, making them more compatible with intermittent renewable generation, the technology is not as mature and capital costs are approximately double that of alkaline types [91].

An alkaline electrolyser consists of two electrodes, the anode and cathode, operating in an alkaline electrolyte solution. The passage of a direct electric current through the water causes oxidation at the anode and reduction at the cathode, leading to the overall reaction equation shown below:

$$2H_2O\,(l) \longrightarrow 2H_2(g) + O_2\,(g)$$

Electrolysers require high purity distilled water to operate. If the water is drawn from the sea, a desalination plant would be required as well. Only a mechanical vapour compression-type desalination plant can produce the high purity water required by alkaline electrolysers [92].

The primary methods of hydrogen storage are: compressed gaseous hydrogen, liquid hydrogen and storage in metal hydrides. Compressed gaseous hydrogen is most suited to the ammonia production process as metal hydrides are not yet commercially available for large scale systems and liquefied storage has significant energy requirements and high capital costs. As well as this, an alkaline electrolyser can be operated at either atmospheric or at an elevated pressure. Therefore, if operated at high pressure, the hydrogen output is ready for compressed storage with less additional energy input required.

Nitrogen production and storage

Nitrogen makes up 78% of the Earth's atmosphere and it is widely used in industry. There are three established air separation technologies: cryogenic distillation, polymer membrane separation and pressure swing absorption (PSA). Cryogenic distillation is the most commercially mature technology of the three and constitutes 90% of all nitrogen production today [89].

The reactors in the Haber-Bosch process require high-purity nitrogen, which is best provided by cryogenic distillation. It is also the technology that is most cost-effective and best suited to the scale of industrial green ammonia production.

Cryogenic air separation units (ASUs), separate air into its primary components, nitrogen and oxygen (and sometimes argon), by exploiting their various boiling point temperatures.

The air is first compressed and cleaned, then cooled either by cooling water or a gas stream. The various fractions of cold air then condense at different levels in the distillation column. The oxygen and nitrogen can be drawn off as a cryogenic liquid or vaporised by heat from the incoming air. In the case of large-scale nitrogen production, it is often extracted and stored in liquid form.

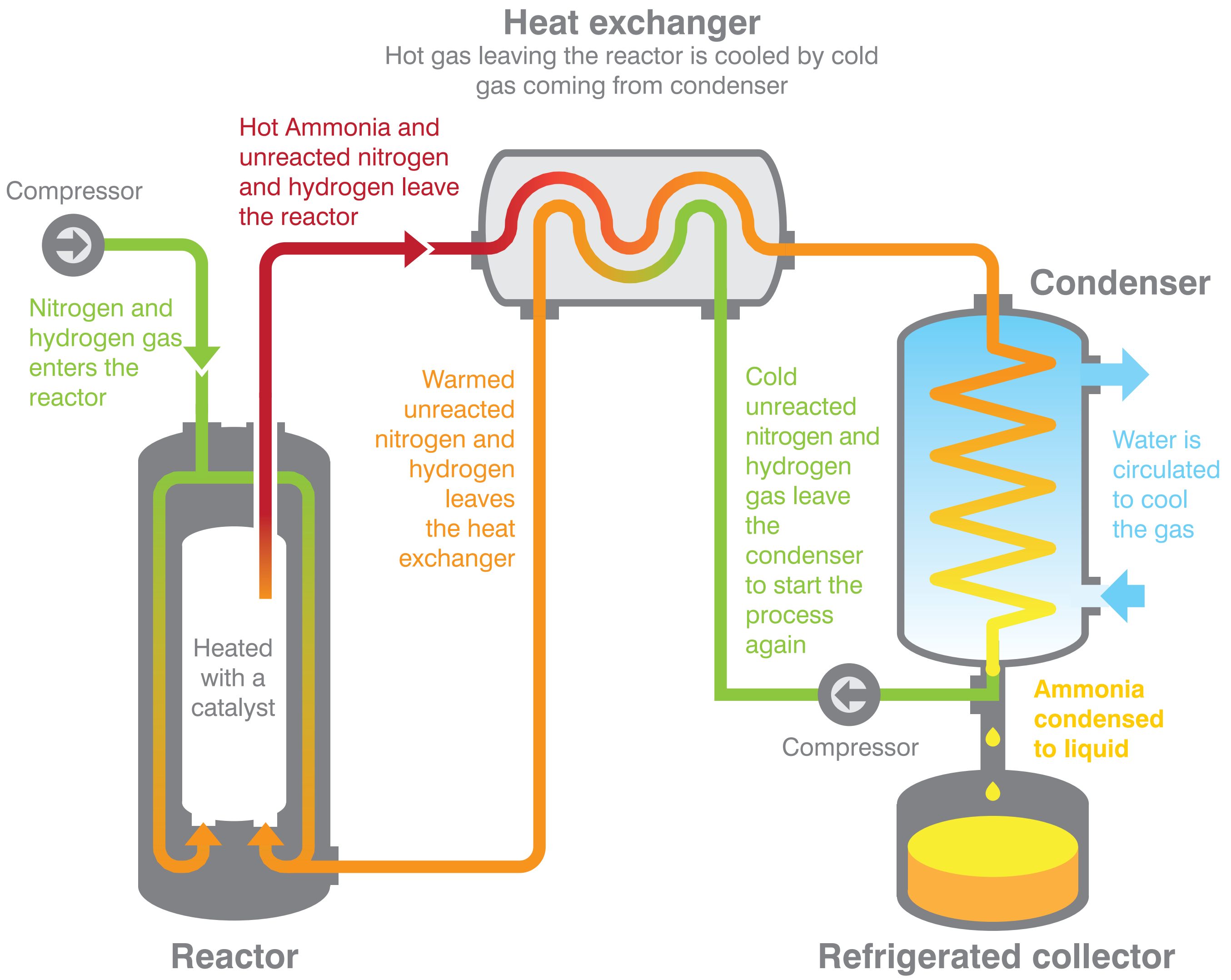
The Haber-Bosch process

The Haber process was invented in 1918 and improved to become the Haber-Bosch process in 1931. It has been used as the main way to create ammonia since that time. Therefore, it is a very mature technology.

The Haber-Bosch process is shown in Figure B1. Three-parts hydrogen and one-part nitrogen are passed through a compressor to reach a pressure between 20MPa and 40Mpa (200 bar and 400 bar) before being introduced to the reactor. Higher pressures are preferable but expensive to maintain. A temperature of 450°C is maintained for an acceptable yield and reaction rate. The reactor core contains a number of typically iron-based catalyst beds to increase the rate of reaction.

FIGURE B1:

Diagram of the Haber-Bosch process



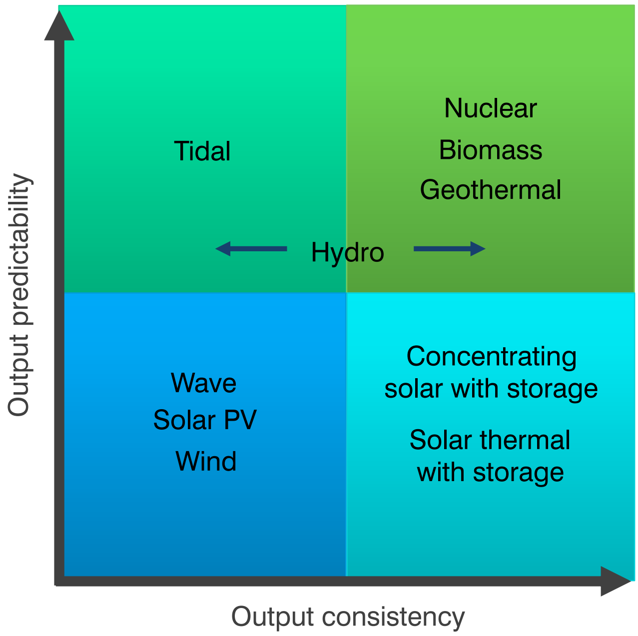
The exit stream of gasses is cooled to condense and separate the ammonia. Uncondensed nitrogen and hydrogen gases are recirculated back into the reactor. The continual recycling of the unreacted gases allows for overall conversion to reach 98%. The ammonia is stored in a low pressure, low temperature unit ready to be transported.

Appendix C: Overview of low-carbon electricity options

Various low-carbon technologies are shown in Figure C1, with their relative positions in terms of output consistency and predictability, which are important considerations for a green ammonia plant.

FIGURE C1:

Predictability and consistency of output for various low-carbon technologies



Consistency, shown on the horizontal axis, means the ability to control output within a desired band (i.e. that it does not fluctuate due to variability of the energy input). On the vertical axis, predictability means that, regardless of whether the output is consistent or not, variations in output can be predicted relatively accurately.

Solar PV and wind plants (without storage), for example, are often called 'intermittent' because their outputs vary based on weather conditions, making them inconsistent and relatively unpredictable. Similarly, wave energy plants are affected by weather conditions at sea. Tidal technologies are more predictable because they depend on tidal patterns, but they have low consistency because output fluctuates through the course of daily tidal cycles.

Concentrating solar and solar thermal technologies are often designed with integral storage facilities, so they can be controlled to provide a more consistent output than the intermittent sources. Although the output of hydro plants can be predicted relatively accurately based on rainfall and other hydrological conditions; the consistency of output depends on the size and type of hydro facility (run-of-river, dam or pumped storage).

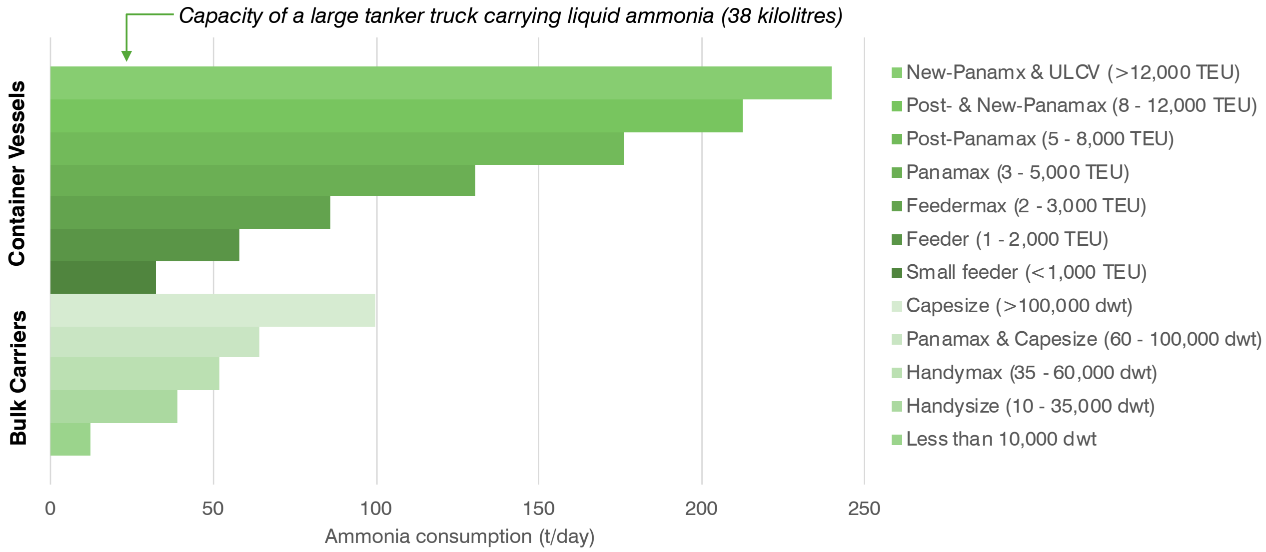
The green ammonia production process can be designed to operate with intermittent electricity sources (see Section 3.1 of the paper), but it is optimally suited to generation plants that can provide consistent and predictable output – like geothermal, some types of hydro, biomass, nuclear, or more intermittent sources combined with large energy storage devices.

Appendix D: Daily ammonia consumption

Figure D1 shows the estimated daily consumption of ammonia for various type of vessels[19].

FIGURE D1:

Estimated daily consumption of ammonia for various type of vessels

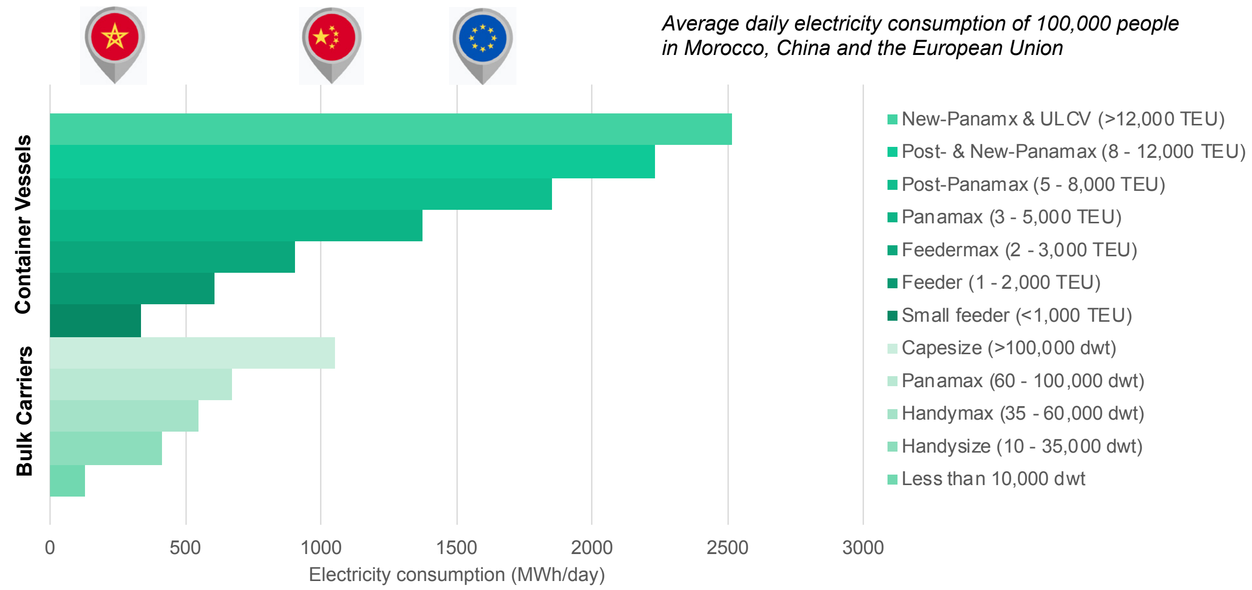


Capacity of a large tanker truck carrying liquid ammonia (38 kilolitres)

Figure D2 shows the estimated amount of electricity that would be required if a production plant was dedicated to supplying enough green ammonia to keep each of these vessels running continuously.

FIGURE D2:

Estimated electricity consumption required to produce green ammonia for each type of vessel



Average daily electricity consumption of 100,000 people in Morocco, China and the European Union

Source of per capita electricity consumption: [40]

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[19] Ammonia consumption was calculated based on the average at-sea conventional fossil fuel consumption for each vessel category listed in Table 4 of *Third IMO Greenhouse Gas Study 2014* [24], assuming that it is burned in an internal combustion engine at the same thermal efficiency as a liquid fossil fuel.

Similarly, Figure D3 shows the amount of demineralised water required to produce enough ammonia for each type of vessel (this excludes the water required for operation and maintenance of electricity plants).

FIGURE D3:

Estimated demineralised water consumption required to produce green ammonia for each type of vessel

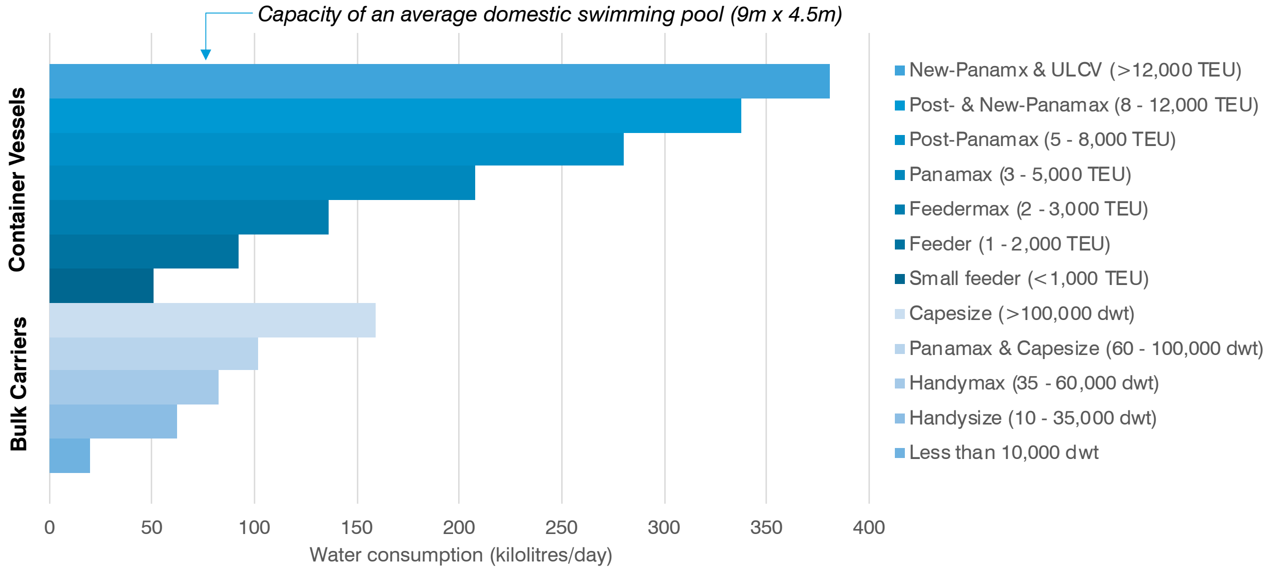


Figure D3 shows that a significant amount of water would be consumed. Many regions with high solar potential experience water scarcity, so this would need to be considered carefully. Since green ammonia plants are likely to be located near ports, desalination facilities can be incorporated into the design.

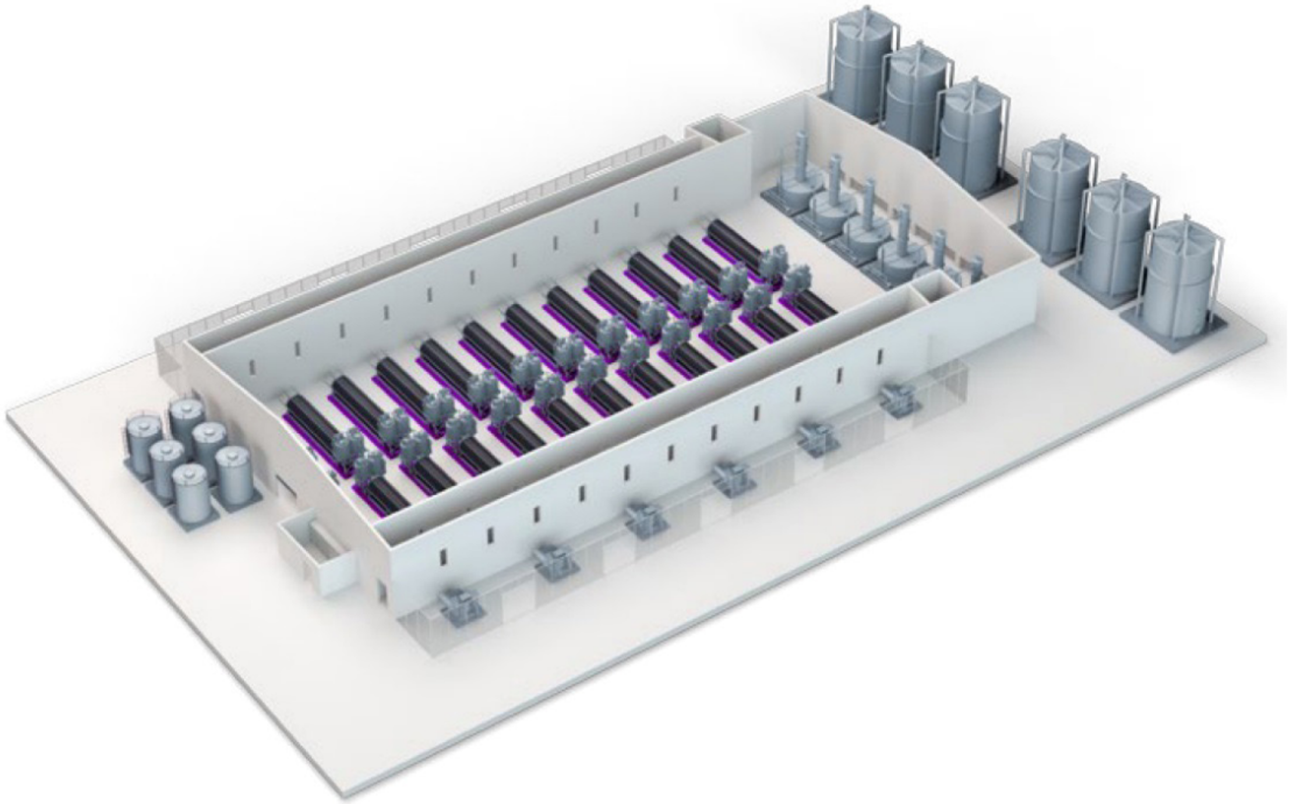
Appendix E: Methodology and inputs for financial analysis

A plant with a capacity of 700 tonnes of green ammonia per day (tpd) was used as the basis for the financial analysis, which is approximately equivalent in energy terms to the daily fuel consumption of 4 post-Panamax size vessels. Plants of this size would be considered mid-scale by the standards of ammonia plants using traditional fossil-based feedstock, with 'world scale' sizes in the region of 2,000tpd and above. However, green ammonia plants exhibit different economies of scale due to the electrolyser plant, as described below.

The common approach to designing electrolyser plants at this scale is to combine multiple modular units. A high-level survey of the current electrolyser market suggests there is a balance between unit size and ease of manufacture, which results in an optimal largest unit size of about 2 MW [91]. The 700tpd plant would require about 141 x 2MW units[20]. For example, Nel has a 50MW solution comprising 24 units (see Figure 30). Hence, the 700tpd plant would require about six similar warehouses.

FIGURE 30:

50MW Electrolyser plant from Nel



Source: [90]

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[20] Based on a power consumption of 55 kWh/kg of hydrogen produced.

This modular approach makes it challenging to achieve effective economies of scale with the electrolyser plant when more than about 10 units are used [90]. Although plant design optimisation was not considered for this paper, the electrolyser plant footprint becomes very large compared to other plant components at current world-scale production rates. Further investigation, including interviews with potential equipment suppliers and contractors, is required to examine the potential for further capital cost reductions through economies of scale in larger green ammonia plants.

A financial model was used to analyse the high-level costs of building and operating a green ammonia plant. The inputs to the model were obtained from indicative estimates provided in feasibility studies for green ammonia plants [89, 92] and major plant components [91], as listed in Table E1 below. A sensitivity analysis was used to indicate the confidence range of the results considering the uncertainties involved in the cost estimates.

The levelised cost of ammonia (LCOA) was calculated as follows:

$$LCOA = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{A_t}{(1+r)^t}}$$

Where:

I_t = Investment expenditures in the year t;
M_t = Operations and maintenance expenditures in the year t;
A_t = Ammonia generation in the year t
r = discount rate (rate of return); and
n = economic lifetime of the plant

TABLE E1:

Financial model assumptions

Description	Assumption	Source	Further details
Model start date	1 January 2019		
Project development period	1 January 2019 – 31 December 2020		Assumed based on similar chemical process plants
Construction period (including commissioning)	1 January 2021 – 31 December 2023		Assumed based on similar chemical process plants
Operational period	30 years		Assumed based on similar chemical process plants
Plant capacity	700 tpd		Informed by discussions with green ammonia industry experts
Annual operational hours	8,000 hours per year (~91%)	[110]	
Development costs	Prefeasibility study: USD100,000 Feasibility study: USD500,000		High-level estimate based on similar plants. Requires further investigation.
Land acquisition cost	Nil		Not considered to eliminate site specific assessment.
Ammonia plant investment costs	High capex case: USD791 million Low capex case: USD619 million	Ricardo calculation based on [89, 92, 91]	Parametric approach has been used. Includes desalination plant, alkaline electrolyser plant, hydrogen storage, nitrogen production and storage, ammonia synthesis plant ammonia storage.
OPEX (excluding utilities)	2% of CAPEX	[111]	Based on past experience on comparable projects.
Annual unplanned replacement cost	0.5% of electrolyser CAPEX per year	[109]	
Electrolyser refurbishment cost	15% of electrolyser CAPEX per year	[109]	Every 7 years
Haber-Bosch unit refurbishment cost	10% of Haber-Bosch unit CAPEX per year		Every 7 years
Average electricity consumption	306MW	Ricardo calculation	Based on green ammonia conceptual design
Electricity tariff	USD43.2 / MWh	[93]	10% discount has been applied on the latest bid by ACWA on Noor PV I Programme (USD48 / MWh) to reflect recent reductions in solar PV costs
Water production / usage	51.3 tonnes / hour	Ricardo calculation	Based on green ammonia conceptual design
Green ammonia production	29.2 tonnes / hour	Ricardo calculation	Based on green ammonia conceptual design
Water price	Nil		Desalination plant will produce purified water using sea water. No water intake cost has been considered.
Inflation	Nil		Real model: To exclude the effects of inflation and to be able to make comparisons which are not location specific.
Discount rate	7.50%	[19]	Typical rate used for renewable energy-related projects

The capital cost make-up is shown in Table E2.

TABLE E2:

Capital cost make-up (USD millions)

Description	High case	Low case
Desalination plant	46	31
Alkaline electrolyser plant	418	418
Air separation unit	52	35
Ammonia synthesis plant	236	110
Hydrogen storage	13	9
Nitrogen storage	7	4
Ammonia storage	18	12
Total capital cost	**791**	**619**

Note: In the absence of a detailed pre-feasibility study, the assumptions are mainly based on indicative estimates taken from publicly-available sources and therefore only a high-level economic analysis could be done.

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