D6.2 Foresight report on future availability of green/blue ammonia in 2030, 2040 and 2050

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Executive Summary

Until 2021, green ammonia production was very small with about 20 kt ammonia produced per year in Peru and with no known production of blue ammonia (i.e. without enhanced oil recovery). Now, the global green and blue ammonia production industry has, however as per 2022 announced 112 clean ammonia projects with a total production of 182 MTPA. Since the majority of the projects appeared in 2021 and 2022, it is expected that similar numbers will be announced in the coming years, and some of these projects may also contribute further to the 2030 supply of green and blue ammonia.

The projects are distributed globally, however with a large share of green ammonia projects located in Australia and the majority of the blue ammonia projects in the USA. The majority of the projects are in very early stage of development with inherent large uncertainty for their implementation. Nevertheless, 80% of the production capacity is announced to be available in 2030. Only 11-13% of the announced production capacity is of the blue variety.

There are a number of factors that determines the share of green versus blue ammonia in a country. An important one is the access to resources (like natural gas and renewable electricity potential) and their consumption in the local market. Excess of natural gas can be exported as the liquids LNG, methanol or ammonia. Ammonia is the only one of the three that comes without carbon, i.e. for the others the CO_2 has be removed by the consumer, whereas for ammonia the CO_2 can be removed centrally by the producer of blue ammonia if permanent storage sites are available. For green ammonia, there are a number of regions globally with large potential for wind and/or solar power, where the local demand for renewable electricity is limited and with good framework conditions, such that this potential can be exploited to export of green ammonia. Green ammonia is in principle scalable, since it only requires the resources of renewable electricity, water (including sea water) and air.

Another major factor is the production costs of green and blue ammonia. There will be competition both for green and blue ammonia, and with the alternatives in the various markets (like maritime fuel, fertilizers, power production and hydrogen production). This will depend on the regulations in the markets and GHG taxes and likely increasingly on the stakeholder’s expectations. Even though there will be a competition that depends on the purchasing power in these markets, there is also a positive interaction with learning curves that leads to reduced costs.

Unlike the current ammonia production, which is consumed mostly locally, the vast majority of future clean ammonia is targeted for international export. The distribution of size of the production facilities is dominated by the large plants above 0.1 MTPA, and 11 clean ammonia plants aim for production capacities larger than the largest ammonia facility today.

Today’s ammonia market is dominated by the fertiliser market (80% of the demand), but clean ammonia aims at new applications such as shipping fuel, power plants and as a hydrogen carrier. A majority of the producers (140 MTPA) aims to cater to multiple market sectors, with only 42 MTPA committing to a single end use. Many possible off takers will contribute to drive up the production amount.

Likelihoods of implementation were evaluated in this report, and this leads to decreased final ammonia output in 2030. Instead of the announced 182 MTPA, 33 MTPA is estimated to be available in the most realistic scenario. From these, about 11 MTPA is projected to be blue. Green ammonia dedicated to shipping may be in the range of 3.6-6 MTPA. In addition, potentially, 17-23 MTPA will be available as a share between fertilisers, energy and fuel markets.

Most renewable energy sources are represented for the green ammonia production, but more than half relying on a combination of wind and solar PV technology.

The demand for ammonia as a maritime fuel is estimated for 2030 to 2.3 MTPA, but the demand will increase quickly to 62 MTPA in 2040 and 245 MTPA in 2050. In the maritime sector only green and blue ammonia will be used.

In total the amount of green and blue ammonia realistically available is estimated to be more than an order of magnitude higher than the anticipated demand for maritime sector in 2030. And if the announced ammonia production goes to where it is announced, then the availability for the maritime sector is sufficient; comparing the supply green ammonia dedicated to shipping in 2030 with the modelled demand for 2030. Maritime internal combustion engines might be available from about 2025 and hence a demand in the maritime sector becomes possible. The ammonia producers appear to be hedging, and the main approach is a mixture of off takers. The risks are clearly reduced when an investor has three to four distinct end uses, instead of only maritime fuel. However, this may also lead to competition from other off takers if they have a higher purchasing power. Green ammonia production growth does from our investigation not appear to be limited by electrolyser production capacity, as the estimated 52 GW by 2030 is likely achievable. However, the demand growth after 2030 is steep and accelerating and the supply & demand balance may change fast in the 2030s. In the longer term, supply and demand would be balanced, and the appropriate approach is to model the demand as carried out in the present report.

Version and contribution control

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V1.0	21.06.2023	Hendrik Brinks, Oleksii Ivashenko, Tianyu Wang, Bent Erik Bakken, Hans Anton Tvete	First version
V2.0	29.06.2023	Hendrik Brinks, Oleksii Ivashenko, Hans Anton Tvete	Minor edits by DNV

1 Introduction

In the Ammonia24 project, DNV is responsible for a foresight activity carried out to access the supply and demand of green and/or blue ammonia in the years 2030, 2040 and 2050. This is related to the risk of supplying a sufficient amount of green/blue ammonia at key trading ports around the world, also taking into account competing end uses for ammonia like fertilizer production, use in power plants and use of ammonia for producing hydrogen. The present foresight study is also based upon DNV's Maritime Forecast to 2050 publications that takes into account cost developments for renewable energy, electrolysers and ammonia synthesis as well as regulatory and policy developments. Relevant results will be published on DNV's Alternative Fuel Insight dashboard, in addition to the present report.

Ammonia has attracted wide interest as a source of zero emission fuel for shipping. Ammonia does not contain carbon and can be CO_2 emission free under the right circumstances. Barriers to adoption relate among others to the source of ammonia and the future cost of green ammonia. Almost all ammonia in use today is made from hydrocarbons, and as such confers almost no carbon abatement advantage, while simply adding costs. By contrast, green ammonia – produced by electrolysis powered by renewables or nuclear – is an excellent source of zero-emission fuel. Ammonia from fossil sources with carbon capture and storage (CCS) is labelled blue ammonia. Clean ammonia is used as a term for both green and blue ammonia.

Today most ammonia, about 80%, is used for fertilizers. The remainder is used variously for explosives, plastics, synthetic fibres and resins, refrigerants and chemicals like nitric acid. However, ammonia has been suggested as an alternative for transporting hydrogen by ships, in addition to liquid hydrogen and liquid organic hydrogen carriers. Hence use of ammonia for producing hydrogen is a competing end use for ammonia as a marine fuel.

Most ammonia is produced by the Haber-Bosch process, which combines nitrogen gas and hydrogen gas at high pressures and elevated temperatures to form ammonia. The feedstock for providing nitrogen and hydrogen for the process varies as illustrated in Figure 1.

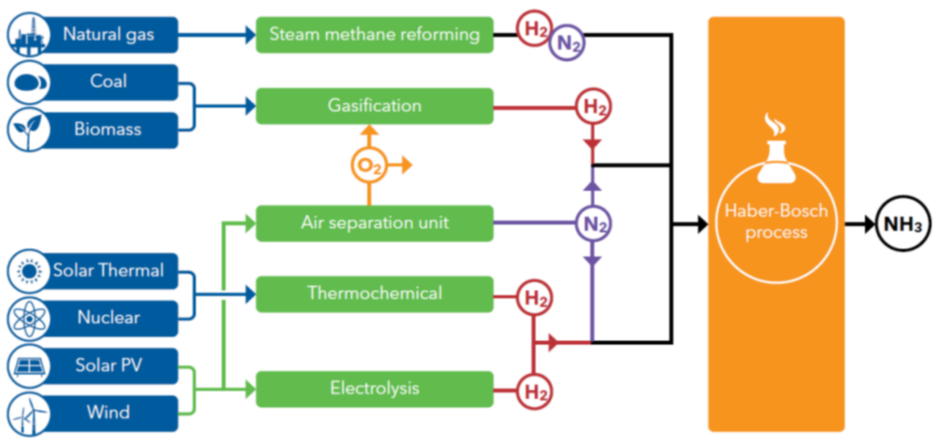


Figure 1: Production pathways for ammonia from [1].

Blue ammonia is ammonia produced from natural gas or coal with close to complete carbon capture and permanent storage. CO_2 used for enhanced oil recovery (EOR) is not considered blue, since the CO_2 utilized this way - even though most of the original CO_2 finally will end up in subsurface storage - will lead to additional oil production that will approximately double the CO_2 emissions compared to the CO_2 stored. Furthermore, CO_2 used for urea production is not considered permanent storage of CO_2 since it is released upon use as fertiliser.

The fuel consumption of all ships was estimated to be 300 million tonnes in 2012, which corresponds to 650 million tonnes of ammonia on an energy basis. The global ammonia production today is close to 200 million tonnes per year. In order to avoid that shipping fuel competes with food production, new production capacity of green and blue ammonia needs to be developed. This production capacity does not necessarily have to be developed where the demand is, but may be built close to the supply of the feedstock. This can be natural gas that cannot be easily transported or wind and solar/wind resources without a sufficient local demand for it. The produced ammonia may be transported by ships. Close to 20 million tonnes of ammonia is traded internationally today. This is done by gas carriers designed for ammonia transportation, which are similar to LPG carriers. Typically, the ammonia shipments are done with gas carriers with up to the size of 60 000 m^3, but 80 000 m^3 is also possible today.

Ammonia prices vary significantly over time and have historically been between 200 and 700 $/tonne between 2010 and 2020. In the latter half of the decade mostly between 200 and 300 $/tonne. Production of green ammonia is more capital expensive than from natural gas, mainly because of the cost of electrolysers.

The production cost of green ammonia will largely depend on two parameters: The price of electricity and capital expenditure. To illustrate how the ammonia production price depends on capex and electricity price, a hypothetical ammonia production price for a plant producing ammonia from electricity is shown in Figure 1. This is based on an internal rate of return for the project over 20 years at 10%, with an efficiency of 52%, a 5% discount rate, and annual operational expenditures at 2.5% of the capex.

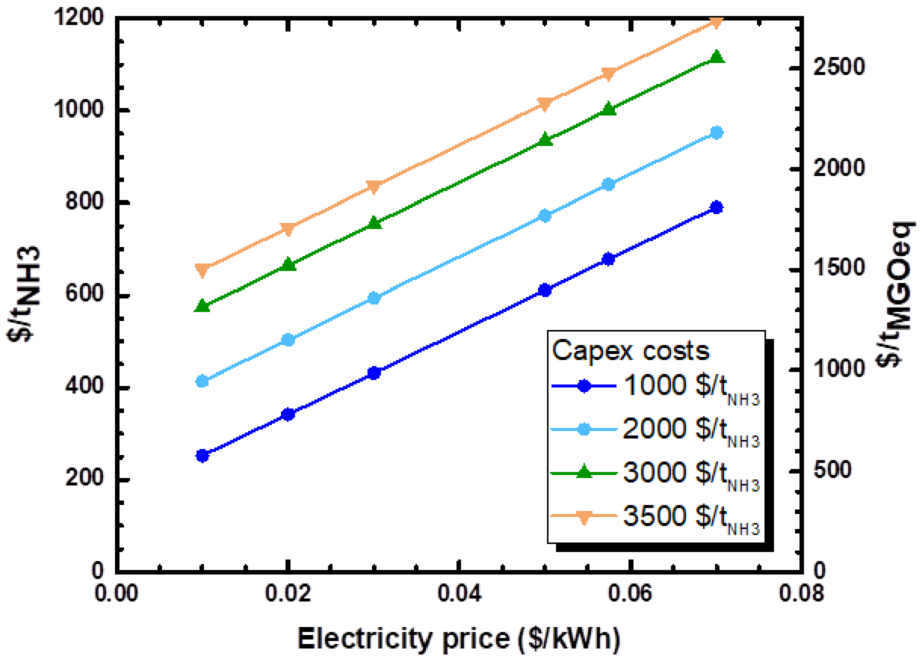


Figure 2: Calculated green ammonia costs based on electricity costs and capex from [1].

With current renewable electricity prices of about 0.04 $/kWh and capex prices for a green ammonia plant of 2 200 – 3 500 $ per annual production capacity in tonne for ammonia, the ammonia price would be in the 650 to 850 $/t range. This is two to three times higher than the ammonia produced from natural gas, which was at a similar level as VLSFO in 2019, on an energy basis. The green ammonia price will likely decrease in the future, because of reduced electrolyser prices and reduced costs of renewable electricity, cf. Figure 3. In addition, fossil fuels are expected to be subject to taxes and regulations, that will alter the competition. With a CO_2 tax of 150 to 200 \$/tCO_2, green ammonia is competitive with oil-based fuels today [1].

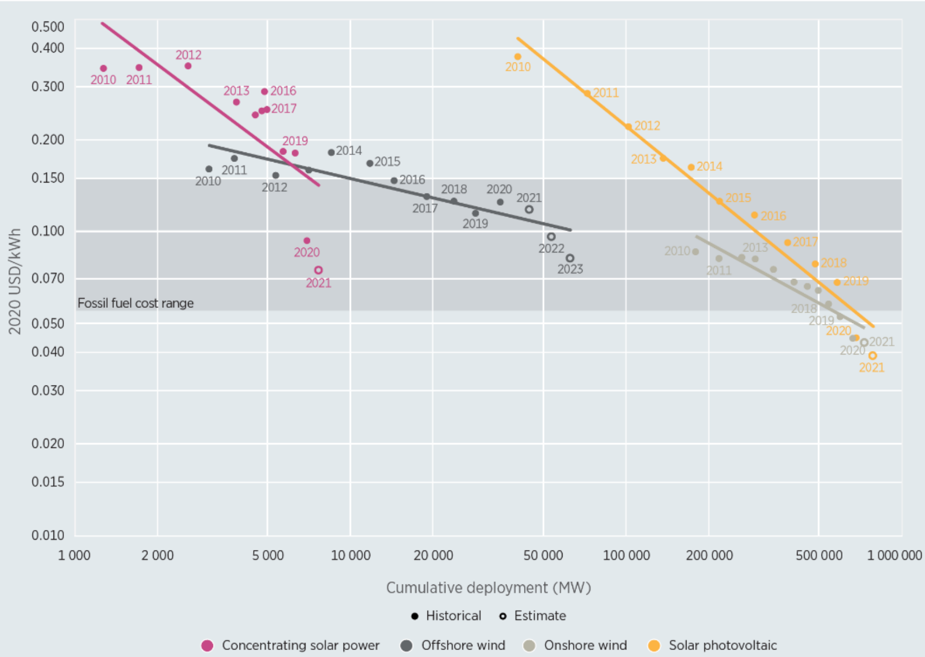


Figure 3: Learning curves for LCOE of renewable electricity from [2].

Commercial ammonia production started in the 1920s by the use of Haber-Bosch process and related processes. In 1930, about 30% of the total ammonia production capacity was electricity-based, with the largest capacities in one plant of up to 100 kTPA (in Rjukan in Norway) [3]. The global production capacity of green ammonia peaked in the 1960s at about 650 kTPA, which at the time was about 4% of global ammonia production [3]. However, green ammonia was outcompeted by natural gas-based ammonia, because of lower cost.

Green ammonia production is in principle scalable since it is produced from water, air and renewable electricity, which may be produced in regions without sufficient local electricity demand. The present study analyses the likely supply and demand of ammonia for the marine sector.

2 Methodology

A number of green and blue ammonia projects have been announced in recent years. These have been linked to a number of end uses like fertilizers, marine fuel, power plants (both co-firing in coal power plants and gas turbines) and use for hydrogen. The number of projects added to the pipeline is increasing. But the timeline for the projects from announcement to full production is from a few years up to about 15 years for the largest projects. For large stand-alone projects with dedicated renewable electricity, the lead time is necessarily longer; the largest proposed projects require 100-200 TWh/yr of new renewable electricity. The Ammonia24 project is considering supply and demand for the years 2030, 2040 and 2050. We have collected the announced projects until the end of 2022. It is possible to use this pipeline to make a prediction for the ammonia supply in 2030 based on a likelihood assessment.

However, for completed ammonia plants in 2040, most of the announcements will likely come at a later stage. Therefore, in order to investigate the supply and demand in 2040 and 2050, it is more pertinent to consider this from a demand point of view. In a mature market, there would likely be balance between supply and demand. Even though it is too early to know, the green and blue ammonia market would at least be more mature in 2040 than in 2030. The demand for ammonia in the maritime market is estimated based on among others the cost of ammonia relative to traditional fuels, taking into account possible CO_2 taxes and regulations as well as trade growth. This has been done based on efforts DNV previously has done in relation to the Energy Transition Outlook as well as the Maritime Forecast. More details are described in the next chapters.

2.1 Methodology for 2030 supply of ammonia

The 2030 supply of ammonia is based upon the announced projects until the end of 2022. The announced projects have been gathered from all projects found from open sources. In particular, but not limited to, these sources are used for completeness: Ammonia Energy Association website [4], IEA hydrogen database 2021, EMSA report on "Potential of Ammonia as Fuel in Shipping" [5] and IRENA innovation outlook "Renewable Ammonia" [6].

The cut-off date was set to end of 2022, and we have aimed at including all projects announced and still considered. Certainly, more projects will be announced in 2023 and forward, that also may be realized within 2030. This will most likely underestimate the 2030 supply of ammonia. An ammonia plant could typically take 3-4 years to realize, and e.g. the large 1.2 MTPA (million tonne per year) NEOM project in Saudi Arabia was announced in 2020 and plans to be operational in 2025. We have also noticed that the production capacities vary depending on which source is used for the same project. Therefore, the total production capacity is a rough approximation. When the date of operation start was missing, an estimated year was included as follows: 3 years from 2022 for <10 kTPA, 5 years for 10-100 kTPA, 7 years for 0.1-1 MTPA and 9 years for >1 MTPA.

Cross-checking of data has been carried out. One of the checks is to compare the installed capacity of the electrolyser with the annual production capacity. Typically, 10 MWh electricity is required to produce 1 tonne ammonia, i.e. about 52% efficiency from electricity to ammonia on a lower heating value basis. This means that for an 85% capacity factor of the electrolyser and Haber-Bosch plant, the installed capacity of 100 MW electrolyser corresponds to 75 kt ammonia/yr. A higher ratio between production capacity and electrolyser capacity is not realistic, unless Solid Oxide Electrolyser Cell (SOEC) with higher efficiency is used. For a stand-alone ammonia plant with a dedicated renewable electricity supply, the capacity factor is lower unless a large battery capacity is built (or Concentrated Solar Power with a large molten salt storage). In many projects, the installed capacity of the renewable electricity is announced to be higher than the installed capacity of the electrolyser, and this will lead to a higher capacity factor for the electrolysers.

The possible end uses have been defined in three categories: Emission-free shipping, emission-free fertilizers and ammonia for energy purposes. The latter category can e.g. be co-firing of green ammonia in coal-fired power plants, use of ammonia in gas power plants and use of ammonia to produce hydrogen. The three categories can be combined either for a combination of two categories (in three different ways) or all three categories. Hence, there are seven categories of end uses in total. Each project in the pipeline has been checked for any specific mentioning of end use. If no reference is made to the end use, it is assumed that the end use is a combination of all three categories. In addition, when a fertilizer producer is mentioned as one of the project participants, it is assumed that fertilizer production is one of the end-uses.

Likelihoods were assessed based upon both on the status of the project (concept, feasibility study, front-end engineering design, final investment decision, under construction or operational) and an additional evaluation of the project. The likelihood was then converted to probabilities. The size of the project activity and the year the project was aimed at being onstream also affected the probabilities for the 2030 production capacity. In addition to the most likely probabilities, low and high probabilities were also defined. This resulted in three different predicted production capacities for green and blue ammonia in 2030.

2.2 Methodology for 2040 and 2050 demand of ammonia

For 2040 and 2050, the focus was on the demand side for ammonia, i.e. how much the market requires of green and blue ammonia based on the regulations and financial aspects, instead of focusing of how much would be available in the market from the supply side. In order to model the 2040 and 2050 demand for ammonia, the GHG Pathway model was used. This DNV model was developed in 2017 [7] and has been updated extensively afterwards [8].

The GHG Pathway model takes the existing shipping fleet as the starting point, and the IHS Fairplay database is used for this purpose. The most financially attractive pathway is chosen for each ship to minimize the emissions to be in line with the global, regional and local regulations. This is done in a yearly decision gate from the starting year up to 2050. The decision is taken based on the financial metric net present value, and a mixture of various investment periods from 2 to 10 years is used. Input parameters, in particular capex and fuel prices, are in general varied over time. The Pathway model is illustrated in Figure 4.

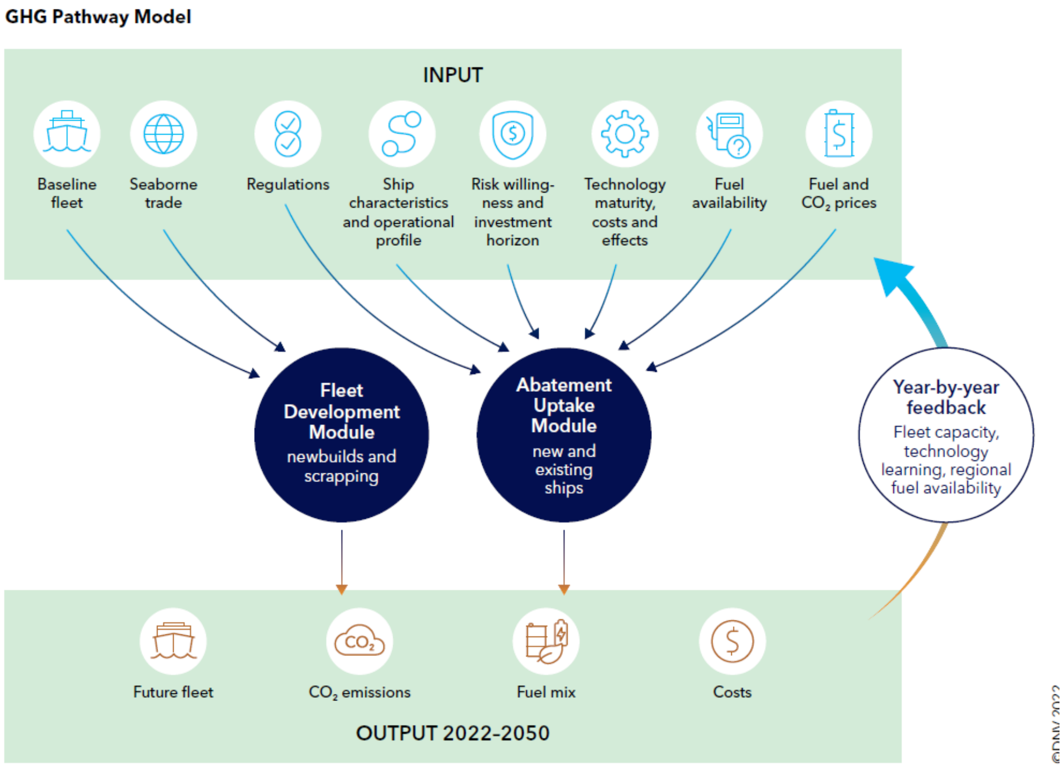


Figure 4: DNV's GHG Pathway model as illustrated in DNV Maritime Forecast to 2050 [8].

The model takes into account the expected trade growth in each segment and the current age of the existing ships. Hence a decision is yearly taken whether to scrap an existing ship, order a newbuild or retrofit an existing ship with another technology.

In order to evaluate new technologies (in the categories of hydrodynamics and machinery) that reduces the fuel consumption, the capex, opex and the amount of fuel savings are used as input parameters. The model also evaluates the operational measure of slow steaming. Furthermore, the model includes expected regulations from IMO on GHG reductions; a total GHG emission reduction of the global fleet by 50% in 2050 and reduction of the emission intensity by 70%.

The key input parameters with regards to alternative fuels are capex and fuel costs, which are built into the DNV Pathway model. Capex depends among others on installed capacity in MW of the engine and the necessary capacity of the tanks in MWh. The tank capacity again depends on the operational profile of the ship.

The operational profile of each segment is determined by AIS data. The fuel consumption related to this operation profile is modelled by use of the technical data for the ships. For fuel costs geographical differences are to a certain degree taken into account. Expected CO_2 taxes are taken into account in the fuel prices.

Hence, the model considers the entire world fleet of ships. It uses databases for technical data and AIS data. The fuel consumption is modelled. Furthermore, the fuel cost and capex for ammonia and all competing fuels are included. Also the capex, opex, fuel savings for all technologies for improving the energy efficiency are included as well as the option of slow steaming is allowed. From these models the net present values are for all options are calculated and ranked. Based on the assumption of rational decision yearly in order to find the most financially attractive way to reduce the GHG emissions to be aligned with tightening regulation, it is possible to get an output of which ships will be ammonia-powered. From the modelled fuel consumption of these ammonia-powered ships, the total demand of ammonia for ship propulsion is calculated.

This has been done for several scenarios of input parameters, and the most realistic scenarios were combined, resulting in the demand curve for ammonia shown in Chapter 4.

3 Results on 2030 supply of clean ammonia

In this chapter, to obtain the fact-based estimation of ammonia supply in 2030 and beyond, we conducted market research on the green and blue ammonia projects announced up to end of 2022. The following sections will systematize the project features, such as size and yearly production, location, development duration and date on-stream, well-to-tank emissions, use of renewable energy infrastructure, demand for electrolysers, and targeted applications. By adjusting the announced production according to project likelihood, we provide a range of low, realistic, and high ammonia production estimates and corresponding fuel availability for 2030. The list of all projects discussed in this chapter is available in Appendix 1.

3.1 Introduction

As of 2022, the global portfolio includes 112 blue and green ammonia projects, with some consisting of 2-4 phases, expanding into 146 unique project phases. The announcement boom occurred in 2021-2022, with more than 50 new projects stages consecutively announced each year. Figure 5 shows that the planned clean ammonia production is a global undertaking. Indeed, it spans 36 countries and engages 189 industrial and academic project partners across all continents. The total announced production capacity for clean ammonia is summing up to 182 MTPA), comparable to the current fossil-based (grey, brown) production of about 186 MTPA.

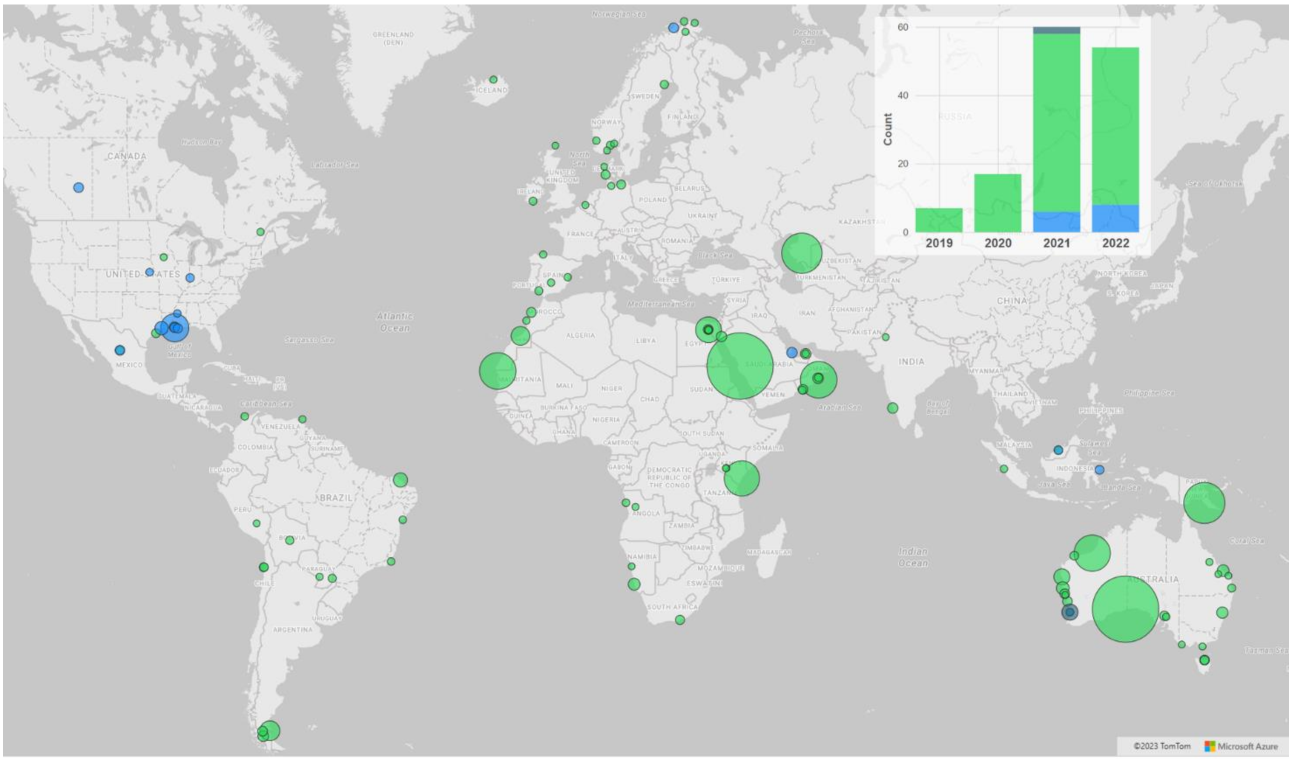


Figure 5: Map of 112 green, blue and mixed (dark blue) ammonia announced projects, with number of projects announcements for the past years. The bubble size indicatively represents the announced production capacity.

3.2 Development of clean ammonia projects

Announcement analysis. The onset of green and blue ammonia projects occurred in 2019-2020 when 7 and 17 projects were announced, respectively. Despite the market disruption during the pandemic period, the number of announced projects has surged every year from 2019 to 2021 (cf. Figure 5). The record number of 65 projects, predominantly green ammonia projects, where announced in 2021. 2020 marked the end of the first five-year cycle defined in Paris Agreement, according to which every country needs to update its National Determined Contribution (NDC) every fifth year [9]. In the subsequent years of 2021 and 2022 the number of projects announcements was consistently high, and therefore it is fair to anticipate a comparable number also in 2023-2024.

Project stages. Per 2022, the announced projects have varying completion status (Figure 6). In the order of increasing maturity, the projects were categorized as follows: 41 concept projects (39%), 51 feasibility studies (27%), 18 projects in Front-End Engineering Design (FEED) stage (23%), 14 with final investment decision (FID) (7%), 19 under construction (4%), 2 operational (0.01 %) and 1 unknown (0.14%). The majority of the projects (91 out of 146 project phases) and corresponding production of 119 MTPA are in the early stages of development (concept or feasibility), which introduces large uncertainties to 66% of the production. This is discussed further in the likelihood section below.

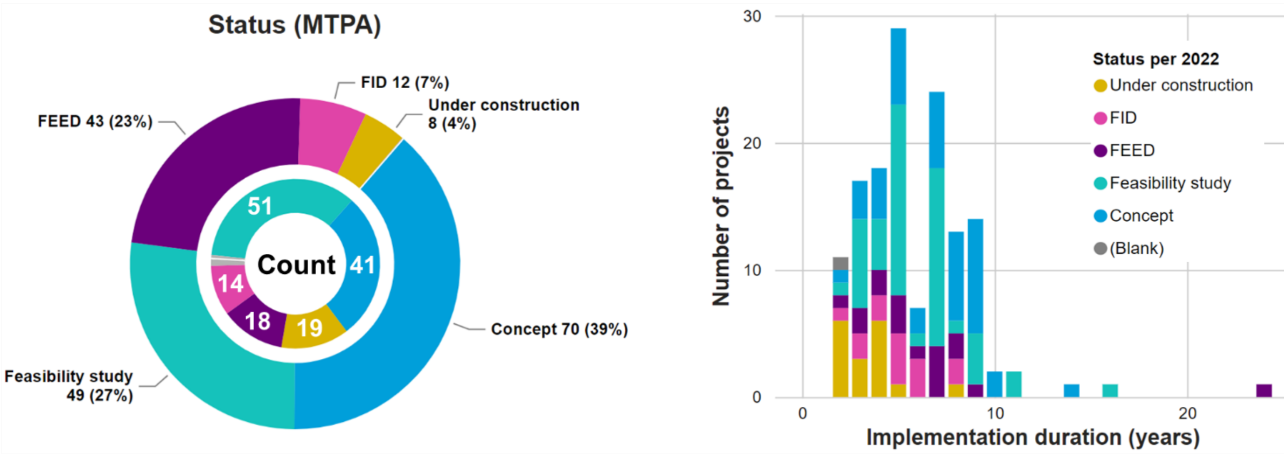


Figure 6: Distribution of ammonia production by the current stage (left), and distribution of project implementation duration (right). In the left panel, the outer disk indicates production capacity in MTPA for each current stage, and the inner disk shows number of projects for each status.

Date on-stream. The majority of the projects (80%) indicate the anticipated date on-stream within 2030. Several large plants, Western Green Energy Hub (2045), Green Energy Oman (2038), SAREH phase 2 (2035) and Alfanar Green Ammonia Project (2032) aim to become operational later on. It is likely that for these extra-large projects with combined final output of 35 MTPA, a certain fraction, below the announced target, will be onstream within 2030. The likely production scenarios in the Section 3.7 consider some low fraction of the capacity to be operational within 2030.

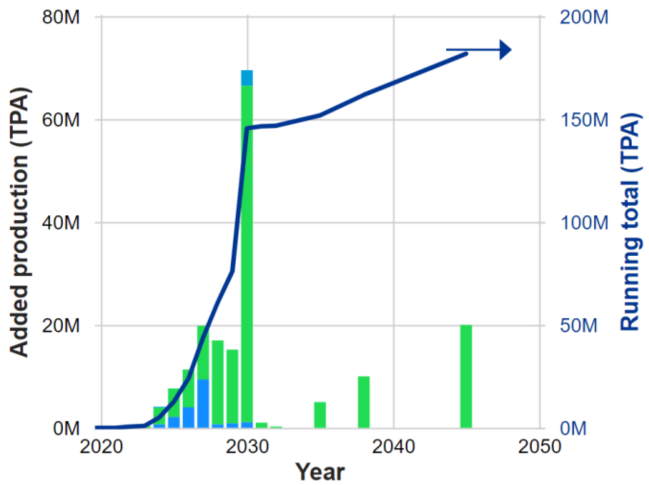
Completion time. Overall announced projects have completion duration between 2 and 24 years, averaging 13 years and peaking at 5-7 years. The shortest completion time of 2 years appears for Palos de la Frontera, HEVO Ammonia, H_2 Pilot in Namibia, the Barra do Dande, and Yazoo City Blue Ammonia. In general, the shorter construction duration appears for the mature projects which are well underway or adding CCS to an existing natural gas-based plant. Overall, the majority of the projects (96%) aim to be completed within 10 years after their initial announcement of the intention to build the plant. The projects with longest implementation all have extra-large production capacities (> 1 MTPA).

The construction duration somewhat correlates with ammonia production size even though the scatter in the data is large, especially for the faster projects. The indicative linear dependency can be roughly expressed as follows: Duration [years] = 0.7 × announced output [MTPA] + 3 [years].

It should be noted that since the likely duration for the project completion is of about 5-7 years, new projects yet to be announced in 2023-2024 have a significant likelihood to contribute to the 2030 supply. Additionally, there are differences in announcement strategies. Some, more risk-taking developers aim at first movers' advantage, use early concept and feasibility announcements in order to attract investors. Other, more established players, tend to announce the projects after it successfully passed feasibility stage. This introducers differences in the perceived project implementation duration, and implies that some, not yet announced projects may already be in the development.

Production development. The evolution of the yearly added production, number of new operational projects, and aggregated annual capacity are summarized in Figure 7. The onset of the production and the only historic ammonia plant still operational since 1975 is the Peruvian project Industrial Cachimayo with a production capacity of 17.3 kTPA. From 2024, the announced production capacity increases significantly with approximately a doubling in the year of 2030. If all plants were to be completed on time, the announced ammonia production capacity in 2030 would be 146 MTPA, which is 80% of the total announced capacity. In 2045, the combined output of all the projects would reach 182 MTPA.

The apparent change in the production behaviour from the rapid, exponential-like increase to a more monotonic growth in 2030 (Figure 7) is unlikely to happen. From the rapid growth of demand for clean ammonia, predicted for 2030-2050 [10], it is realistic that the new, yet to be announced projects will continue a trend of rapid growth into the 2030-2040s (as well as the growth in the end of the 2020s will be less rapid than announced, as described below in Chapter 3.7).



On-stream	New projects	Added %	Running total (% of 2045)	Announced (TPA)
1975	1	0.0%	0.0%	0.02M
2021	1	0.0%	0.0%	0.02M
2022	3	0.3%	0.3%	0.60M
2023	7	0.2%	0.5%	0.95M
2024	16	2.3%	2.8%	5.06M
2025	23	4.2%	7.0%	12.71M
2026	24	6.2%	13.2%	24.04M
2027	16	10.9%	24.1%	43.86M
2028	11	9.3%	33.5%	60.85M
2029	16	8.4%	41.8%	76.04M
2030	23	38.2%	80.1%	145.56M
2031	1	0.6%	80.6%	146.56M
2032	1	0.1%	80.7%	146.81M
2035	1	2.8%	83.5%	151.81M
2038	1	5.5%	89.0%	161.81M
2045	1	11.0%	100.0%	181.81M
Total	**146**	**100.0%**	**100.0%**	**181.81M**

Figure 7: Production capacity (yearly and cumulative) versus Date on stream for the announced projects.

Compound annual growth rate (CAGR) of clean ammonia production between 2023 and 2030 is 111%, calculated the values of 0.95 MTPA in 2023 and 145.5 MTPA in 2030. For comparison, IEA estimates that to reach the 2050 net zero goals [11], green and blue hydrogen production should have CAGR 66% between now and 2030. Only a fraction of the hydrogen production is envisioned to be used to produce green ammonia. From the announced projects, the commitment for the annual production until 2030 exceeds the targets set for hydrogen within 2030.

Technology. The key steps in ammonia synthesis are production of hydrogen and subsequent reaction with nitrogen to obtain NH_3. All the projects plan to use Haber-Bosch (HB) technology to produce ammonia, which is the only commercially scalable and robust method and is used exclusively in all existing production facilities today. This method has been mature for many decades and is currently able to produce reliably up to 1 MTPA in a single HB line. The maximum limit of 1 MTPA on throughput of ammonia synthesis line implies the need for constructing multiple lines for the larger MTPA projects.

Ammonia production facilities have long lifetimes of up to 50 years [12]. The current average age of installed (fossil-based production) capacity is around 25 years. This means that the new green and blue production plants have potential to be operational until ca. 2080s. However, the existing coal or natural gas-based facilities which are in their middle lifespan and aim to upgrade with CCS, may need to consider that by 2050 the plant could reach the end of its lifecycle.

3.3 Geography of the announced projects

The location of the green ammonia projects is one of the key factors determining its success. The right location allows a project to benefit from: 1) access to renewable energy; 2) direct connection to a major maritime hub for export; 3) stimulating regional policies for renewable energy and derivatives.

In terms of combination of cost-effective production and distribution [13], projects located in the Middle East countries may benefit the most due to both, abundant and cheap solar and wind conditions, and are strategically located in proximity to the major shipping routes. North America and Africa also have favourable conditions, with affordable renewables and competitive logistics. Australia and South America feature one of the lowest costs of renewables but require increased distribution costs to the demand centres such as Japan, Asia and Europe. The projects located in the Eastern Asia could be strategically placed in few places with low costs of renewables, which are not in vicinity of distribution hubs. Europe has favourable location and developed distribution network, however, with few exceptions, has limited access to cheap renewable energy.

Considering the need to account for these three factors, the question arises whether the locations of the announced projects match the renewables and distribution costs, as well as follow regional policy incentives.

3.3.1 Countries hosting production

The projects are distributed globally, cf. Figure 8. The production is balanced between Southern and Northern hemisphere. However, the Eastern hemisphere hosts more than double clean ammonia capacity than that of the Western, 136 MTPA vs 46 MTPA. About 33% of the production are planned in Oceania, 28% in Asia, 20% in Africa, 9% in North America, 7% in South America, and 3% in Europe.

Figure 8 lists all 36 hosting countries. 97% of the total world's clean ammonia output is hosted in first 22 countries (up to, incl. Germany). Top 10 countries host 85% production. For comparison, the existing fossil-fuel based ammonia is produced in 64 countries [14].

Country	Share	Announced (MTPA)	Installed power (GW)	Green (MTPA)	Blue (MTPA)
Australia	26.30%	47.82	109.91	44.22	0.42
Saudi Arabia	11.66%	21.20	30.67	21.20	
United States of America	7.86%	14.29	3.03	0.80	13.49
Oman	7.16%	13.02	33.70	13.02	
Papua New Guinea	6.33%	11.50	15.33	11.50	
Kazakhstan	6.18%	11.24	20.00	11.24	
Mauritania	5.50%	10.00	30.00	10.00	
Kenya	5.34%	9.70	25.37	9.70	
Chile	4.40%	8.00	16.30	8.00	
Egypt	4.38%	7.97	11.53	7.97	
Morocco	2.85%	5.18	17.25	5.18	
Brazil	1.64%	2.99	3.87	2.99	
Norway	1.23%	2.24	1.63	1.24	1.00
Namibia	0.94%	1.70	3.01	1.70	
Mexico	0.83%	1.50	0.67	0.50	1.00
United Arab Emirates	0.77%	1.40	2.30	1.40	
Malaysia	0.68%	1.23	0.84	0.63	0.60
India	0.66%	1.20	3.51	1.20	
Qatar	0.66%	1.20			1.20
Canada	0.65%	1.17	1.53	0.17	1.00
Spain	0.54%	0.99	8.50	0.99	
Indonesia	0.51%	0.92	0.40	0.22	0.70
Germany	0.47%	0.85	1.10	0.85	
South Africa	0.44%	0.80	1.07	0.80	
Denmark	0.42%	0.76	1.01	0.76	
Paraguay	0.32%	0.58	0.75	0.58	
Sweden	0.29%	0.52	0.60	0.52	
Bolivia	0.28%	0.50	0.49	0.50	
Ireland	0.21%	0.38	0.50	0.38	
Angola	0.20%	0.36	0.47	0.36	
Colombia	0.14%	0.26	0.35	0.26	
Trinidad and Tobago	0.08%	0.15	0.13	0.15	
Iceland	0.04%	0.08	0.10	0.08	
Netherlands	0.04%	0.08	0.10	0.08	
Peru	0.01%	0.02	0.02	0.02	
United Kingdom	0.01%	0.01	0.01	0.01	
Total	**100.00%**	**181.81**	**346.04**	**159.22**	**19.41**

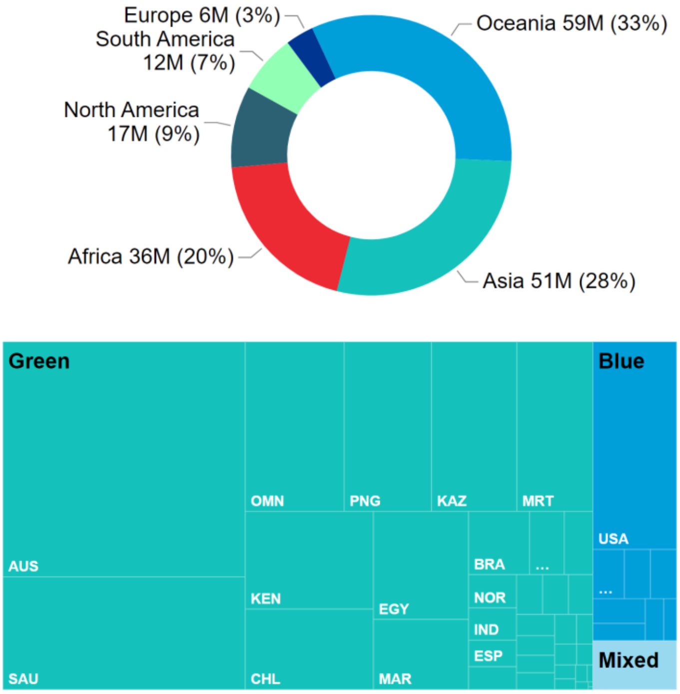


Figure 8: The projects are located in 36 countries. The disc diagram shows the distribution between the continents and the tree map displays the key countries producing green, blue and mixed (both) ammonia.

Australia may become the world's largest producer, with plans to produce about 26% of the global output of green ammonia. Today they produce less than 2 MTPA of fossil-derived ammonia, and they aim at nearly 27 MTPA in 2030 and 48 MTPA in 2045 of added green and some blue ammonia. A notable example of blue ammonia production is the United States, where blue ammonia production constitutes 94% of the planned production, and where 70% (13.5 MTPA) of global blue ammonia is concentrated. USA already hosts the biggest (grey) ammonia plant in Donaldsonville with production capacity of 4.3 MTPA. The new Ascension

Clean Energy with 7.2 MTPA blue ammonia in the same location will be the biggest blue facility once operational in 2027.

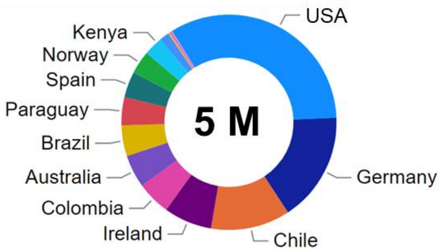
Saudi Arabia, Oman, Papua New Guinea, Kazakhstan, Mauritania are countries with production exceeding 10 MTPA and which focus exclusively on developing green ammonia.

If a majority of the projects will be successful, this will lead to changes in which countries that are the largest ammonia producers.

3.3.2 Local consumption

Today about 18.5 MTPA (10%) of ammonia is exported, traded, and transported globally [1]. The announced ammonia production is predominantly export-oriented. Only 27 projects with combined production of 5.2 MTPA ammonia (2.8% of the announced) target the domestic market. These include several big blue ammonia facilities in the USA, and a number of smaller green projects across all continents.

Most likely the fraction of the local consumption will increase with increased pressure to decarbonize fertilizer production. In particular, the incentives to upgrade the existing facilities with CCS can lead to both, higher fraction of blue ammonia and higher fraction of ammonia consumed locally, mainly for fertilizer production. Indeed, fertiliser market represent an important segment of the targeted local production, with 1.4 MTPA and 27% share.



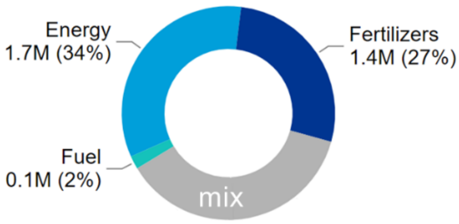


Figure 9: Projects focusing on clean ammonia production to be used locally, i.e. not for export.

3.4 Size distribution, categorisation and investment costs for clean ammonia projects

In 2021 the number of ammonia plants in the world counted about 490 active facilities [14], i.e. that the average production size is 0.38 MTPA, whereas the green and blue ammonia projects aim at producing on average 1.25 MTPA. The key motivating factor for this increase is the improvement in the cost efficiency of ammonia production as the production increases.

3.4.1 Size distribution

For analysis of the size distribution, the projects were categorised into four scales (Figure 10): small, S (<0.01 MTPA), medium, M (0.01-0.1 MTPA), large, L (0.1-1.0 MTPA) and extra-large, XL (>1 MTPA).

From the count of the projects in Figure 10, smaller projects (S and M) with annual production below 0.1 MTPA, were less frequently announced. These 40 projects constitute about 28% of all announcements and contribute less than 1% of the ammonia production. In the projects of this size, the electrolyser sizes are up to about 100 MW.

The dominant portion (75 project phases, 51%) of the announced projects belongs to the large (L) category with the production of 0.1-1.0 MTPA, contributing with 34 MTPA, including 11 blue ammonia facilities. Green projects in this category use electrolysers with capacity in the range of 0.1 - 5.0 GW.

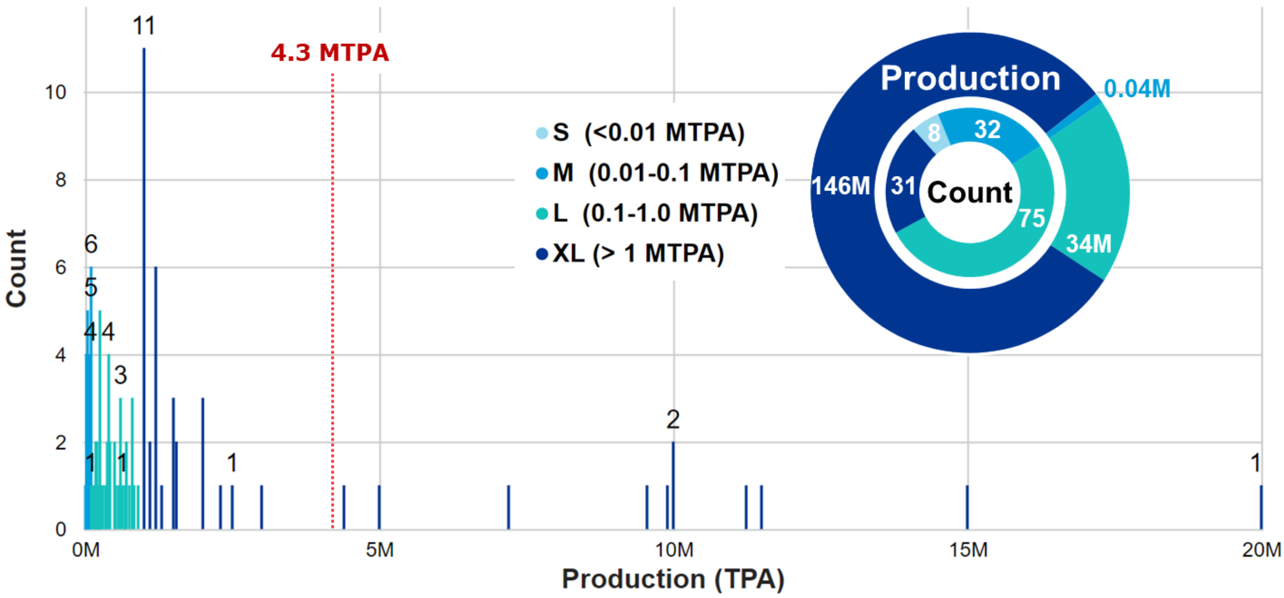


Figure 10: Distribution of the project production size. The disks show production capacity (outer disk) and count (inner disk). 11 projects aim for record high production size, exceeding the today's largest production facility of 4.3 MTPA.

There are 31 XL projects which contribute with 146 MTPA in total, constituting 80% of the production scope. In such big projects of up to record 20 MTPA (Western Green Energy hub), the electrolyser sizes are in the gigawatt range, between 1.6 and 50 GW. Four blue ammonia projects fall into this category, including the biggest blue ammonia facility announced, Ascension Clean Energy, with 7.2 MTPA.

There are 6 projects that plan production 10 MTPA and beyond, Western Green Energy Hub (20 MTPA, AUS), SAREH (15 MTPA, SAU), Papua New Guinea Projects (11.5 MTPA, PNG), Hyrasia One (11.2 MTPA, KAZ), AMAN (10 MTPA, MRT), Green Energy Oman (10 MTPA, OMN). In particular, FFI's Papua New Guinea 12 MTPA Projects portfolio has been counted as one project due to the constrained news release, while its energy system comprises of 7 hydropower and 11 geothermal energy projects.

The biggest existing (grey) ammonia facility produces 4.3 MTPA [15], and 11 projects have an ambition to break this record. Today the upper limit for a single Haber-Bosch line is ~1 MTPA. Unless developments in the engineering of the HB plant occurs, allowing for significantly bigger production lines, the minimum number of HB lines needed for the construction of all the announced projects is 260, including 145 single train HB lines for ≥1 MTPA projects and 115 for the smaller ones.

3.4.2 Production categorisation

The majority of the energy consumption and hence the emissions in the ammonia production arise from hydrogen production, and therefore the ammonia colour is equivalent to the colour of hydrogen used in the Haber-Bosch plant. While some sources consider ammonia with 60% carbon capture technically as blue, these projects were not included into the current scope of clean ammonia production projects. If these projects were included, the fraction of blue projects in the 2030 supply would have increased.

From the announced 182 MTPA of green and blue ammonia, 19 MTPA will be blue, 159 MTPA will be green and 3 MTPA mixed. However, due to shorter implementation stage, the blue ammonia plants would represent a significant portion (38%) in 2027. The proportion of blue ammonia is decreasing as more green ammonia production become operational, to 13% in 2030 and eventually to 11% in 2045. There are plans for 15 blue ammonia facilities (Figure 11).

70% of the global blue production pipeline, 13.5 MTPA, would be concentrated in USA. The rest of the blue ammonia is planned to be produced by 7 countries: Qatar (1.2 MTPA), Canada (1 MTPA), Mexico (1 MTPA), Norway (1 MTPA), Indonesia (0.7 NTPA), Malaysia (0.6 MTPA), and Australia (0.42 MTPA). In addition to purely green production, H2Perth project in Australia aims to produce both green and blue ammonia, with combined output of 3.2 MTPA in 2030.

Project name	Announced production (MTPA)	Country	Date onstream
H2Perth, blue - 1	0.42	Australia	2024
H2Perth, mixed - 1	0.18	Australia	2024
H2Perth, mixed - 2	3.00	Australia	2030
Blue Ammonia & Blue Methanol	1.00	Canada	2026
PT Panca Amara Utama Ammonia plant	0.70	Indonesia	2028
H2biscus - 2	0.60	Malaysia	2029
Tarafert - 1	1.00	Mexico	2026
Barents Blue	1.00	Norway	2025
Ammonia-7	1.20	Qatar	2026
Ascension Clean Energy (ACE)	7.20	United States of America	2027
Beaumont Blue Ammonia plant - 1	1.10	United States of America	2025
Beaumont Blue Ammonia plant - 2	1.10	United States of America	2030
Donaldsonville Blue Ammonia	1.00	United States of America	2027
Geismar Clean Ammonia Plant	1.20	United States of America	2027
Olive Creek 2	0.28	United States of America	2029
Wabash CarbonSAFE	0.57	United States of America	2022
Waggaman Ammonia plant	0.80	United States of America	2026
Total	22.59		

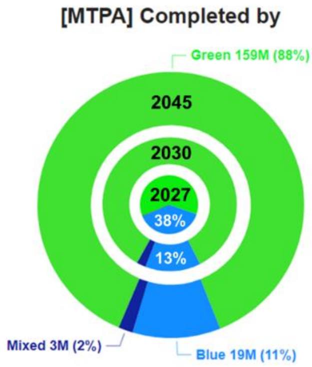


Figure 11: Projects focusing on production of blue and mixed ammonia (left) and fraction of blue ammonia (right).

In reality, the proportion of blue ammonia is likely be higher, as pressure to decarbonize existing production likely will increase, resulting in more grey and brown ammonia facilities upgrading with CCS to produce blue ammonia. Announcements of such conversions will likely appear from the countries which are strong producers of fossil ammonia such as China, Russia, India, USA, and Indonesia. In particular in USA, it can be expected that IRA would further incentivize more of blue ammonia projects in the coming years [13, 16]. Following the requirement to begin the construction before 2026, these facilities are likely to be completed near 2030 and therefore further contribute to the scope of clean ammonia supply in 2030.

3.4.3 Investment size

Ammonia production benefits from the economy of scale, with investment costs per production unit decreasing as ammonia production grows [17]. 57 of the project stages have advertised the intended investment size. Cumulatively they plan to invest 414 billion $ in order to produce 92 MTPA (line in Figure 12).

Although information is available only for a selection of the projects, the corresponding production represents about half of the announced scope, and by extrapolation the total investment would be about 828 billion $. The investments until 2030 are on average 39 billion $ per year. For comparison, DNV's maritime forecasts to 2050 estimates 28-90 billion $ yearly investments to scale up alternative fuels production, distribution and bunkering infrastructure, depending on decarbonization scenarios and targets [8].

On average, 3.7 billion $ is required per MTPA ammonia production capacity (Figure 12). There is a large data scatter for the projects below 3 MTPA. This implies both that smaller projects can deviate significantly from 3.7 bn/MTPA average and that the economy of scale is not evident.

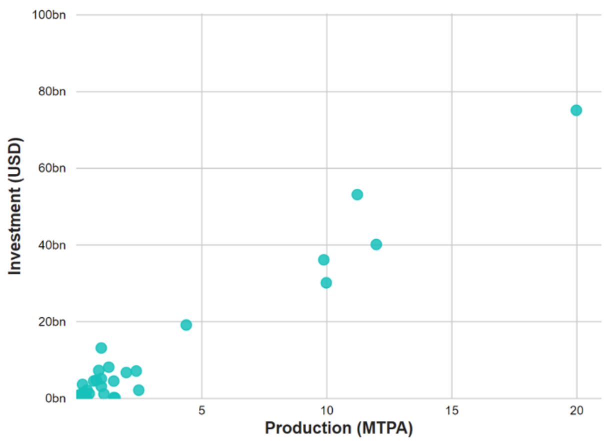


Figure 12: Correlation between the announced production scale and corresponding investment, with indicative linear dependency as 3.7 billion $ per 1 MTPA ammonia production.

3.5 Renewable energy and use of electrolysers

For every ton of green ammonia, 10 MWh of electricity is typically needed [1], out of which about 90% is used for electrolysis. Therefore, to produce 159 MTPA of green ammonia it would require about 1 590 TWh of renewable power, comparable with yearly electricity production of India. Thus, the renewable energy supply is a critical part of the green ammonia production facilities.

3.5.1 Types of renewable energy used

Almost all possible renewable energy sources are represented in the announced projects, including solar PV, wind, hydropower, geothermal power, and their combinations. Only, nine projects in the early stages have yet to define the renewable energy type to be employed in the production, corresponding to 14% of the production capacity.

The majority of the announced projects (41 in total, which represents 54% of the production capacity) relies on a complementary combination of solar and wind power generation. In contrast, only solar energy is used in 29 projects, which corresponds to approximately 4% of the total announced capacity. Hydropower is used in 14 projects, contributing 1.8% to the overall production. Wind onshore and offshore are expected to contribute approximately 2-3% each.

Geothermal energy is particularly attractive renewable energy source due to its continuous availability which results in high utilization factors and thus continuous production throughout the year. This was used in 5 projects which rely on geothermal or geothermal energy combined with hydropower, with expected production contribution of 6-7% each. These include several XL projects. For example, “Green Ammonia and Fertilizer facility” in Kenya will use geothermal energy producing 9.6 MTPA, representing 96% share in this category. Geothermal with hydropower energy in Papua New Guinea is the only project with this combination, contributing with 11.5 MTPA. It is likely that more announcements will follow from the countries with developed geothermal energy infrastructure, such as USA, Indonesia, Philippines, Turkey, New Zeeland, Mexico, Italy, Iceland or Japan.

Overall, the dominant role of wind and solar power generation is in line with DNV’s hydrogen forecast to 2050 [18], which indicates the expected 40% reduction in costs of solar panels and 27% reduction in wind turbine costs this decade.

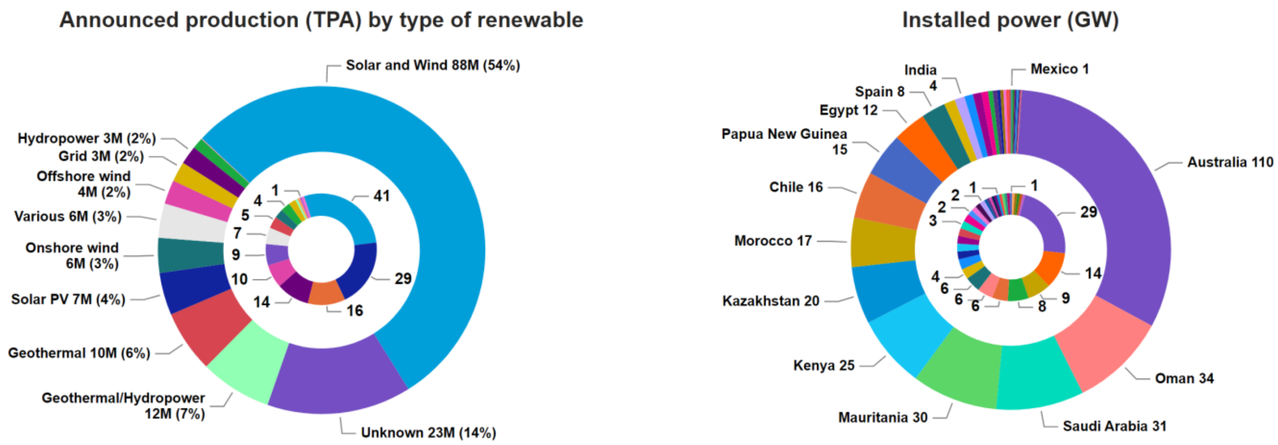


Figure 13: Distribution the renewables by type (left) and by country (right) for green ammonia production. Inner disks show number of projects in each category and outer disks show total values for production (left) or installed power (right). .

Grid electricity, which sometimes receives yellow label to the produced hydrogen and ammonia, is used in 2% of the announced capacity. This percentage is expected to grow after 2030, when more variable renewable energy sources (VRES) will be connected to the power grids, supplying cheap or even free surplus energy towards electrolysers and ammonia production. In fact, DNV's estimates show that due to growth of VRES, grid-connected electrolysis will be one of the most cost-competitive route of hydrogen production in 2050 [18]. Notably the origin of grid electricity plays a key role to ensure truly clean ammonia production. Hydrogen produced by electrolysis from grid electricity derived from the fossil fuel, can have more than double the climate impact of the hydrogen produced from steam reforming of natural gas (17-40 kg CO_2/kg H_2 vs 9 kg CO_2/kg H_2) [19].

Finally, despite significant portion of electricity output produced by nuclear power, no advertised project is associated with the use of nuclear energy. Announcements from the countries with multiple reactors such as EU, USA, Japan, China, India, Saudi Arabia and UAE are expected in the coming years. Despite of low emissions and mature technology, DNV forecast predicts only 1% of H_2 to be produced via this route by 2050, primarily in China [18].

3.5.2 Installed electrolyser capacity

Electrolyser capacities were announced for majority of the projects (Figure 13 and Figure 8), and the missing values were derived from the announced green ammonia production using the conversion factor of 0.75 kt NH_3/MW. Overall announced total electrolyser capacity is close to 346 GW.

The largest announced installed electrolyser capacity is in the countries with the largest green ammonia production capacity, i.e. Australia (110 GW), Oman (34 GW), Saudi Arabia (31 GW), Mauritania (30 GW), Kenya (25 GW), Kazakhstan (20 GW), Morocco (17 GW).

Only 16 projects announced the electrolyser technology to be used to produce hydrogen. Amongst the announced, alkaline and PEM technology have comparable shares, followed by SOEC (3 projects). The technology is described in more detail in Section 6.2.1.

The evolution of electrolyser installation (Figure 14), unsurprisingly, resembles closely the yearly evolution of ammonia production (Figure 7). The modern days' onset of installations occurred in 2021, in which more electrolysers came online than any previous year, ca. 0.2 GW.

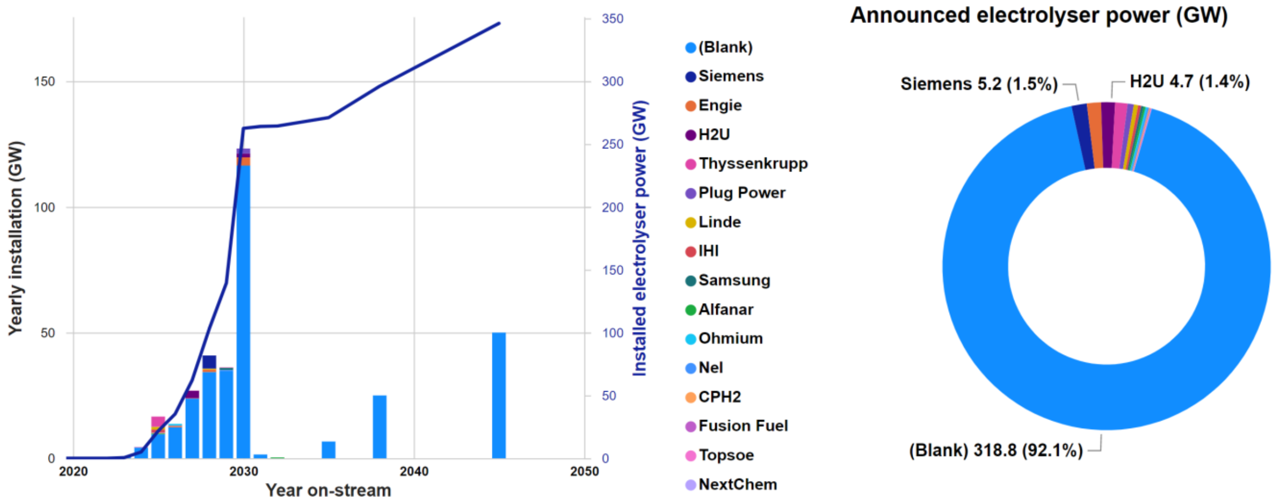


Figure 14: Announced yearly installation of electrolysers, and selected producers of the electrolysers.

From the announced ammonia projects, two plants became operational, ACME's Rajasthan hydrogen and ammonia plant (0.01 GW) and Puertollano plant (0.02 GW). The installed electrolyser power is projected to exceed GW value for the first time in 2024, with 4.5 GW. In particular, the Transhydrogen Alliance project in Brazil with 3.3 GW electrolyser will be the first to reach GW milestone, with announced production of 2.5 MTPA.

After 2025, the yearly installations will be consistently high, in the range 15-40 GW. This results in available installed electrolyser power of 22 GW operational in 2025, 62 GW in 2027, 103 GW in 2028, and reach 256 GW in 2030. The currently announced capacity will total to 346 GW in 2045. Since many developers aim for completion by 2030, this results in a record 108 GW electrolyser power capacity installed in a single year. It is possible that 20 projects which aim to be operational this year, could spread around 2-3 years around 2030. These extra-large projects are FFI Green ammonia and fertilizer facility in Kenya (25 GW), Hyrasia One in Kazakhstan (20 GW), and SAREH-I in Saudi Arabia (20 GW).

There are four extra-large projects aiming to become operational after 2030, GERI-II (1.5 GW, 2031), SAREH-II (6.7 GW, 2035), GEO (25 GW, 2038) and Western Green Energy Hub (50 GW, 2045). It can be anticipated that incremental portions of their GW capacity electrolysers will be on stream gradually, possibly contributing some MTPA capacities within 2030's, i.e. earlier than final completion date.

Several projects indicated a producer of the electrolyser units; however, most leave this information unspecified. Indeed, a detailed into description of several large and extra-large project descriptions reveals that the final choice of electrolyser supplier, as well as type of technology (Alkaline, PEM or alternative) is to be taken after FEED stage, i.e. the FEED package serves as a basis for the bidding for execution phase contracts. According to Figure 6, 89% of the projects have not completed FEED stage, what is consistent with 93% of unallocated electrolysers supply in Figure 14.

3.5.3 Productivity analysis

To compare the projects the term *productivity* has been defined as the yearly production output per installed electrolyser power. There are several factors that impact productivity, namely capacity factor of the electrolyser, capacity factor of the Haber-Bosch unit and efficiencies. This will depend on availability of renewable electricity and storage solutions, as well as the installed capacities relative to the resources. The renewable energy system will not be at its peak continuously, and the plant's electrolyser will not operate at nominal capacity continuously for 24h every day of a year. Typical load factors vary in the range 30-80%, with exceptions of nuclear and geothermal power operating close to 100% on demand.

More than half of the green ammonia projects use a combination of wind and solar, which complement each other (diurnal complementarity) and allow for more stable, uninterrupted operation of the electrolysers. State-of-the-art hybrid solar PV/wind plants in the best locations could reach capacity factors above 5000 h (57%). Similarly, complementary renewable electricity from the grid and battery energy storage further allow for running the electrolyser in a more predictable manner. Overall, a state-of-the-art facility, utilizing a combination of solar and wind infrastructure, may reach a capacity factor reaching 70% [20].

Electrolyser itself produces hydrogen with an efficiency of around 68% for the most commonly used alkaline, electrolysers. Some improvements in electrolyser technology could improve the efficiency in the future. Overall, a productivity above 0.75 kTPA/MW is not realistic, see section 2.1.

There are 7 projects which claim high productivity of 1.0 kTPA NH_3/MW and above, NewGen (1.18), H_2TAS (1.07), Aquamarine (1.04), Oruro plant (1.02), Donaldsonville Green Ammonia (1.0), Fortescue Green Hydrogen and Ammonia plant (1.04), Unigel (1.0) – most of which are large projects with annual output in the range 0.1-0.8 MTPA. Since the productivity factor above 1.0 kTPA NH_3/MW is not feasible physically, it is likely that to reach the announced production, the projects would need to increase the installed electrolyser power.

Another 10 projects have also above average productivity in the range 0.75-0.9 kTPA/MW, which may indicate use of 100% utilization factor. Altogether these 17 projects have combined production of 5 MTPA.

17 more projects with combined output of 27 MTPA have productivity in the range 0.4-0.7 kTPA/MW, with average value of 0.55 kTPA/MW. 9 of the projects in this category will use renewables combinations such as wind and solar PV, wind and hydropower, geothermal and solar.

Finally, some projects did not focus exclusively on ammonia production but also hydrogen, which may result in apparent low productivity below 0.4 kTPA/MW.

Overall, we find that combination of renewable energy sources can allow reaching higher loads.

3.6 Clean ammonia projects by end use

Currently the end use of ammonia is dominated by the fertilizers market, which consumes about 80% of existing ammonia production [1]. There is significant uncertainty on which market segments that will take up the clean ammonia. In this section the announced projects were reviewed in terms of end-uses either to existing fertilizers applications or if it concentrates on the new end uses.

Besides the “fertilizers”, multiple project descriptions mentioned applications such as “shipping fuel” and “energy”. Interestingly, the combinations of these three categories were also often encountered in the project descriptions.

The Venn diagram (Figure 15) visualises the distribution of the targeted 182 MTPA ammonia among the targeted applications. Surprisingly, the traditional end use of ammonia for fertilizers appeared as the smallest category with 6 MTPA, but production dedicated to more novel applications, fuel and energy, is nearly triple of that, 17 and 19 MTPA, respectively.

The remaining 140 MTPA production has mixed applications. Thus, the four combinations categories are “Fertilizers and fuel” (2 MTPA), “Energy and fertilizers” (6 MTPA), “Energy and fuel” (92 MTPA) and Energy, fuel and fertilizers” (40 MTPA). Clearly the developers preferred to cater multiple applications with the overall mixed end use of 140 MTPA, significantly larger than the specifically dedicated end use of 42 MTPA. This reflects the future dynamic distribution of ammonia, which will depend on driving forces to decarbonize a particular sector. Furthermore, it is likely that with the projects' maturity closer to 2025-2027, uptake contracts between the suppliers and consumers will define the final end use better.

To provide insights into availability of green and blue ammonia as a shipping fuel, the mixed end use projects with 140 MTPA projects were further grouped into the two categories "mix with fuel" or "mix without fuel". The top 10 countries (Figure 15, right), which plan to output 85% of the announced production, have a prominent focus on a mixed application. Australia and Egypt are the two countries with the major dedicated fuel production of 10 and 5 MTPA respectively. A notable example of the country that does not target the fuel market and plans to specialize in the energy segment is Mauritania with green 10 MTPA Aman project.

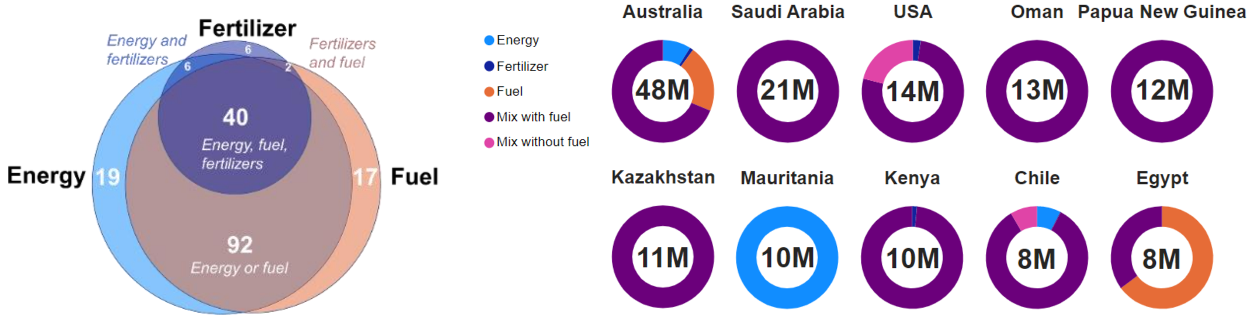


Figure 15: Left: Venn diagram schematically showing distribution of 182 MTPA of clean ammonia and overlap between the three sectors "Fuel", "Fertilizer", and "Energy". Right: Distribution of ammonia by the targeted market sector in top 10 producing countries (85% of total).

The map of dedicated and mixed end use projects in Figure 16 shows the locations of the planned facilities.

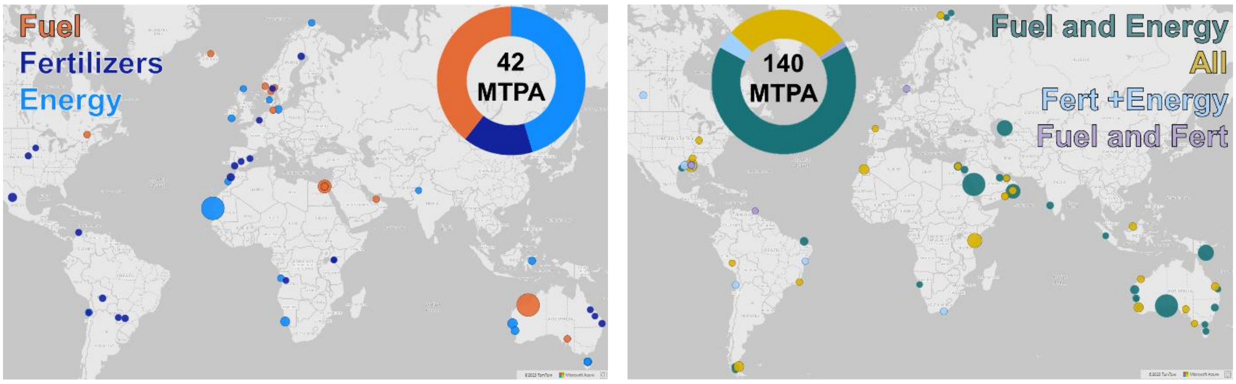


Figure 16: Left: Map of production with dedicated end use showing Fuel (orange), Fertilizers (dark blue) and Energy (light blue) projects. Right: Map of production with mixed end use, Fuel and Energy (pine forest), All (yellow), Fertilizer and Energy (sky blue) and Fuel and Fertilizer (lavender).

3.6.1 Fertilizer

Ammonia for fertilizers projects are located in 14 countries (Figure 17). Among the notable examples of the 22 dedicated fertilizer projects are Terafert project in Mexico (1.5 MTPA, green and blue); Green investment plan for renewable ammonia in Morocco (1 MTPA); three green ammonia projects in Spain, Palos de la Frontera, Puertollano, and Catalina with combined output of 0.8 MTPA; two green projects in Paraguay, Alto Parana and ATOME with combined production of 0.6 MTPA. It is notable that in Australia, which aims to produce nearly 48 MTPA of ammonia, there are just three ammonia for fertilizers projects with combined production of 0.55 MTPA, Dyno Nobel Renewable Hydrogen, Gibson Island Green Ammonia and Queensland Nitrates Renewable Hydrogen and Ammonia.

In addition to the dedicated renewable fertilizers projects, several projects target combinations of fertilizers and either fuel, or energy, with combined production of 47 MTPA. In this category "mix including fertilizers" the leaders are USA (13.2 MTPA, almost all blue), Kenya (9.6 MTPA), Australia (6.7 MTPA), Chile (5.1 MTPA) and Morocco (4.0 MTPA). Overall fraction of blue ammonia in the potential (dedicated + uncertain mix) fertilizer segment is 33%, i.e. higher than overall average of 11 %.

Country	Announced (TPA)	Share	Blue (TPA)	Green (TPA)
Mexico	1.50M	23.36%	1.00M	0.50M
Morocco	1.00M	15.59%		1.00M
Spain	0.82M	12.81%		0.82M
Paraguay	0.58M	9.02%		0.58M
Australia	0.54M	8.41%		0.54M
Sweden	0.52M	8.08%		0.52M
Bolivia	0.50M	7.79%		0.50M
United States of America	0.36M	5.58%	0.28M	0.08M
Colombia	0.26M	4.09%		0.26M
Kenya	0.15M	2.34%		0.15M
Angola	0.08M	1.17%		0.08M
Netherlands	0.08M	1.17%		0.08M
Norway	0.02M	0.32%		0.02M
Chile	0.02M	0.28%		0.02M
Total	**6.42M**	**100.00%**	**1.28M**	**5.15M**

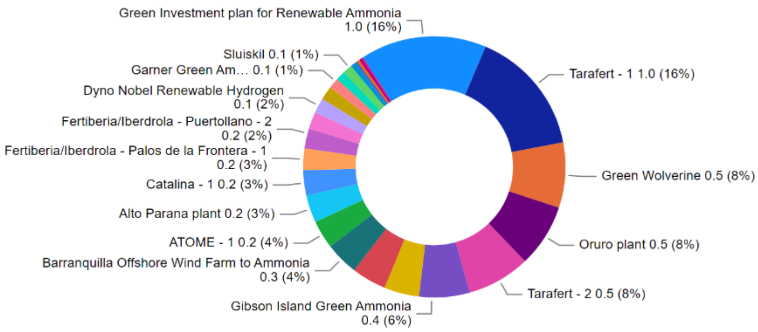


Figure 17: Countries and projects comitted to development of clean ammonia projects for fertilizer market.

3.6.2 Power generation and hydrogen carrier

Hydrogen and ammonia offer great potential to decarbonize fossil-reliant power generation. For example, substituting a major fraction of coal in power plants with ammonia allows avoiding a large part of the emissions. The use of ammonia for power generation purposes is particularly attractive in countries with limited access to renewable energy, and where coal power plants fulfil large share of the local power demand. Japan, South Korea and Taiwan are prominent examples. Combusting ammonia without generating undesired NO_x and N_2O emissions is a known challenge. It is expected that ammonia co-firing will have initial technology demonstration around 2025, followed by large scale implementation closer to 2030 [10].

Ammonia might be the most promising candidate for long distance hydrogen transportation. While the demand for ammonia for energy and hydrogen carrier applications will be forming in the next years, the projects that plan serving this market is reviewed in this section.

16 projects target ammonia as an energy carrier specifically, with the total output of 19.1 MTPA, 96% of which is green ammonia. In this sector, AMAN in Mauritania is an outstanding project with 10 MTPA with a 52% share. Other notable examples are Murchison PtX (2 MTPA), Hyphen hydrogen energy (1.7 MTPA), Midwest Green Ammonia (1 MTPA), and H2TAS (1 MTPA).

Countries leading production of ammonia for energy are Mauritania (10 MTPA), Australia (4.3 MTPA), Namibia (1.7 MTPA), Germany (0.8 MTPA), Indonesia (0.7 MTPA), Chile (0.6 MTPA), Ireland (0.4 MTPA), Angola (0.3 MTPA), Norway (0.2 MTPA) and Morocco (0.2 MTPA). The fraction of blue ammonia in the scope is 3.6% with 0.7 MTPA contribution from the only PT Panca Amara Utama ammonia plant in Indonesia.

The projects which focus on multiple application sectors, including ammonia for energy and either fertilizers, fuels, or both have combined production of 137 MTPA (not shown).

Country	Announced (TPA)	Share	Blue (TPA)	Green (TPA)
Mauritania	10.00M	52.40%		10.0M
Australia	4.25M	22.27%		4.3M
Namibia	1.70M	8.91%		1.7M
Germany	0.75M	3.93%		0.8M
Indonesia	0.70M	3.67%	0.7M	
Chile	0.60M	3.14%		0.6M
Ireland	0.38M	1.96%		0.4M
Angola	0.28M	1.47%		0.3M
Norway	0.23M	1.21%		0.2M
Morocco	0.18M	0.96%		0.2M
United Kingdom	0.01M	0.05%		0.0M
Denmark	0.01M	0.03%		0.0M
India	0.00M	0.01%		0.0M
Total	**19.08M**	**100.00%**	**0.7M**	**18.4M**

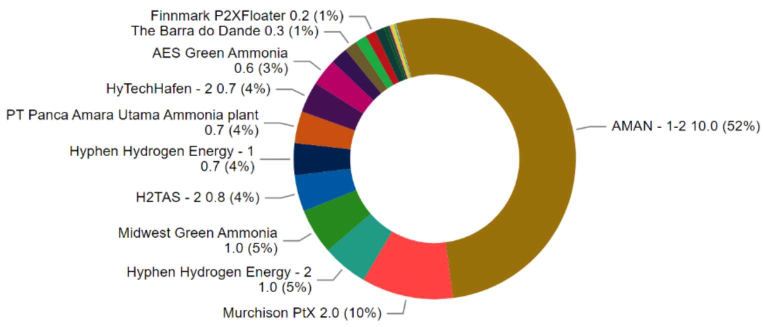


Figure 18: Countries and projects comitted to development of clean ammonia projects for energy market.

3.6.3 Shipping fuel

Ammonia combustion itself does not produce CO_2 emissions on a tank-to-wake basis, and if GHG emissions are avoided in the production process of ammonia, it will be emission free.

Ammonia for shipping fuel is targeted by 16 projects in 6 countries with combined output of 16.6 MTPA. All these projects plan for green ammonia. AREH in Australia is the largest project with 9.9 MTPA (~60% share), while the remaining 15 projects have yearly output 0.1-1.5 MTPA. The leading countries are Australia (10.1 MTPA), Egypt (5.2 MTPA), Norway (0.8 MTPA), Canada (0.2 MTPA), Germany (0.1 MTPA), Iceland (0.1 MTPA).

In addition to these 16 projects, 67 other projects indicated mixed applications including fuel, amounting to 134 MTPA. If all the announced projects are successful according to their planned date on-stream, the possible supply of ammonia for shipping fuel would be in the range 16.6 – 151 MTPA, with 16.6 – 114 MTPA in 2030.

Project name	Country name	Announced (MTPA)	Share
AREH	Australia	9.9M	59.6%
Total - 2	Egypt	1.5M	9.0%
Green Ammonia in SCZone	Egypt	1.0M	6.0%
ReNew Power - 2	Egypt	0.9M	5.4%
AMEA - 1	Egypt	0.4M	2.4%
AMEA - 2	Egypt	0.4M	2.4%
Herøya Green Ammonia (HEGRA) - Energy	Norway	0.4M	2.4%
Total - 1	Egypt	0.3M	1.8%
The Port Pirie Green Hydrogen	Australia	0.2M	1.3%
EDF Renewable - 2	Egypt	0.2M	1.3%
Project Sauda Iverson Efuels	Norway	0.2M	1.3%
Courant	Canada	0.2M	1.0%
Khalifa Industrial Zone Abu Dhabi (KIZAD) - 2	United Arab Emirates	0.2M	1.0%
EDF Renewable - 1	Egypt	0.1M	0.8%
MEP	Egypt	0.1M	0.8%
Aquamarine	Germany	0.1M	0.6%
North Ammonia Arendal	Norway	0.1M	0.6%
ReNew Power - 1	Egypt	0.1M	0.6%
Slagen Terminal	Norway	0.1M	0.6%
Egypt Green Ammonia (Two plants)	Egypt	0.1M	0.5%
Green Fuel Iceland - 2	Iceland	0.1M	0.3%
Green Fuel Iceland - 1	Iceland	0.0M	0.1%
Total		**16.6M**	**100.0%**

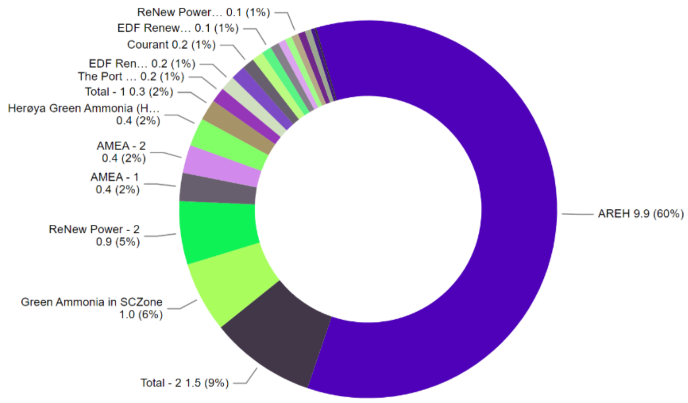


Figure 19: Projects comitted to the development of clean ammonia projects for fuel market.

3.7 Likely supply of clean ammonia in 2030

Apparently, the projects in the pipeline are about to double the global ammonia production. In this section we consider how uncertainties in the projects' implementation could lead to a production lower than announced. Essentially, this section aims at providing several likely, risk-aware scenarios for ammonia production within 2030. Most risks that affect the project likelihood (see methodology) are related to the project implementation, with early-stage projects having the largest risks. Additional risks, which are beyond the current study, include construction of an ammonia plant near a natural reserve, inducing opposition from the government, stakeholders, investors, environmental agencies and activists, resulting in delays or relocation [21]; shift in national energy strategy as a result of government change; disappointing results of the feasibility study; difficulties in procurement of raw materials (steel, etc); challenges with renewable infrastructure. In addition, certainly there will be a risk related to the customer's willingness to pay. The availability of electrolyser technology and possible impact on green ammonia supply in 2030 is discussed in the Section 6.2.

3.7.1 Possible scenarios for clean ammonia

To obtain several possible scenarios, the project features such as size, location, technology, maturity and date on-stream were evaluated and assigned with three distinct success probabilities. The probabilities essentially describe how likely it is for the project to reach the announced targets within 2030, and lead to the high, realistic and low scenarios.

The obtained scenarios state that the production will be 38, 33 and 27 MTPA respectively for high, realistic and low estimation. All of the possible production scenarios conclude that the likely supply of the clean ammonia will be significantly (about 5 to7 fold) lower than the announced 182 MTPA. This is not very surprising since the majority (66%) of the projects are in the earliest stages of their development. Moreover, additional 35 MTPA are planned to be on-stream after 2030.

Blue and green plants pose distinct risks and technological challenges. For example, conversion of an established brown ammonia facility to use carbon capture and storage, producing blue ammonia, requires less technical development than development of a new green ammonia plant and is estimated to pose lower risks. Consequently, the average reduction in blue production is noticeably smaller than average reduction in the green production. This increases the fraction of blue ammonia in the scope from 12% to about 33%, consistently for all likelihoods. The majority (75%) of the blue production is to be developed within 2027. The likely range of blue (including mixed) ammonia is 10-12 MTPA in 2030. The green ammonia is estimated to be in the range 17-26 MTPA in 2030, with significant amounts to be added on-stream closer to 2028-2030.

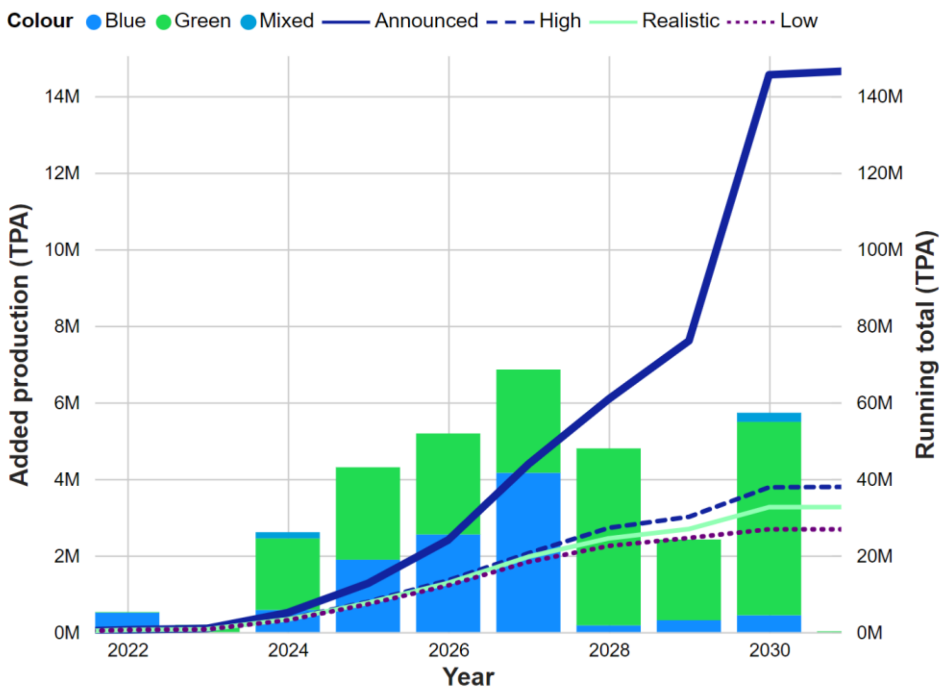


Figure 20: Yearly added production according to realistic scenario (vertical bars) and running total yearly production in high (dashed), realistic (solid) and low (dotted) scenarios. Distribution of green, mixed and blue ammonia in the estimated scenarios is shaded in the columns. Running total NH_3 production capacity according to the announcements is added for reference (solid black).

The distribution of ammonia amongst the different end use categories is altered by the use of likelihoods, e.g. in the Realistic scenario, Fuel is decreased by 75%, fertilizers by 52% and energy applications by 90%. A moderate decrease in fertilizers category is mainly due to significant fraction of blue ammonia projects present in this application.

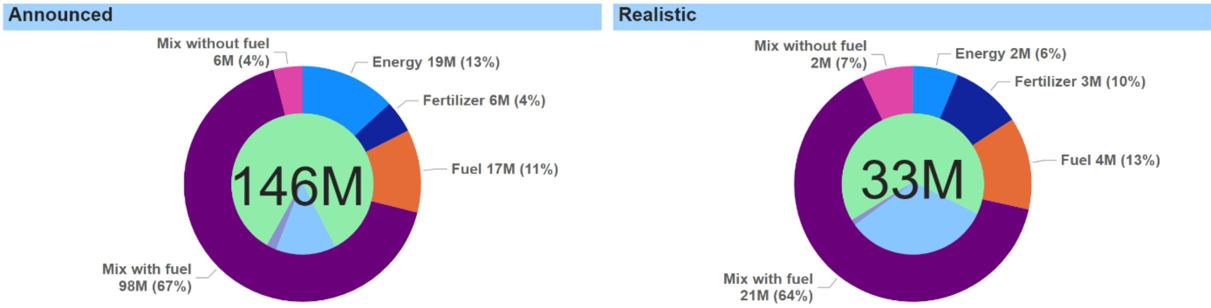


Figure 21: Comparison of distribution ammonia end use according to the announced and realistic scenario in 2030. The inner pie chart shows the fraction of green, mixed and blue ammonia.

3.7.2 Likely supply of ammonia as a fuel for shipping

Focusing on the availability of ammonia as a low carbon shipping fuel in 2030, the announced capacity targets the range of 17-114 MTPA, which includes 17 MTPA specifically dedicated to fuel and 98 MTPA with uncertain fraction of ammonia for fuel. Our scenario analysis provides three likely ranges: a) Low 3.6 - 20.6 MTPA; b) Realistic 4.2 - 25.2 MTPA; c) High 6 - 29.4 MTPA.

In the realistic scenario, the lower limit of the fuel-dedicated amount of 4.2 MTPA can be considered a minimum realistic supply of ammonia for fuel. Correspondingly, the upper limit, which can be regarded as maximum available ammonia for fuel amount, is a combination of dedicated fuel projects (4.2 MTPA) and the Mix with fuel (21 MTPA), resulting in 25.2 MTPA. The future demand for clean ammonia will be driven by the market demand, and thus the distribution of mixed category will be dynamic. However, for a rough estimate, assuming equal share between the three sectors, indicative fuel availability could be in the range 9-14 MTPA.

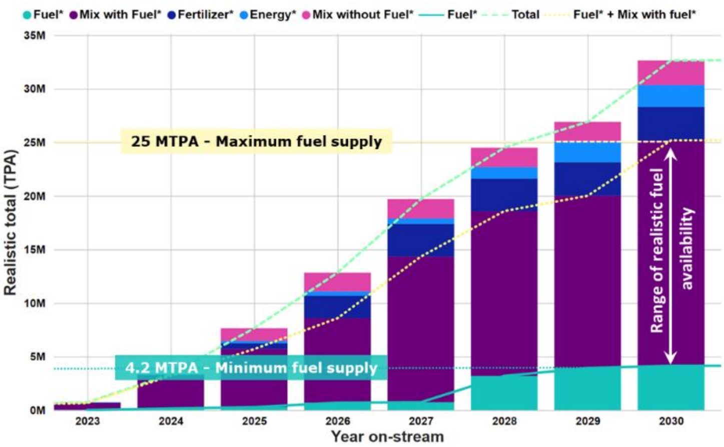


Figure 22: Evolution of realistic production of clean ammonia per use category.

Notably, all of 4.2 MTPA of dedicated fuel supply is green, with additional 20.8 MTPA for the mixed market applications including fuel (7.5 MTPA blue and 13.3 MTPA green).

In the realistic scenario, the majority (31 MTPA, 94%) of the produced ammonia will be for export and only 1.6 MTPA will be used locally. This means that, regardless of the end use, there will be a need for transporting large amounts of ammonia by the sea, which is one of the major reasons why ammonia production plants are within few kilometres from the distribution port.

3.7.3 Realistic installations of electrolysers

To produce 22 MTPA of green ammonia estimated in the realistic scenario (all applications included), 52 GW electrolysers will be needed by 2030. The yearly installations vary in the range 4-12 GW, with an average value 8 GW/year. Section 6.2 explores the trends and implications of the upscaling of electrolyser manufacturing.

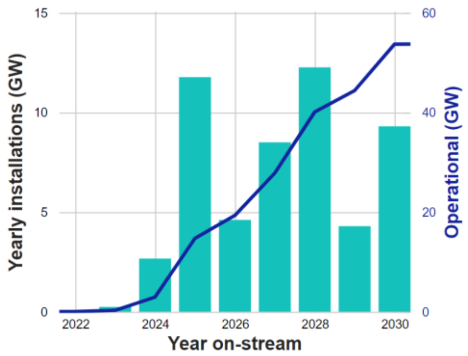


Figure 23: Realistic yearly (columns) and total (line) installation of electrolyser

4 Results for the years 2040 and 2050

4.1 Global demand of ammonia

By use of the DNV Pathway model, as described in Chapter 2.2, the demand for ammonia as a maritime fuel will grow from 2.3 million tonnes in 2030 to 62 million tonnes in 2040 to 245 million tonnes per year in 2050. The demand for each year is shown in Figure 24. Both green and blue are included.

Furthermore, in addition to the DNV Pathway model for the maritime sector, another DNV model used in the DNV Energy Transition Outlook (ETO) 2022 [10] has modelled the entire energy system. In the ETO2022 model, demand for ammonia as a feedstock, in particular for fertilizers and explosives, shows a moderate growth to 2050 from about 186 MTPA in 2021 to about 200 MTPA in 2050. The strong growth is for ammonia as a maritime fuel from nothing today, to surpass the feedstock use by 2046 and then to reach 245 MTPA in 2050.

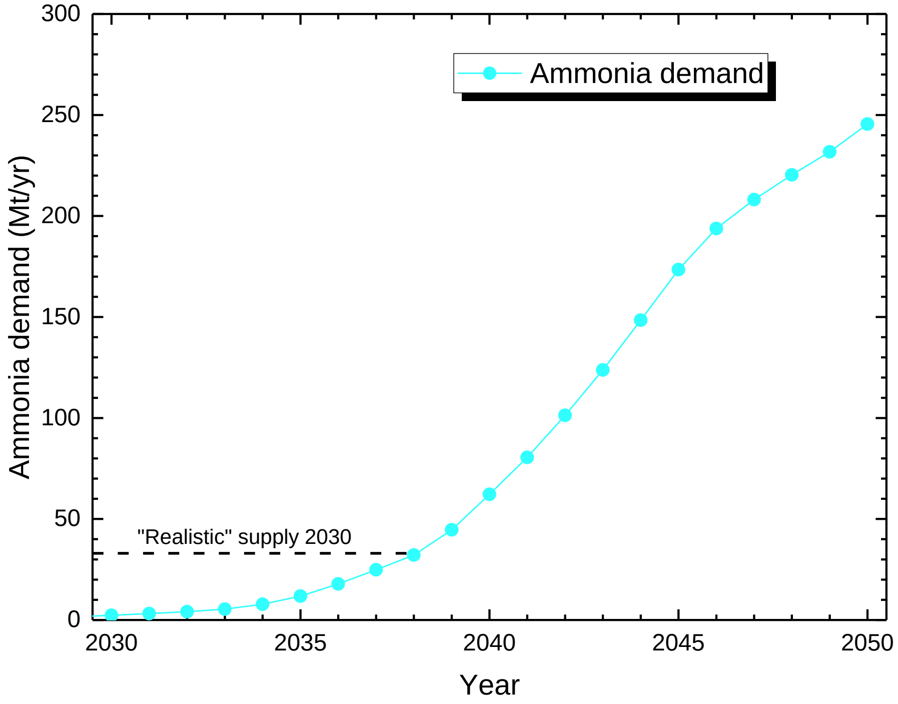


Figure 24: Demand for ammonia as a maritime fuel by the DNV Pathway model; both green and blue contributions [8].

In addition to these final demand uses, there will grow an intermediate demand, for ammonia conversion where the final demand is for hydrogen, but it will be more economical to deep sea transport it as ammonia to crack it back to hydrogen where it will be used. This trade will emerge in 2030, but grow to over 150 MTPA in 2050, 90 of which from the region Northeast Eurasia (includes Russia, Ukraine and other former Soviet republics). Interestingly, differential costs and distance to final use makes different supply chains used for the use categories. Use of ammonia for co-firing in coal power plants or in gas power plants does not in the ETO model contribute with a significant demand.

While over 30% of production used for feedstock in 2050 will still be unabated ammonia from methane reforming, maritime energy use will be entirely abated. Indeed, the only reason why ammonia will be used in shipping will be able to declare it is clean.

In the following ammonia as an energy carrier and ammonia as a feedstock are both depicted. The main reason is that the sources of ammonia differ. For feedstock, grey ammonia will in 2050, according to the ETO model, still be largest with 39%, while blue will represent 35%, and green 26%. For ammonia as energy carrier, i.e. for marine fuel, blue ammonia dominates by 76%, cf. Figure 25.

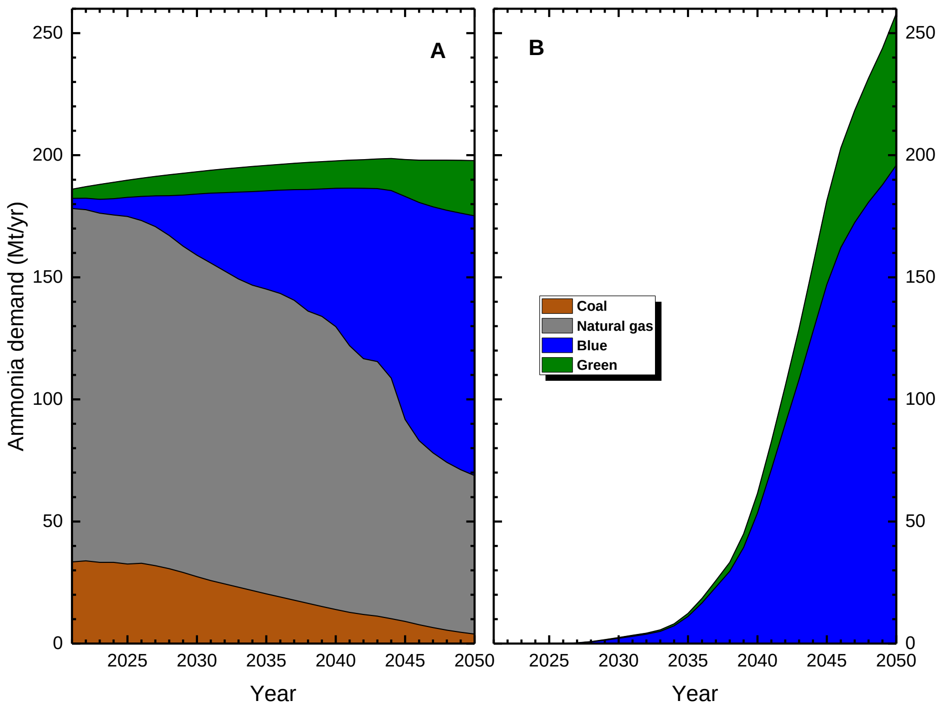


Figure 25: Global ammonia demand for A) Feedstock and B) Energy demand (mainly marine fuel). Green consists of solar PV, wind and nuclear. Blue consists of both natural gas and coal with CCS [10].

4.2 Regional supply for the global demand of ammonia

The ammonia production differs from region to region as described below.

Northeast Eurasia (NEE) includes both Russia, Ukraine and other former Soviet republics. The forecast assumes that the current war in the region with its sanctions will be short-lived and pre-war trade patterns will be re-established before 2030. As a major producer of natural gas, this region will provide over a third of global final demand ammonia in 2050, almost entirely based on its fossil resources, and entirely dependent on CCS as seen in Figure 26.

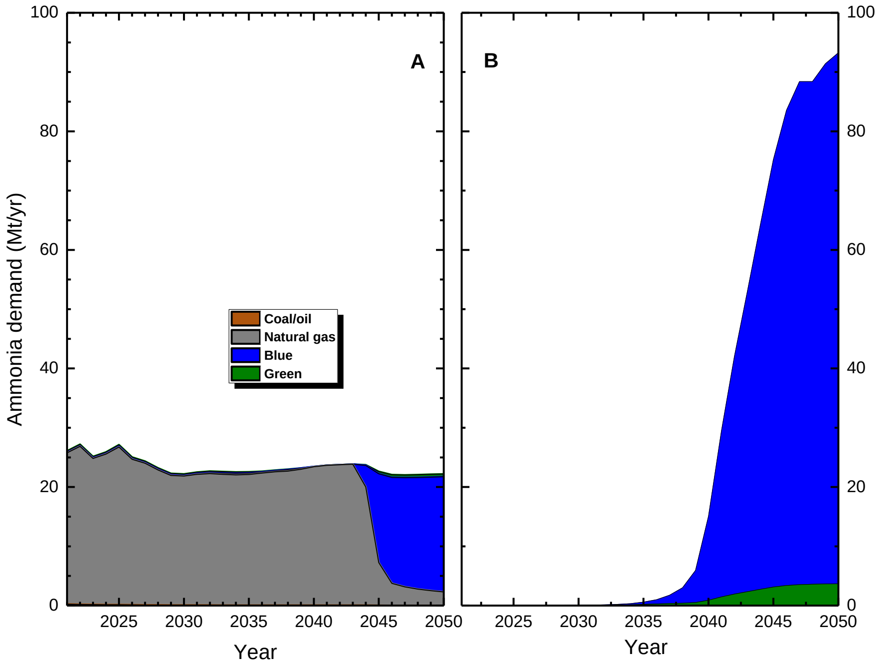


Figure 26: Ammonia supply in Northeast Eurasia for A) Feedstock and B) Energy demand (mainly marine fuel). Green consists of solar PV, wind and nuclear. Blue consists of both natural gas and coal with CCS [10].

China will see its significant ammonia production decarbonize, but not entirely. Due the dynamics depicted in Figure 27, it will see less growth in energy uses than other regions. Also due to support to nuclear power and its global dominance of renewables, electrolyser based technologies will dominate also in feedstock production. Note, however, that coal-sourced ammonia with CCS will be a technology on par with others. This happens in no other region, and is a way that Chinese coal avoids becoming a stranded asset.

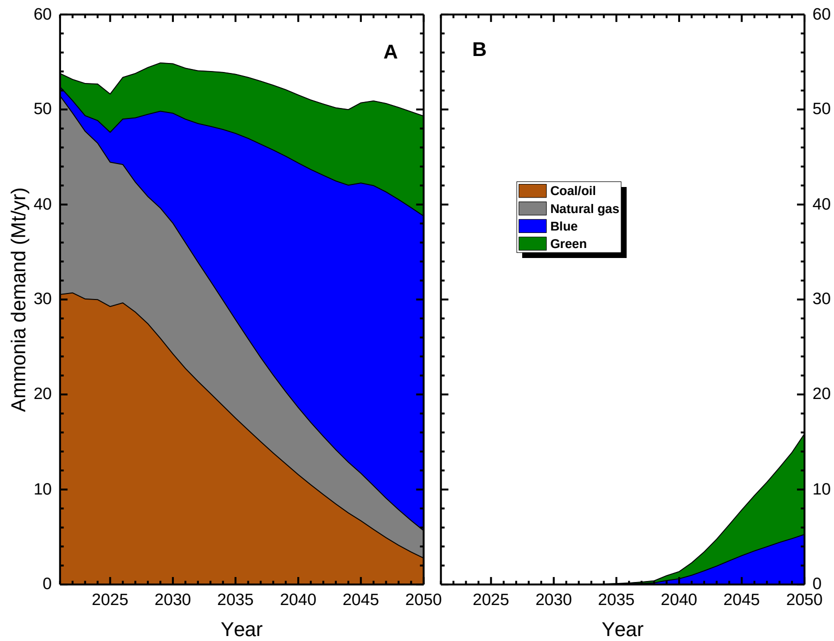


Figure 27: Ammonia supply in China for A) Feedstock and B) Energy demand (mainly marine fuel). Green consists of solar PV, wind and nuclear. Blue consists of both natural gas and coal with CCS [10].

In line with the above mentioned regions, also in North America fossil-based ammonia will dominate, cf. Figure 28. Note that the region will only produce half of the ammonia delivered by NEE, and also that while NEE will see all of its methane based production decarbonized, North America will still keep a quarter of its feedstock directed production remain unabated.

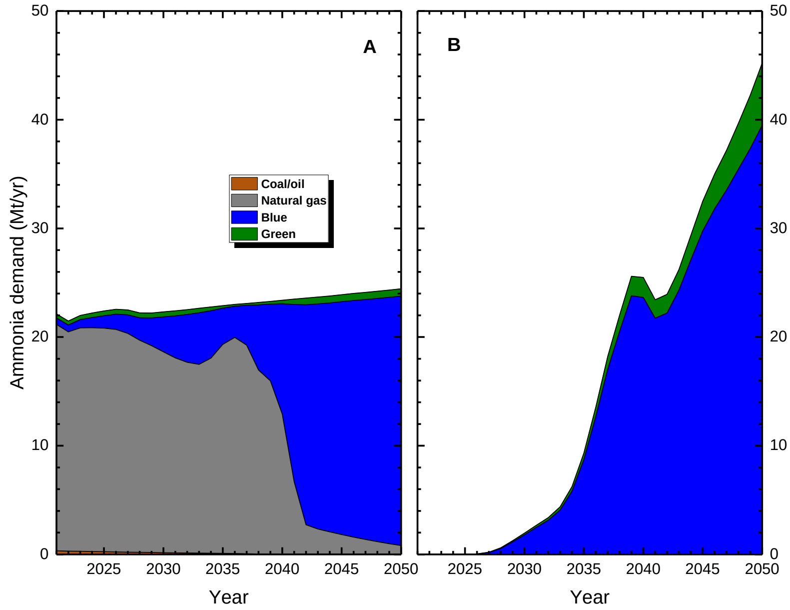


Figure 28: Ammonia supply in North America for A) Feedstock and B) Energy demand (mainly marine fuel). Green consists of solar PV, wind and nuclear. Blue consists of both natural gas and coal with CCS [10].

Another region rich in natural gas is Middle East and North Africa, cf. Figure 29. This region is less concerned with CO_2 emissions, and will see lower CO_2 prices than global average. Consequently, ammonia destined for feedstock will not significantly decarbonize.

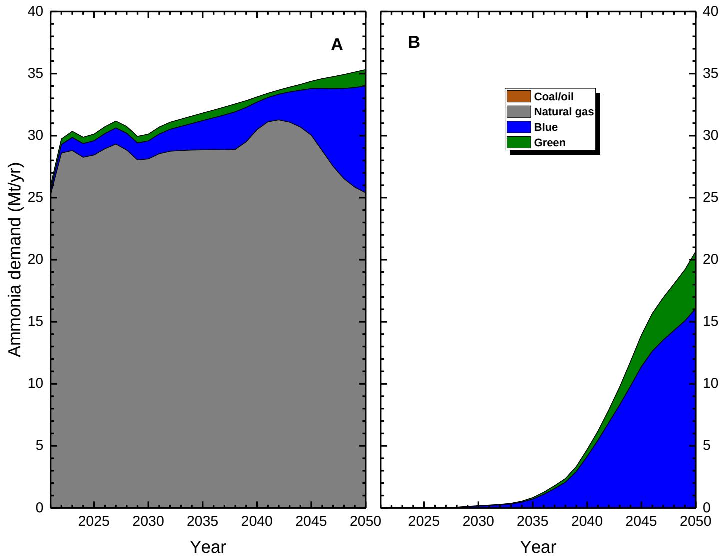


Figure 29: Ammonia supply in Middle East and North Africa for A) Feedstock and B) Energy demand (mainly marine fuel). Green consists of solar PV, wind and nuclear. Blue consists of both natural gas and coal with CCS [10].

In contrast to the previously mentioned regions, Europe is relatively poor in natural resources. Though Norway will be the exception and still rely on natural gas as a source (with increasing levels of CCS), the continent will almost entirely see electrolyser providing ammonia in 2050. Note also that feedstock-destined production will lose global competability and so see its output cut in half by mid-century.

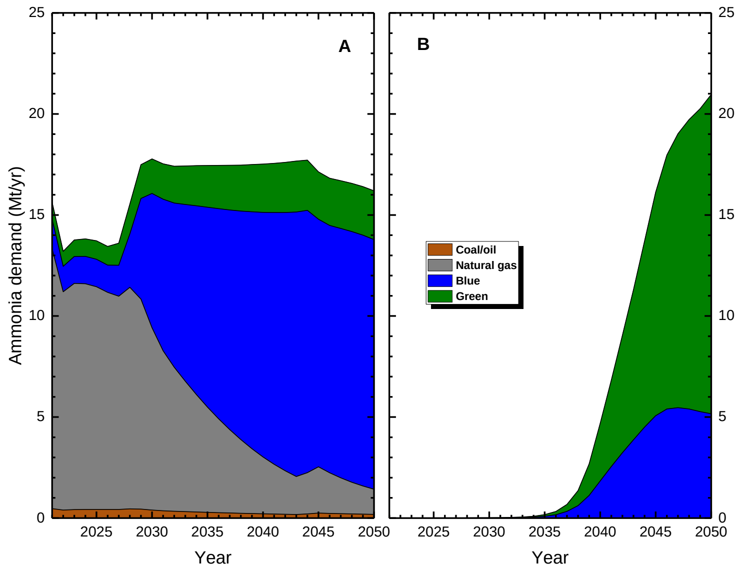


Figure 30: Ammonia supply in Europe for A) Feedstock and B) Energy demand (mainly marine fuel). Green consists of solar PV, wind and nuclear. Blue consists of both natural gas and coal with CCS [10].

Rest of the world will, with the exception of Australia, leverage its natural fossil resources and supply less climate conscious markets. Consequnetly, feedstock users will be supplied with unabated methane reforming based ammonia, while energy destinations will see over three quarters of ammonia coming from blue sources.

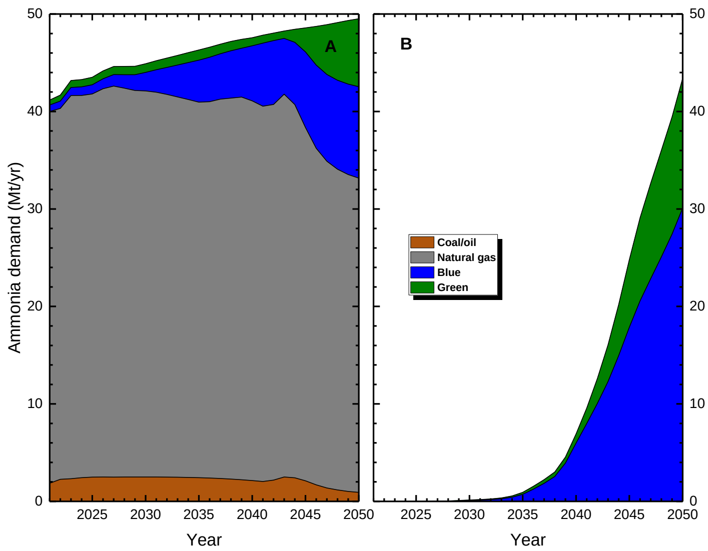


Figure 31: Ammonia supply in Rest of the World for A) Feedstock and B) Energy demand (mainly marine fuel). Green consists of solar PV, wind and nuclear. Blue consists of both natural gas and coal with CCS [10].

5 Market dynamics

Up to 2023, ammonia is an industrial feedstock used primarily in fertilizer production. The growth will come from ammonia use as a carrier of clean energy. Ammonia is often termed a ‘hydrogen derivative’, as it requires hydrogen and the Haber-Bosch conversion. The presumption that ammonia can serve as a major shipping fuel, is promoted by the development of a wider demand of hydrogen and ammonia also in other sources of demand. As shown in Figure 32, ammonia as a marine fuel does not exist today, but will most likely make up 35% of all shipping fuels in 2050 [10]. Yet, even this spectacular growth must be seen in a broader context as hydrogen feedstocks’ end uses will almost quadruple to 2050. Here, marine ammonia fuel is a very small fish in the pond, making up less than 10% of clean hydrogen, ammonia and e-fuels in 2050 [18].

The need for zero emission fuels arise because of societal demand for reductions in GHG emissions. In recognition of the need to get the above self-reinforcing loop to get the ‘snowball rolling’ [22] and increase its speed and size, there are are numerous support programs to help the ammonia market take off. As an example the IRA program in the US covers more than half of the green and blue hydrogen cost [23]. This will accelerate demand and thus further help supply to develop. Demand and supply dynamics are interlinked through cost learning and scale economies in a self-reinforcing feedback process as depicted in Figure 33.

Yet, for demand to develop, lower price is not the only driver. The ammonia needs to be made physically available. This again requires supply chains of both production and distribution. Here, shipping takes on at least two distinct roles. Ammonia fuel makes shipping a demand driver. But as has been seen, shipping is also an important part of the ammonia supply chain. It is likely that also hydrogen will be transported on keel as ammonia, as this avenue appears less costly (converting hydrogen to ammonia and back is less energy intensive and therefore less expensive than liquefying hydrogen [18].

It must be noted, however, that zero-emission fuels are in their infancy. There are several contenders, both hydrogen, methanol, other e-fuels, and biofuels. Each of them will compete for market share in the zero-emission ship fuel market, and the zero-emission fuel market is again competing for share of the total maritime fuel market. It is given that this market share will increase, but the DNV ETO ‘most likely future’ estimates ammonia will supply about 35% of all maritime fuels in 2050 [10], or 50% of all clean fuels. In a less likely net-zero emissions by 2050 future, the clean ship fuel market share reaches 85% in 2050, of which 60% will be ammonia, 6% will be biofuels, 24% methanol, and 10% will be electricity [10].

As indicated in Figure 34, the global energy system, depicted in order to better understand the dynamics of the clean ammonia market consists of three interconnected self-reinforcing loops. This implies first mover advantages, because of path dependencies [24] and technology lock-ins: an early zero-emission entrant might become dominant, as a well-developed supply chain might lock actors into this fuel and consequently leave others out – cold – for ever. But the finding of the ammonia share of the maritime clean fuel market of 50-60%, depending on the scenario, also implies that there are local and regional context that prevents a ‘winner takes all’ future.

Compared to biofuels and methanol - electricity cannot be used for ocean freight, only coastal and river-based - ammonia is characterized by important supply chain advantages: As a significant fraction of (grey) ammonia is already shipped on keel today, there is a supply chain in the form of pipelines, ports, and terminals. Moreover, as many LPG ships can accommodate ammonia, also this part of the supply chain exists. Still, the DNV ETO futures Most Likely Future and Pathways to Net Zero still projects methanol, and biofuels, and ammonia to split the market share. This is because cost differentials will be small, cost learning rates are similar, and local supply chain fits will differ.

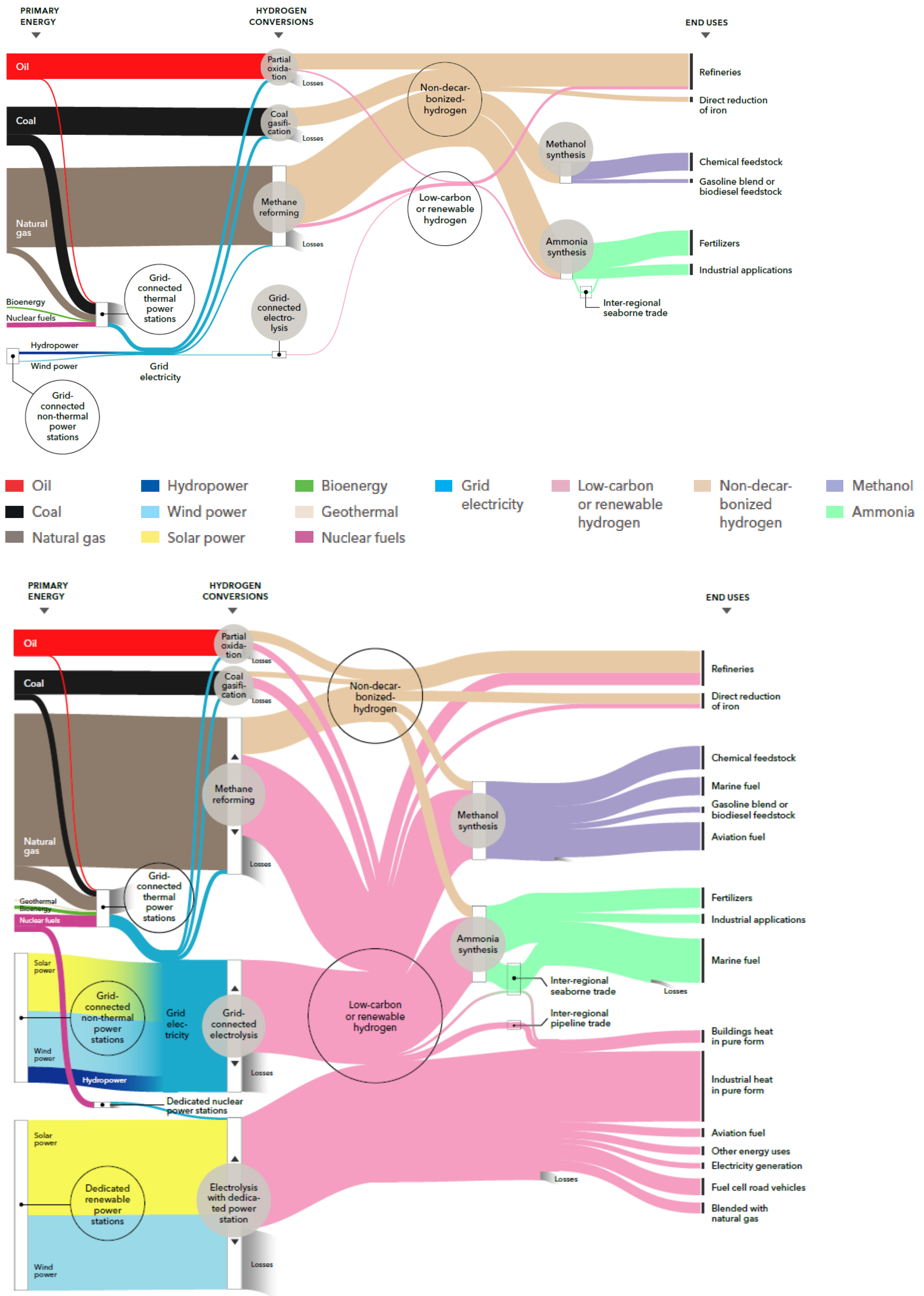


Figure 32: Sankey diagram of hydrogen production and end uses in 2020 (top) and 2050 (bottom).

D6-2-Future availability of green/blue ammonia in 2030, 2040 and 2050

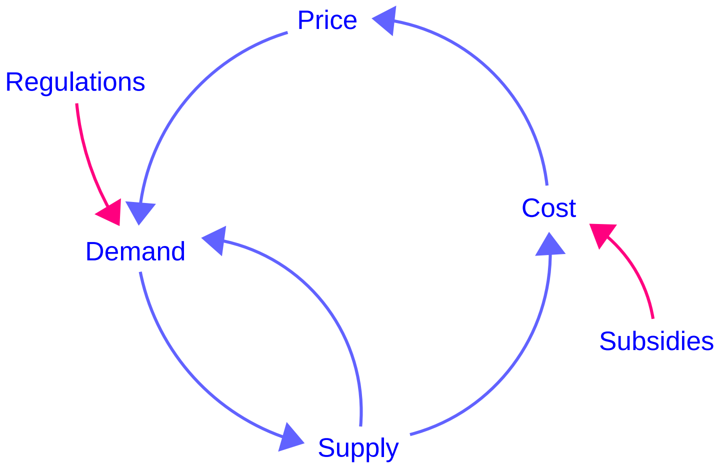


Figure 33: *Global combined demand and supply of grey, blue, and green hydrogen and ammonia in a self-reenforcing loop driving each other, where subsidies and regulations are external forces.*

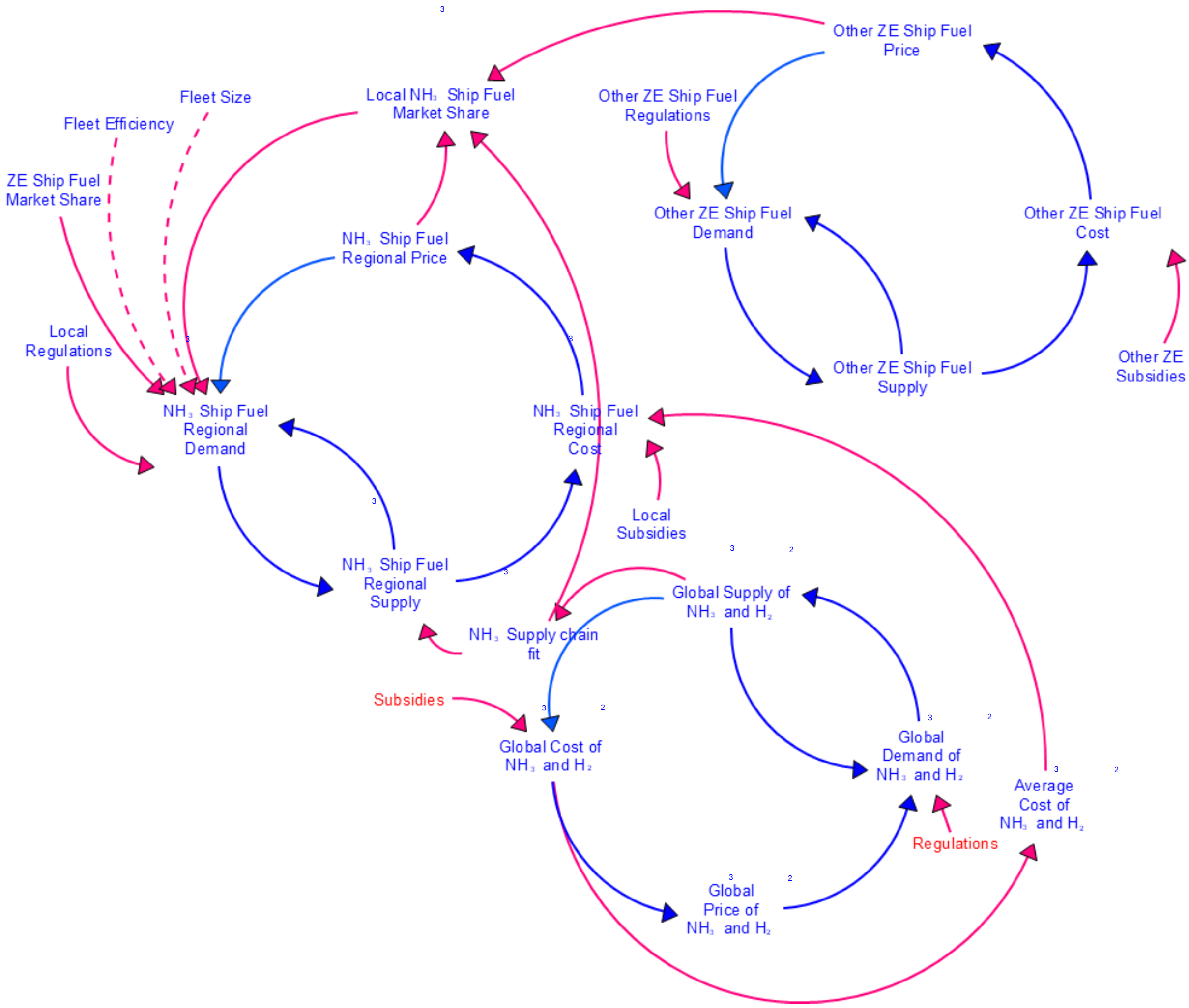


Figure 34: Clean ammonia demand and supply for shipping fuel are nested within the broader global loop, having its own local subsidies and regulations as external forces. The global loop is a much stronger driver than the regional shipping one. Note that there are also competitor zero-emission fuels, with similar dynamic characteristics.

The Haber-Bosch process has already accumulated 100 years of experience, and steam methane reforming has been the dominant production technology behind hydrogen for almost as long. Yet, both CCS to make blue hydrogen and electrolysers to create green are in their infancies. For the latter to become cost competitive, their costs must come down. Cost learning, through both local and global accumulation of experience is required. In Figure 34 parlance, this means that the upper left loop, (whose combined demand is less than 10% of the bottom right loop) is totally dependent on the dynamics of the global production processes of green, blue and grey ammonia, including that of CCS and electrolysers.

5.1 Regulations

Economists typically favor GHG emission prices as the most cost-effective way to ensure emissions reduction. To ensure temperature rises below 1.5 °C, analysts typically find CO_2 prices over 160 \$/tCO_2 already by 2030 [25]. As no one predicts the viability of such price levels emission reductions will partly come from emission regulations. Such regulations will partly be at the technology level (banning of coal power stations, sale of internal combustion engine cars), partly be through mandated emission limits in various sectors.

For the maritime industry, IMO has already in 2020 shown its clout by mandating sulfur emission limitations in parts of the world [26], requiring reductions by a factor of 7. Similarly, it is forecasted that the 70% reduction in GHG intensity in maritime transport to 2050 [27] will be followed by national and international regulations that will ensure that goal's accomplishment.

Yet, as indicated by Figure 32, and the interlocked feedback loops, regulations in other parts of the hydrogen and ammonia value chains will play a greater role. Regulations in various parts of the world are working in tandem with subsidy schemes to enable emission targets to be met.

5.1.1 US

The US IRA policy portfolio is mainly a financial support package that will run until 2032 [28]. Yet, it also contains regulations. The most known are the CAFE emission regulations for light duty vehicles, with only marginal impact on hydrogen value chains. Though fuel cell electric vehicles (FCEV) may theoretically blossom as a result of tailpipe emission reduction targets, it is highly likely that the great energy and cost advantage of battery electric vehicle technologies will abort FCEV for the light duty sector [18]. Yet, requirements that also a fraction of government owned heavy-duty vehicles shall run on Alternative Fuels will in practice support FCEV and demand for hydrogen. As H_2 is the main ingredient for NH_3, H_2 regulations that will increase H_2 production and hence reduce its cost. This will also benefit ammonia costs.

It is highly likely that sectors such as aviation will soon see regulations requiring increasing levels of zero-emission fuels in the mix. Hydrogen and derivates will benefit also from this.

5.1.2 Europe

The European Green Deal [29] highlights not financial support, but by creating a simpler and more predictable regulatory environment for clean technologies, The Green Deal Industrial Plan supports the transition to climate neutrality by enhancing the competitiveness of Europe's net-zero industry. In March 2023, three of its key proposals were presented: the European Critical Raw Materials Act, the Net-Zero Industry Act and the reform of the electricity market design. These will support the Plan by helping create a simpler and more predictable regulatory environment for clean technologies to either find or secure their home in the EU.

A part of this, is the Net-Zero Industry Act, where regulations will be in place to help ensure faster fielding of new green and blue low emission technologies. Most countries have regulations in place that will mandate zero-emission heavy duty vehicles before 2040. This has spurred manufacturers to spearhead FCEV development for heavy trucks, and related hydrogen fuel station planning.

5.1.3 Asia

Japan is set to mandatory close coal fired power plants in the 2040'ies. Instead of stranding such plants, they are set to be co-fired with ammonia with minimal update costs [30], and successfully increase the ammonia fuel share in these plants to 100% within 20 years. In Japan, the goal is to use 30 Mt ammonia for power generation by 2050 [6]. Similar policy initiatives are under way to use hydrogen for electricity generation and home heating. Though Japan fuel cells in homes, and use of ammonia in power plants benefits from regulations, such use suffers from much greater energy losses than comparable technologies. DNV foresees such energy efficiencies to impair further development in a most likely case, wherein only 6% of buildings energy use is hydrogen and ammonia. But once Pathways to Net Zero future is envisaged, regulations will follow, and also hard to abate parts of buildings energy use will be decarbonized leading to a full 25% of buildings energy use coming from hydrogen. Using hydrogen and ammonia for power generation will highly likely never take off, even in a net zero future. The alternatives, notably renewable electricity and storage combinations, typically are twice as energy efficient, and for extreme 'dunkelflaute' situations, other and less energy wasteful options will suffice.

China's and India's future regulatory environment will first address local and not climate emissions. Yet as a side effect, these will help hydrogen and ammonia developments.

5.2 Subsidies

Two observations are central to the discussion of how fast the hydrogen economy will evolve (if at all). First, as energy carriers, hydrogen and ammonia are much more expensive than the fossil fuels they replace, and uptake will only take place if it is regulated or subsided (or both). Second, as with other aspects of the energy transition, national and regional economies, such as USA, China, and EU understand pathway dependence, first mover advantages, and barriers to entry. Therefore, support to hydrogen and ammonia is interlinked with industrial policy and support. Using a global and regional framework, and integrating industrial and climate policy forces, the below tables show subsidy levels (developed spring 2022, before IRA and the EU and Chinese responses to it). Average regional support mechanisms are already in full swing. They will remain at current levels for the reminder of the present decade [10]. Then they will linearly taper off to reach half of current levels in 2050. The combination of financial muscles, climate ambitions, and industrial policy makes for a full half of all capital investment funding in hydrogen plants will come from taxpayer in OECD countries and China through 2030. Similarly, Middle East, North Africa, and India's governments will foot 15% of the investment bills in their home turfs, a fraction lowered to 10% for Latin America. Neither Sub Saharan Africa nor Northeast Eurasia will have any public funds available for such investments. Nuclear powered dedicated hydrogen facilities will be less easy to sell to the public, and so receive only half these support levels as seen in Table 2.

OECD North America, Europe, Japan, Australia, South Korea
CHN PRC, Taiwan
MEA Middle East, North Africa
LAM Latin America
SSA Sub Saharan Africa
NEE Northeast Eurasia

Table 1: Average regional investment support levels, grid electricity and dedicated renewable electricity

	OECD+CHN	MEA+IND	LAM	SSA+NEE
2023	50 %	15 %	10 %	0 %
2030	50 %	15 %	10 %	0 %
2040	38 %	11 %	8 %	0 %
2050	25 %	7 %	5 %	0 %

Table 2: Average regional investment support levels, dedicated nuclear

	OECD+CHN	MEA+IND	LAM	SSA+NEE
2023	25 %	8 %	5 %	0 %
2030	25 %	8 %	5 %	0 %
2040	19 %	6 %	4 %	0 %
2050	13 %	4 %	3 %	0 %

The above tables include investment support to all hydrogen facilities for both Most Likely future and Pathway to Net Zero future. In addition, the initially most costly way to produce hydrogen, being also the most desirable climate ways, are variable renewable electricity dedicated to hydrogen. In order for these to take off, to ensure an emissions-free world by 2050, additional operations support will be required. In OECD, governments in such a pathway will subsidize a full quarter of all operating costs. Other regions will in our estimate foot 4-10% of the bill depending on the region. Note that for wind and solar PV facilities require no fuels, so this type of support includes only the maintenance and infrastructure upkeep, a relatively modest amount.

Table 3: Production cost support levels for dedicated hydrogen

	OECD	CHN	LAM+MEA+NEE	IND	SSA
2023-2050	25 %	4 %	10 %	7.5 %	5 %

5.3 Who will the clean ammonia players be?

Around the world, companies and governments are forecasting that clean ammonia will be an integral part of a future with low or no GHG emissions. As most forecast that ammonia will be a refined product through the Haber-Bosch or other technologies, clean hydrogen and ammonia cannot be considered as separate developments.

It is also clear that even with a foreseeable 200 $/t$CO_2$ price (twice the EU observed price peak), clean ammonia will still be significantly more expensive than fossil alternatives for virtually all applications [10]. Governments will support clean ammonia projects for the foreseeable future as indicated in Table 2, covering half of all investment costs in OECD and China until 2030, a support level only cut in half in 2050. Other regions, with the exception of Sub-Saharan Africa, which cannot support it, and Northeast Eurasia, which is less concerned about climate change, will have lower support levels, but still significant, at 10-15% of initial investment costs. The current US IRA plan and its EU response clearly shows this.

Current global ammonia production is almost entirely grey/brown, and there currently exist supply chains that enable trade of ammonia. The players in these existing supply chains have experience with and knowledge of SMR production as well as the handling and transportation of ammonia. They are already positioning themselves for cleaning up GHG emissions from the SMR processes through CCS additions to existing plants and/or planning to produce blue hydrogen from new plants. Heavy current users of ammonia include fertilizer producers such as Yara and Nutrien, and oil refinery operators such Chevron and BP. Such players have knowledge of current markets, supply chains, and SMR technologies. They are positioning themselves for the forecasted quadrupling of hydrogen and ammonia demand to 2050 [10], where current feedstock production will remain stable, while H_2 used for energy purposes come to dominate, increasing from no use today to 75% of global production, representing 240 Mt H_2 by mid-century.

A second group of players in the nascent clean ammonia value chains are those that currently produce natural gas. This resource is foreseen to eventually become a stranded asset, unless it is decarbonized into hydrogen through SMR and CCS. Equinor and BP are examples of this set of actors.

Another set of players are found in renewable electricity. Some plan to build dedicated electrolyser facilities with integrated renewable electricity capacity (aka green hydrogen and ammonia). These include Iberdrola and Statkraft. But with lacking electrolyser competence, such renewable players often team up with electrolyser technology companies such as IHI Corporation.

The two latter set of players see resources and technologies, rather than value chain insights as keys to future success. They are interested in producing hydrogen, but this depends on the local demand for hydrogen. If that is too small, it needs to be transported away as an e-fuel. And ammonia is probably the best choice for that.

A key question is to what extent ammonia will act as a storage and transport element of energy. As it can easily replace coal in power production, especially Japan develops plans to acquire, produce and use ammonia for this purpose, where current coal handlers plan handling of ammonia, but also to extend their activities into operating other parts of the ammonia value chain. Similarly, as current feedstock dominated output where natural gas is bought by those in need and converted to ammonia, ammonia will be a commodity. Traded ammonia is forecast [18] to expand from only marginal amounts of current global ammonia produced to most of it by mid-century, as ammonia will become a traded commodity par excellence. Ammonia value chains will therefore include activities of also ammonia to hydrogen cracking, with some players being horizontally integrated, while others will be vertically integrated. But there will also be potential room for niche players specializing in smaller segments (such as ammonia to hydrogen cracking and -trade).

Table 4: Clean ammonia players

Clean ammonia players					
Player class	**Player type**	**Examples**	**Projects**	**Strenghts**	**Challenges**
Grey Ammonia/ Fertilizer	Ammonia User	Yara	Yara Clean Ammonia	Knowledge of feedstock market, production tech, value chain. Significant internal customer.	Limited knowledge of ammonia energy market
		Nutrien Ltd	Geismar		
Heavy Industry	Ammonia Equipment	IHI Corporation	H2TAS	As clean ammonia are emergent technologies, solving and fielding new techs will be core of the new business	Core competence on a small part of value chain
Natural Gas	Ammonia Manufacturer	Equinor	H2M Eemshaven	Ample access to natural gas and energy markets. Only way to prevent methane becoming stranded assets in a GHG free future.	Limited knowledge of ammonia feedstock market
		BP	Nord-West Oelleitung (NWO)		
		Chevron	Clean Ammonia/Indonesia		
Renewables	Ammonia Manufacturer	Iberdrola	Puertollano	Ample access to GHG free electricity. Focused on ammonia as an energy carrier.	Core competence on a small part of value chain

As indicated in Table 4, the various player classes all have strength and challenges. Oil companies such as Equinor and BP are increasingly also active in renewable energies, where they purport to spend the majority of future energy capex. This will alleviate some of their challenges. Another way to overcome challenges is for players of various classes to cooperate. A case in point is Yara and Engie who are collaborating in the Yuri project in Western Australia. This a hybrid project where both steam methane reforming and green technologies will be developed in parallel.

In sum, there are no showstoppers for any player class. Various entrants (all in clean ammonia are entrants, as this sector does not exist today on an industrial scale) all come with various strengths and challenges. It is hard to see that any single player class is better positioned than others, but it appears that various player classes can benefit from cooperation with players from others. Indeed, such cooperation appears to be the norm for most future projects.

5.4 Price elasticity

The fact that ammonia starts with natural gas, and its energy content is reduced while its cost increases along its value chain, makes ammonia more expensive than gas as an energy carrier. Removing and storing carbon dioxide (CCS) from the reforming process will of course add to that cost. Though green ammonia may well be cheaper than blue, most forecasters believe that the cost learning potential for green ammonia, though substantial, will lead to similar cost to blue ammonia once both technologies' cost learning curves flatten after 2040.

As is evident from current press releases, many sectors foresee the hydrogen economy in the shift to a decarbonized future. As indicated in Figure 35, there are two demand elasticities with respect to price that are of importance: The first is the demand elasticity to price of green ammonia in maritime sector relative to demand elasticity of other sectors. The other elasticity in question is that of ammonia as opposed to other zero emission fuels.

One way of assessing the first demand elasticity is to contrast the additional fraction of (operating) costs that switching from traditional to ammonia fuels represents for various sectors. According to Stopford 2009 [31], fuel costs are 30% of total ship transportation costs. According to IEA [32], clean ammonia is 215% more expensive than diesel. This means that switching to clean ammonia as fuel increases fuel fraction of total shipowner costs to 65%, assuming all other costs remain the same (in the short run, these would also increase, but not necessarily in the long run).

The main ammonia demand today comes from fertilizer production. That demand will remain stable until mid-century [10]. Ammonia is the main cost of producing fertilizer, and clean ammonia will double its cost from methane reforming without CCS [33] [1]. If total costs nearly double for fertilizer producers, but only increase by two thirds for shipowners by using clean ammonia instead of the alternative, one could conclude that the shipping industry ammonia demand would be less clean ammonia price sensitive and so crowd out fertilizer demand. But Yara's perspective is different. For the fertilizer user, such as a Midwest corn producer, fertilizer represents only 18% of total costs. This means that the total cost for the farmer would for clean ammonia use would only increase to 30%. Therefore, the fertilizer producer would easily crowd out shipowners for the clean ammonia.

With respect to clean ammonia's demand elasticity vs other fuels, the below IEA figure [32] does not tell the whole story: availability and capital costs are not identical across fuel types. Yet in the long run, they could be assumed to be similar and so fuel cost differentials can – as a first approximation – indicate shipowners' demand elasticities. Also here, ammonia is more expensive than the alternatives.

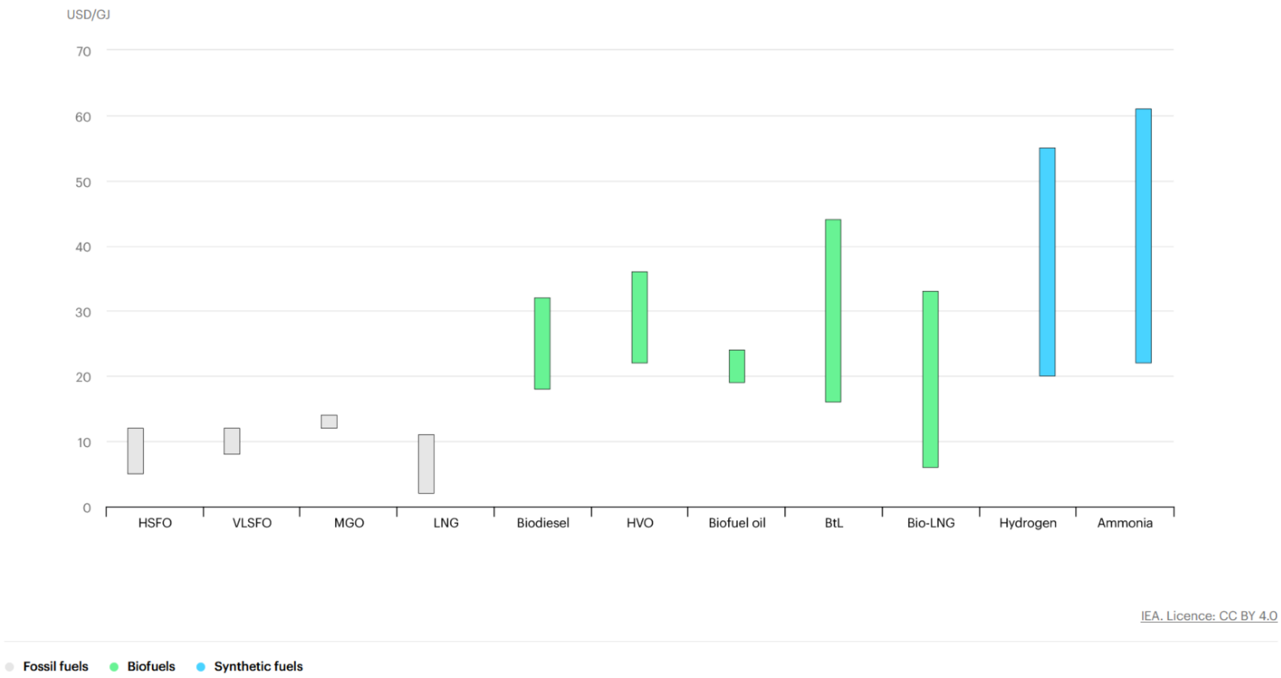


Figure 35: Cost comparison of shipping fuels [32].

6 Discussion

6.1 Export and the nearest major maritime hub

The project developers plan to produce about 177 MTPA for international export by 2045. If all the projects were to become realized on time, already in 2030 the amount of load on the existing ammonia transportation infrastructure would increase nearly 10-fold to 140 MTPA. That would also require more ships available for shipments. For transportation by the sea, a Large Gas Carrier is capable of carrying up to about 40 000 tonnes ammonia, whereas the largest ships, for example Very Large Gas Carrier, may carry up to 54 000 tonnes of ammonia. If all of 140 M tonnes of ammonia for export was to be transferred by the sea, it would require 3 500 individual voyages of LGC in the single year of 2030.

Ammonia to be transported by the deep sea will closely rely on ports, which offer infrastructure for storing and fuelling ships with alternative fuels, such as ammonia. Therefore, below we analysed which of the major maritime hubs are nearest to the announced projects, and what total production potentially would be shipped through them.

The notable feature of the almost all production facilities is that they are located within few km from a nearby a port, which facilitates easy transportation by the sea. To describe ammonia export traffic, we chose 8 major maritime hubs (Fremantle, Jeddah, Suez Canal, Casablanca, Houston, Santos, Rotterdam, and Singapore), and identified which of the major hubs is the closest to the project location. Note that this approach allows for indicative export traffic picture, showing the regional origin of the produced ammonia. Choosing a larger number of ports can provide a more realistic scenario, however, is beyond the scope of this study.

Based on the nearby production facilities, the busiest port exporting clean ammonia could be Fremantle in Australian South West with 59 MTPA, followed by Jeddah (48 MTPA), Suez Canal (20 MTPA), Casablanca (16 MTPA), Houston (15 MTPA), Santos (11 MTPA), Rotterdam (3.5 MTPA), and Singapore (3.4 MTPA). This distribution of ammonia export is not reflecting the actual availability of ammonia in that port but indicating the amount of produced ammonia in the vicinity. In reality, for example in South America, multiple export hubs would be participating in ammonia transportation, further sharing the 11 MTPA produced there among multiple ports. Similarly, port Singapore is at the forefront of the development of bunkering infrastructure and will play a major role in ammonia fuel trade.

Figure 36: Eight ports describe the nearest major maritime hub to the announced projects, with corresponding amount of clean ammonia produced in their vicinity.

6.2 Electrolyser vendor landscape towards 2030

According to the announced projects, in 2030 yearly green ammonia production is expected to reach 123 MTPA, which would consume about 22 MTPA of hydrogen and would require 256 GW of electrolysers. To conclude whether the today's electrolysers manufacturing capacity can scale up to the announced 256 GW, or to realistic estimate of 52 GW in 2030, this section reviews the state-of-the-art in electrolyser technology and its potential.

6.2.1 Electrolyser technologies

In green ammonia production, electrolysers use electric current to split water into targeted hydrogen and oxygen as by-product. Electrolysis is the most promising method of hydrogen production from water, with efficiency exceeding that of thermochemical and photocatalytic methods. The currently available technology comprises of Alkaline (ALK), Proton Exchange Membrane (PEM), Solid Oxide Electrolyser Cells (SOEC) and Anion Exchange Membrane (AEM) electrolysers.

The alkaline is the oldest, most mature (TRL 9), commercially available technology which uses noncritical, non-noble metals (nickel) operating in a liquid alkaline electrolyte solution. Simpler design in comparison with other electrolyser types, cost effective construction, and superior durability allowed alkaline electrolyser technology to dominate the installed capacity today and with a strong position expected also in 2030. The future development is focused on pressurised alkaline systems, which respond better (< 10 s vs min for traditional alkaline electrolyser) to variations in power input, and thus ensure future competitiveness with faster PEM [18].

The operational principle of PEM electrolysers is based on a fuel-cell design from 1960s, with a solid polymer electrolyte functioning as a proton conductor, a gas products separator, and an electrical insulator of the electrodes. One of the relevant advantages of PEM is their ability to respond fast (<1 s) to changes in power input from the renewable energy system, thus avoid corrosion of stack components [34]. The prominent disadvantage is in use of noble metal-based catalysts needed to facilitate water splitting in a highly acidic electrolyte environment. As a consequence, PEM technology (TRL 9) needs to address the issue by lowering the amount of precious metals used, and their recycling, what will allow for the large-scale expansion of PEM. In response to the challenges, the technology receives great innovation efforts from the producers, with overall compound average growth rate in patenting of 13% in 2011-2020.

In contrast to liquid or polymers, SOEC technology relies on solid, oxide or ceramic, electrolyte to split water into hydrogen gas and oxygen. SOEC operate at high temperatures of 500-900 °C, and use water steam instead of liquid, what leads to high efficiencies. The use of non-precious metal catalyst allows for cost-competitive scaling of this technology (TRL 7), once the low lifetime limitations are addressed (~20 000 h).

Anion Exchange Membrane (AEM) is the latest development in electrolyser technology (TRL 6). It combines features of alkaline and PEM electrolysers, by using alkaline water and PEM-inspired membrane design but with cheaper, not scarce materials. Similarly to SOEC, the system needs improvement in the lifetime characteristics (5 000 h) before it can be scaled up, and therefore the significant application of this technology is likely after 2030.

DNV concludes that each of these different technologies will have an application area [18]. The traditional, atmospheric alkaline could be a preferred option for a large scale, continuous, high load hydrogen production, with low variation in energy supply (geothermal, nuclear, grid), due to low costs, robustness, and maturity. Likely before 2030, the decreased costs of PEM and pressurized alkaline will be highly competitive to atmospheric alkaline, contributing with efficient, flexible, and fast responding (1-10 s) electrolyser technology to be employed in variable renewable energy systems.

6.2.2 Innovation in electrolysers and learning curves

Since 89% of the projects have yet to reach FID stage, the vast majority of the electrolyser scope will be defined within the next years. The following innovation and patenting trends allow seeing the possible availability of the electrolyser technology closer to 2030.

Analysis of patenting trends in 2001-2020 by IEA concludes [19] on significant growth in patenting of technology for green hydrogen production using electrolysis, while traditional technology relying on fossil fuel methods peaked in 2007 and declined in the following years. Moreover, electrolysis has established a clear dominating position (with 5-10 times more applications) over other low emissions technologies such as production from biomass waste, and other technology for water splitting. For example, patenting on AEM electrolysers has seen compound average growth rate of 11% in the past decade. Overall, the patenting among the four electrolyser types is dominated by PEM with 41% share, followed by SOEC (32%), alkaline (22%) and AEM (5%).

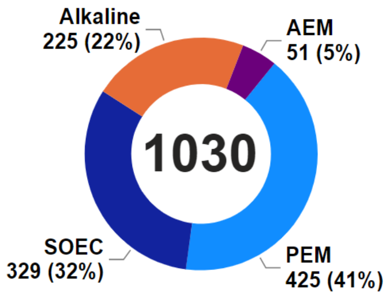


Figure 37: Distribution of patent filing among the four electrolyser types. Based on data from [34].

Over the past decade, Europe was at the forefront (28% share) of the patenting of hydrogen producing technology, with significant contributions from Germany (11%), France (6%) and the Netherlands (3%) [19]. The major European industrial players Linde, Air Liquide, and Thyssenkrupp are in the list of top ten hydrogen innovation clusters. The large share of the patenting is a prerequisite for Europe to lead also installed electrolyser capacity. In this report it is suggested that Europe (alongside of Japan) has also a potential to be also a major electrolysers exporter to the countries where ammonia production would be concentrated. Indeed, since Europe is to host, only 3% of the announced (ammonia) production capacity (Section 3.3.1), the excess of the electrolyser production might be exported to the locations in Australia, Middle East, and Africa. The same can be true for Japan, which held share of 24% of patents [19], but no ammonia project is yet to be developed. Tokyo area alone is an absolute global leader in hydrogen technology innovation and is responsible for 7.5% of hydrogen patenting, primarily focused on applications, which is consistent with country's interest in energy utilisation of hydrogen and ammonia.

Among the top ten companies patenting electrolyser technology (Figure 38), big innovation drive comes from the Japanese producers, who however are yet to significantly invest in scaling up manufacturing capacity. In contrast, European Siemens, De Nora and Thyssenkrupp are already producing and commercialising the electrolyser units [19]. From this list, Siemens, Topsoe and Thyssenkrupp are featured in the list of advertised suppliers for the announced projects in Section 3.5.2.

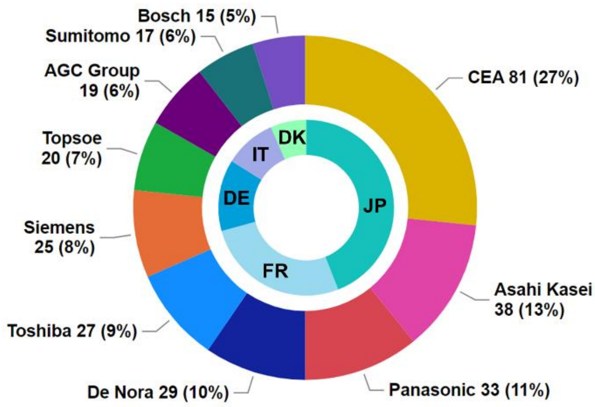


Figure 38: Top companies patenting electrolysers technology, with number of patents within 2011-2020. Based on Source IEA and EPO patenting report [19].

In addition to innovation derived from the dedicated research and development, manufacturing itself is a source of practical insights. Learning and experience curves describe decrease in production costs as the manufacturing doubles, and consequentially generate innovation as the production upscales. For example, with deployment of 100-270 GW electrolysers by 2030, the learning curve is projected to contribute to the 40-55% cost reduction, respectively [19]. The learning curve of electrolysers is related to other technologies, as chlor-alkali production, fuel cells, batteries [19]. The learning rate of electrolyser manufacturing is expected to be in the range of 10-18% in 2020-2030. This should have a significant positive impact on the electrolyser costs and hence more extensive market uptake.

Overall, the ongoing acceleration in patenting of electrolyser technology, which is yet to reach its peak, ensures manufacturers' commitment to supply current state-of-the-art electrolysers, as well as brings continuous improvements to the existing technology.

6.2.3 Countries policies and goals

Many countries hosting the ammonia projects have defined their national goals. These subsidies and targets have already stimulated electrolysers producers as well as some of the announced projects.

The EU hydrogen strategy (2020) aims for at least 40 GW electrolyser capacity installed in 2030 (6 GW by 2024), with several European countries confirming their own commitment, such as Denmark (4–6 GW), France (6.5 GW), Italy (5 GW), Germany (10 GW), Spain (4 GW), Netherlands (3.5 GW), Poland (2.5 GW), UK (> 5 GW), and Ukraine (10 GW).

Table 5: Comparison of countries' targets for the installed electrolyser capacity in 2030 with the planned installation announced in the projects within 2030. Gap values show the difference between the two, such that positive values indicate overachieving the goals, and vice versa.

Country	Announced (GW)	Aim (GW)	2030 Gap (GW)
Australia	55.2		55.2
Mauritania	30.0		30.0
Kenya	25.4		25.4
Saudi Arabia	24.0		24.0
Kazakhstan	20.0		20.0
Morocco	17.2		17.2
Papua New Guinea	15.3		15.3
Egypt	11.2		11.2
Spain	8.5	4.0	4.5
Brazil	3.9		3.9
Namibia	3.0		3.0
United Arab Emirates	2.3		2.3
Norway	1.6		1.6
United States of America	1.1		1.1
Malaysia	0.8		0.8
Paraguay	0.8		0.8
Sweden	0.6		0.6
Ireland	0.5		0.5
Bolivia	0.5		0.5
Angola	0.5		0.5
Indonesia	0.4		0.4
Canada	0.2		0.2
Mexico	0.7	0.5	0.2
Trinidad and Tobago	0.1		0.1
Iceland	0.1		0.1
Peru	0.0		0.0
Oman	8.7	10.0	-1.3
Colombia	0.4	2.0	-1.7
Poland		2.5	-2.5
Netherlands	0.1	3.5	-3.4
Denmark	1.0	5.0	-4.0
Italy		5.0	-5.0
France		6.5	-6.5
United Kingdom	0.0	7.0	-7.0
Belgium		8.0	-8.0
Chile	16.3	25.0	-8.7
Germany	1.1	10.0	-8.9
South Africa	1.1	10.0	-8.9
Ukraine		10.0	-10.0
China		35.0	-35.0
India	3.5	55.0	-51.5
Total	**256.0**	**199.0**	**57.0**

Notably, South Africa does not host the projects as of 2022, but their Hydrogen Society Roadmap (February 2021) aims for renewable hydrogen exports, targeting a 4% global market share by 2050 with the following timetabled production capacity targets: 1 MW electrolyser production piloted to 2024; expansion to 10 GW (2025–2030); and 15 GW capacity installed (2030–2040).

Oman's National Hydrogen Strategy (2021) pursues blue and green hydrogen with capacity targets of 10 GW by 2030 and 30 GW by 2040. Chile aims to have 5 GW of electrolyser capacity under development by 2025, and 25 GW with committed funding by 2030.

China's Hydrogen Development Roadmap targets 10 GW installed electrolyser capacity by 2025, at least 35 GW by 2030, and more than 500 GW by 2050. In fact, Chinese producers benefit from low material and labour costs, and have the potential to disrupt the market. Today their portfolio of electrolysers counts 14 producers and more than 232 models. But the export is limited due to large and demanding local Chinese market, capable of consuming all of the produced capacity. Despite the lower costs, there are a number of factors, including performance, reliability, lifetime, yield, maintenance, which render Chinese systems less competitive with Western electrolysers [18].

Comparison of the announced electrolyser capacities (cf. Table 5) with the nationally set targets for 2030 reveals the gaps in the installed electrolyser capacity. Clearly the announced ambitions exceed the sum of the targets by 57 GW. This number would be negative (more installations needed to meet the target) if more countries adopted and revealed their plans for renewable hydrogen to reach the global net zero of 850 GW [11]. Indeed, the majority of the project hosting countries, including leading Australia, Mauritania, Kenya, Saudi Arabia, Kazakhstan, Morocco, Papua New Guinea, and Egypt are yet without clear renewable hydrogen goals. From the countries that have the goals and host the ammonia production, on track are Spain (plan corresponds to 212% of the target), Mexico (133%), Oman (87%), Chile (65%).

Notably, the top ten countries producers of ammonia are not producers of electrolysers. This implies that majority of the electrolysers produce will be exported, for example from Europe and Japan and installed internationally. For the project development and stable operation, choosing a local electrolyser supplier offers lower risks with regards to guarantees, service and maintenance. Developing local demand already stimulated some major producers to open a branch in the strategically important areas, for example Australia [35].

6.2.4 Upscaling the electrolysers manufacturing

To fulfil the installations announced for 2030, it may require about 2 500 electrolysers with a capacity of 100 MW. The production of such a large number of units demands substantial efforts on upscaling the electrolysers manufacturing.

Upscaling of electrolyser manufacturing reduces the manufacturing costs significantly. In a typical 1 MW electrolyser produced in 2020, the major fraction of electrolyser costs is spent on the infrastructure around the electrolyser (power supply, water processing, cooling, and etc). According to the "Scaling up the electrolysers" report by IRENA [34], upscaling the manufacturing from 10 MW to 1 GW, allows reducing the stack cost by 70%, and most of the price to be dominated by the cost of materials instead of the infrastructure and labour. The strategies to achieve such reduction include switching to more automated stack assembly, standardization, as well as utilizing advanced coating technologies to optimise the use of precious metals. Overall, a 1 GW/year manufacturing plant should benefit from the economy of scale during production, and multiple producers (Thyssenkrupp, NEL, ITM, Siemens) either reached this milestone or target it within the next couple of years.

From the manufacturer perspective, to facilitate the needed scale up of the production, certain risks and factors need to be addressed. Table 6 summarizes known challenges and their impact on scalability.

IRENA estimates that water purification, desalination, deionisation, as well as saltwater availability are not limiting factors [34]. Extensive deployment of electrolysers for green hydrogen production in 2050 could consume the amount of water equal to 0.08% of fresh water consumed in 2020. Similarly, the land area to host 256 GW electrolysers (roughly 34 km^2) is significantly smaller than the land area to be needed for the corresponding production of renewable energy. For example, an estimate for 1 GW alkaline electrolyser plant shows a plot with dimensions of 300×550 m^2 could be required.

Due to longer lifetime above 50-60 000 hours, the ammonia plants to be developed within 2030 will likely use alkaline or PEM electrolysers. Beyond 2030, learning curve, improved maturity of AEM and SOEC, and benefiting from upscaling, all electrolyser types are expected to work longer than 100 000 h [34], with more efficient use of scarce materials.

There are two precious metals used in the electrolysers, platinum and iridium. While platinum appears in both PEM and some designs of alkaline, iridium is primarily used in PEM. Focusing on PEM, the material consumption of Pt is 1 g/kW, and Ir 1-2.5 g/kW [19]. If all of the 256 GW electrolysers were the PEM type, it would require 256 tonnes of platinum and 256-640 tonnes of iridium. Although yearly mining of platinum of 200 tonnes would allow for deployment of electrolysers above 1 000 GW, there is significant pressure to reduce its amount in electrolysers, advance efficiency, increase lifetime and recycle. In contrast, iridium is 10 times less abundant than platinum, and its yearly mining is limited to about 7 tonnes per year, which severely impacts the upscaling, with hypothetical upper limit of 30-75 GW PEM capacity by 2030.

The faster response to variable renewable energy input makes PEM particularly attractive, and balances the drawbacks such as scarcity of iridium and their higher price. Advanced electrode fabrication techniques could allow for more efficient use of the precious metals in PEM, as well as ensure further competitiveness with newer AEM and SOEC.

Table 6: Challenges and their impact on upscaling of electrolysers

Challenges	Typical values (estimates for 256 GW, 123 MTPA)	Conclusion
Water purification	< 1$ / m^3	Not limiting
Deionisation	< 1$ / m^3	Not limiting
Water scarcity	18-24 kg H_2O/kg H_2 (16 530 MTPA)	Not limiting
Land area	Rough estimate 7.5 GW/km^2 [34] (34 km^2)	Not limiting
Lifetime	ALK> 60 000 h PEM> 50 000 h AEM> 5 000 h SO < 20 000 h	ALK and PEM – not limiting. AEM and SOEC – need improvement. All to be improved above 100 000 h
H_2 and energy storage		Not limiting upscaling, allows for flexibility
Iridium scarcity	PEM: 1-2.5 g/kW (256-640 t)	Limiting PEM to about 30-75 GW by 2030, urgent action needed
Platinum scarcity	PEM: 1 g/kW (256 t)	Without Pt recycling feasible > 1 000 GW by 2030, action needed
Emissions from manufacturing electrode metals	12.5 kgCO_2eq/g Pt (3.2 Mt CO_2) 9.5 kg CO_2eq/g Ir	Not limiting (0.01 % of total system's CO_2eq)
Safe design of large systems		Will be addressed in "learning by doing"
Uncertain demand	850 GW in 2030 to reach 2050 net zero goals	Stimulating upscaling, demand far exceeds supply

Other challenges are the growth of supply chain and finding experienced and qualified personnel. New challenges are the readiness of large-scale electrolysis design and development of inherently safe design for ever larger concepts [18].

Considering the lifetime of solar PV technology averaging 25 years, and wind 20 years, it is realistic that the renewable power infrastructure installed before 2030 will be operational until 2050. In contrast, modern electrolysers have lower lifespan (< 10 years, < 80 000h), and will need to be replaced or upgraded. Using upgraded electrolysers after cycles of 8-10 years, higher hydrogen and ammonia production capacities could be reached within the same facilities. The increasing amount of decommissioned electrolysers, in particular PEM type, emerging after 2030 can be used for Pt and Ir recovery and recycling.

Finally, DNV hydrogen forecast reports about the uncertainty of the market itself, making for an unsteady foundation for the kind of rapid-fire decisions and large-scale investments that manufacturers need to make. From the number of green ammonia projects reviewed here, as well as dedicated hydrogen projects, announced and upcoming, the manufacturers of electrolysers can be certain about is demand, with some scenarios predicting the need for 850 GW to reach Net Zero Goals [11]. The announced demand for electrolysers for ammonia projects averages 36 GW/y exceeds the current manufacturing capacity of 7-10 GW/y substantially, which is likely to continue through 2030s. In the case of the likely realistic scenario (Section 3.7.3), the average yearly installation demand is 8 GW and could uptake all available manufacturing.

6.2.5 Competition for electrolysers

IEA database of green hydrogen projects lists 1 112 announced projects involved in production of hydrogen and derivatives such as ammonia, up to October 2022 [36]. From the database, 15% of the announced hydrogen production is targeting ammonia, and another 9% plan for use of hydrogen in form of ammonia for power or fuel.

6.2.6 Predictions on the upscaling and availability

In this section the realistic and announced electrolyser installations in 2030 are compared with the latest available predictions (Figure 39).

When comparing the predictions, it is important to consider the prediction year. Throughout 2019-2022 electrolyser producers were successful in attracting funding, providing significant opportunities in upscaling and rendering higher prognosis each year. In 2020 IRENA offered two scenarios: Planned Energy Scenario and Transforming Energy Scenario, according to which the installed electrolyser capacity in 2030 would be 100 and 270 GW respectively [34]. In 2022, IEA predicted 130-240 GW to be installed by 2030 [19]. The forecast of DNV ETO the same year is higher with 465 GW electrolysers to be deployed by 2030 [10]. All these predictions are significantly lower than IEA's estimate of 720-850 GW necessary in 2030 to be on track to net zero by 2050 [11].

For production of the planned green ammonia, the announced electrolysers capacity of 256 GW exceeds IEA and IRENA (planned scenario) predictions for all hydrogen production, but somewhat aligns with DNV prediction (55% of all electrolysers are for ammonia) and net zero pathway (<35% is for ammonia production). On the other hand, the realistic scenario requires 52 GW, which seems reasonable from many perspectives. It is about 1/5 of the IEA and IRENA predictions of all electrolyser capacity, and is 11% of the DNV ETO prediction. It is

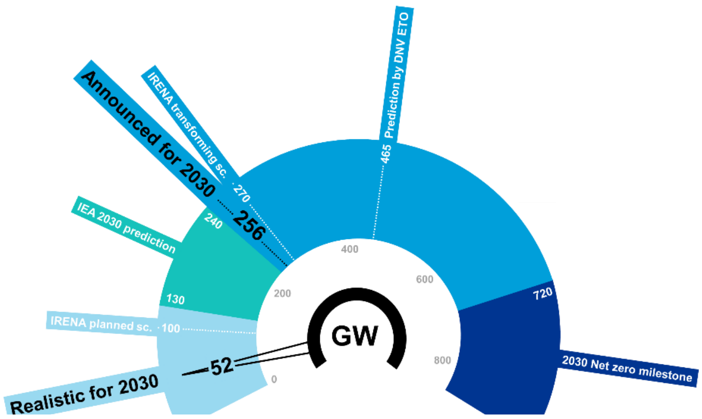


Figure 39: Gauge graph showing the progress towards net zero goal in 2050. To reach the goal, a milestone in 2030 needs to be met with 850 GW. Predictions by IRENA [34], IEA [11] and DNV ETO forecast [10] for 2030 include all electrolyser power, not exclusive for ammonia production. Announced value is based on the projects information and Realistic value is based on the likelihood analysis described in methodology and section 3.7.

likely that within 2023-2024 the new announcements will add additional green ammonia projects to be completed within 2030. This implies that in the realistic scenario, additional 8-16 MTPA are possible with corresponding additional electrolyser installation of 15-30 GW.

IRENA's scenarios imply ramping up manufacturing to 10-60 GW/year by 2030 [34]. IEA patenting review similarly predicts reaching yearly production of 65 GW by 2030 [19], which would include a gigawatt fabrication lines for alkaline, PEM and solid oxide electrolysers.

To derive the rate of upscaling needed to reach 256 GW in 2030, a rough estimation can be made using a linear increase in manufacturing capacity. Thus, solely for announced ammonia production, the electrolyser industry needs to dedicate all the existing 8 GW manufacturing capacity and increase it by 5 GW every year, reaching 50 GW/year in 2030. While such manufacturing rate and upscaling are feasible overall, it is unlikely to be dedicated primarily to green ammonia production industry.

In contrast, for reaching 52 GW of installed capacity in 2030 needed in the realistic scenario, a constant yearly manufacturing capacity of 6.5 GW in the upcoming 8 years will be sufficient. In comparison, for fulfilment of the DNV scenario of 465 GW, the electrolysers industry needs to expand by an additional 10.5 GW each year, such that in 2030 the manufacturing rate is 94 GW. However, to be on track to net zero targets in 2050, the upscaling rate needs to be even steeper, with 21 additional GW introduced each year, up to 180 GW in 2030.

Notably only a fraction of the upscaled manufacturing capacity can be of PEM type due to scarcity of iridium, which is limited to 30-75 GW within 2030. Therefore, the share of PEM electrolysers may range up to 28% in the IRENA Transforming scenario and 16% of the scope in the DNV ETO forecast.

Taking the prediction by DNV ETO of 465 GW as a starting point, the manufacturing capacity growth by 10.5 GW/year will be sufficient to satisfy demand for electrolysers in the presented realistic scenario, as well as demand within the new projects possibly appearing by 2024. The remaining ~400 GW (>85%) electrolysers can be dedicated to hydrogen production. This amount exceeds the amount of 280 GW electrolysers needed for the currently (September 2022) announced green hydrogen projects [36]. It is likely that the realistic hydrogen production is lower, with analogy to the likelihood assessment for ammonia in the present report.

6.3 On the competition between clean ammonia types

Until 2021, green ammonia production was very small with about 20 kt ammonia produced per year in Peru and with no known production of blue ammonia (i.e. without enhanced oil recovery) [1]. From 2021 some smaller green ammonia plants have started producing. There are a number of factors that determines the share of green versus blue ammonia in a country. An important one is the access to resources (like natural gas and renewable electricity potential) and their uptake in the local market.

Some countries have large quantities of natural gas. This may be distributed in the country and region for consumption and might be the most efficient use of the natural gas. However, there is also a number of countries where the population or the established industry are not able to use the supply. Common ways of exporting the excess of natural gas are as LNG, methanol or ammonia. All three options export the gas in a liquid state that facilitate the transport of it. There are also energy losses involved in conversion to these liquids of about 10%, 30% and 36%, respectively. All three natural gas derivates are produced globally in large scale at about 372 Mt [37], 100 Mt [38] and 186 Mt, respectively. The choice of derivates likely depends on market conditions for the derivates and their end uses. Ammonia is the only one of the three that comes without carbon, i.e. that for the others the CO_2 has be removed by the consumer, whereas for ammonia the CO_2 can be removed centrally by the producer of blue ammonia. This has some benefits for some consumers in a world approaching zero emissions permitted. In a region with excess natural gas, it would hence be a more likely choice to use blue ammonia for export than establishment of green ammonia. However, it also depends on access to permanent storage sites for the CO_2. An example of this is the Norwegian Blue Horizon project with access to natural gas without pipeline connection to Western Europe. Another example is the production growth of blue ammonia, both conversions and greenfield, for use of the natural gas resources in US, which is also supported by the Government.

For green ammonia, there are a number of regions globally with large potential for wind and/or solar power, where the local demand for renewable electricity is limited for different reasons, e.g. that the population density is low. There is also a limit to how much intermittent renewable power that can be used in a grid without significant storage possibilities. This potential may be exploited with green ammonia. Green ammonia is in principle scalable [1], since it only requires the resources of renewable electricity, water (including sea water) and air. Hence, if regions are found with good solar or wind power potential, preferably both, close to the sea with low local demand, green ammonia can be produced and exported by sea. Western Australia is an example of this. Arid conditions do not prevent this from being constructed. Stable conditions and good framework conditions are important to realize the projects.

Another major factor are the production costs. If the costs for green or blue ammonia are too high to compete in the international market, it will not be produced even though the resources are present and as such the preference right. The competition will be both between green and blue ammonia, and with the alternatives in the various markets (like maritime fuel, fertilizers, power production and hydrogen production). This will certainly also depend on the regulations in the markets and GHG taxes and likely increasingly on the stakeholder's expectations. E.g. natural gas based ammonia in 2019 was similarly priced per energy unit as LSFO, but without having any GHG benefits. Green ammonia has significant GHG benefits, but has at least twice the price [1] and will have a limited uptake before regulations, GHG taxes and/or stakeholder's expectations are sufficiently strong. This will be alleviated by renewable electricity becoming cheaper [2], and the learning curves also for electrolysers that will reduce their costs. Development of hydrogen production will also contribute to the learning curves of electrolysers for final conversion to green ammonia, but may also lead to temporary deficiency in the marketplace due to competing demands. Currently, blue ammonia may have lower production costs than green ammonia, but this will likely even out because of these two above mentioned reasons [18].

Additionally, existing grey and brown ammonia facilities can be converted to blue ammonia with relatively lower capex costs. Indeed, the conversion of grey/brown ammonia production to blue is a faster process than going through all the stages of project development for building a new green ammonia production. Therefore, the blue ammonia production will likely be larger than the announced number of blue and green ammonia project in the pipeline indicates.

One of the pending questions in the cases of green ammonia production is on the source of CO_2 for fertilizers as well as NO_x emissions control agent AdBlue using selective catalytic reduction units. Urea is produced by a reaction between ammonia and CO_2, and is one of the major fertilizer types. It is also used in a water solution as the AdBlue additive. Using fossil-fuel technology, CO_2 is naturally available. However, this is not the case if all hydrogen is entirely produced by electrolysis, as in the case of green ammonia. It is therefore possible, over time, that green ammonia for fertilizers production will target other fertilizer compounds than urea. The alternative would be to produce urea by CO_2 sources that can withstand the test of time for being carbon neutral.

Assuming global CO_2 prices of 50 \$/t CO_2 by 2030, Arkwright 2021 market study predicts that blue ammonia will be cost competitive with grey ammonia between 2030-2035. Overall, what makes blue ammonia competitive is low gas prices, suitable reservoirs for CO_2 storage, and policy incentives. Based on these criteria, several regions such as North America, Middle East, Australia, and South America offer good potential for development of new blue ammonia projects.

There will also be a competition for green ammonia between different markets like maritime fuel, greening of fertilizers, co-firing with coal or natural gas in power plants or conversion back to hydrogen. This will depend on the purchasing power in these markets, which also will depend on taxes and regulations, and on stakeholder requirements. This is discussed in Chapter 5.4.

6.4 Concluding remarks

The global green and blue ammonia production industry have as per 2022 announced 112 clean ammonia projects with a total production of 182 MTPA. In each of the past two years about 50-60 announcements appeared, which gives expectation for similar number of projects to be announced in the coming years. Some of these may contribute to the 2030 supply of green and blue ammonia. The projects are distributed globally, with a large share of green ammonia projects located in Australia and the majority of the blue projects to be hosted in the USA. The majority of the projects are in very early stage of development (Concept or Feasibility study), which brings large uncertainty in success of their implementation. The projects have announced an implementation duration within 5-7 years, which results in large number of projects completed within 2030 and, if implemented as announced, corresponding 80% of production on stream. Only 11-13% of the announced production capacity is blue ammonia.

Unlike the current ammonia production, which is primarily produced and consumed locally, 97% of future clean ammonia is targeted for international export. The distribution of size of the production facilities is dominated by the large and extra-large plants with scales 0.1-25 MTPA, 11 of which aim for a record high production above the current state of the art 4.3 MTPA. A rough estimation shows that the investment needed scales with production size according to the factor 3.7 billion $/MTPA.

Multiple renewable energy sources are represented for the green ammonia production, with more than half relying on a combination of wind and solar PV technology. The required electrolyser capacity of the entire pipeline of projects is 346 GW, of which 52 GW is estimated to be installed in 2030.

Unlike today's ammonia market dominated by fertilisers market, clean ammonia aims at new applications such as shipping fuel and energy (or a hydrogen carrier). A majority of the producers (140 MTPA) aims to cater to multiple market sectors, with only 42 MTPA committing to a single end use.

Likelihoods of implementation were evaluated in this report, and this leads to a drastic decrease in the final ammonia output in 2030 for all three scenarios. Instead of the announced 182 MTPA, we estimate, 27-38 MTPA will be available. From these, 10-12 MTPA is projected to be blue. The end use is shared between fertilisers, fuel and energy applications. Green ammonia dedicated to shipping may be in the range of 3.6-6 MTPA. Potentially, in addition, 17-23.4 MTPA will also be available to be shared between fertilisers, energy and fuel market.

In total the amount of green and blue ammonia realistically available is estimated to be more than an order of magnitude higher than the anticipated demand for maritime sector in 2030. And if the announced ammonia production goes to where it is announced, then the availability for the maritime sector is sufficient; comparing the supply green ammonia dedicated to shipping in 2030 from chapter 3 (3.6 to 6 MTPA) with the demand for 2030 in chapter 4 (2.3 MTPA). Maritime internal combustion engines might be available from about 2025 and hence a demand in the maritime sector possible, and eventually solid oxide fuel cells may become commercially available. The ammonia producers appear to be hedging, and the main approach is a mixture of off takers. The risks are clearly reduced when an investor has three to four distinct end uses, instead of only maritime fuel. However, this may also lead to competition from other off takers if they have a higher purchasing power. Green ammonia production growth does from our investigation not appear to be limited by electrolyser production capacity. However, as Figure 24 reveals, the demand growth after 2030 is steep and accelerating and supply & demand balance may change fast in the 2030s. In the longer term, supply and demand would be balanced, and the appropriate approach is to model the demand as carried out in chapter 4.

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8 Appendix 1: Announced green and blue ammonia project by end of 2022

#	Project name	Country	Announced Date	Date on-stream	Status	Type of renewable	Announced (MTPA)
1	Minbos Resources Green Ammonia Nitrogen Fertilizer Facility	AGO	2021	2026*	Concept	Hydropower	0.08
2	The Barra do Dande	AGO	2022	2024	Concept	Hydropower	0.28
3	AREH	AUS	2020	2028	FEED	Solar and Wind	9.90
4	Dyno Nobel Renewable Hydrogen	AUS	2019	2026*	Feasibility study	Solar PV	0.12
5	Eyre Peninsula Gateway - 1	AUS	2022	2026	Feasibility study	Solar and Wind	0.04
6	Eyre Peninsula Gateway - 2	AUS	2022	2030	Concept	Solar and Wind	0.83
7	Fortescue Green Hydrogen and Ammonia Plant	AUS	2021	2028*	Feasibility study	Wind/Hydropower	0.25
8	GERI - 1	AUS	2020	2025	Feasibility study	Solar and Wind	0.02
9	GERI - 2	AUS	2020	2031	Feasibility study	Solar and Wind	1.00
10	Gibson Island Green Ammonia	AUS	2021	2025	FEED	Hydropower	0.40
11	H2-hub Gladstone - 1	AUS	2020	2025	Feasibility study	Solar and Wind	0.11
12	H2-hub Gladstone - 2-3	AUS	2020	2027	Feasibility study	Solar and Wind	1.50
13	H2Kwinana	AUS	2020	2025*	Feasibility study	Unknown	0.04
14	H2Perth, blue - 1	AUS	2021	2024	Feasibility study	Blue	0.42
15	H2Perth, mixed - 1	AUS	2021	2024	Feasibility study	Grid	0.18
16	H2Perth, mixed - 2	AUS	2021	2030*	Concept	Grid	3.00
17	H2TAS - 1	AUS	2020	2025	Feasibility study	Wind/Hydropower	0.20
18	H2TAS - 2	AUS	2020	2025	Feasibility study	Wind/Hydropower	0.80
19	Hunter Energy Hub	AUS	2021	2030*	Feasibility study	Various	1.50
20	Hydrogen Portland	AUS	2022	2030	Concept	Wind	0.01
21	HyEnergy - 1	AUS	2021	2030	Feasibility study	Solar and Wind	1.55
22	HyEnergy - 2	AUS	2021	2030*	Concept	Solar and Wind	1.55
23	Midwest Green Ammonia	AUS	2022	2027	Concept	Solar and Wind	1.00
24	Murchison PtX	AUS	2019	2028	Concept	Solar and Wind	2.00
25	Origin Green Hydrogen and Ammonia Plant	AUS	2020	2027*	FEED	Unknown	0.42
26	QLD Bundaberg	AUS	2021	2023	Under construction	Various	0.03
27	Queensland Nitrates Renewable Hydrogen and Ammonia	AUS	2019	2024*	Feasibility study	Solar and Wind	0.02
28	The Port Pirie Green Hydrogen	AUS	2021	2028*	FEED	Unknown	0.21
29	VIC Port Anthony	AUS	2021	2023	Under construction	Various	0.08
30	Western Green Energy Hub	AUS	2021	2045	FEED	Solar and Wind	20.00
31	Yuri - 1	AUS	2019	2024	FID	Solar PV	0.00
32	Yuri - 2	AUS	2019	2026	Feasibility study	Solar PV	0.11
33	Yuri - 3	AUS	2019	2028	Feasibility study	Solar PV	0.35
34	Yuri - 4	AUS	2019	2030	Feasibility study	Solar PV	0.18
35	Oruro plant	BOL	2021	2025	Concept	Solar PV	0.50
36	Porto do Acu Fortescue Ammonia	BRA	2021	2028*	Feasibility study	Solar and Wind	0.25
37	The Transhydrogen Alliance	BRA	2021	2024	FID	Solar and Wind	2.50
38	Unigel Brazil - 1	BRA	2022	2027*	FID	Solar and Wind	0.06
39	Unigel Brazil - 2	BRA	2022	2029*	Concept	Solar and Wind	0.18
40	Blue Ammonia & Blue Methanol	CAN	2021	2026	Feasibility study	Blue	1.00
41	Courant	CAN	2022	2026	Under construction	Hydropower	0.17
42	AES Green Ammonia	CHL	2021	2028*	Feasibility study	Various	0.60
43	Gente Grande	CHL	2022	2026	Feasibility study	Offshore wind	1.30
44	H2 Magallanes	CHL	2021	2027	FID	Onshore wind	4.40
45	HNH	CHL	2022	2026	FID	Onshore wind	1.00
46	HyEx - 1	CHL	2020	2024	Feasibility study	Solar PV	0.02
47	HyEx - 2	CHL	2020	2030	Concept	Solar PV	0.68
48	Barranquilla Offshore Wind Farm to Ammonia	COL	2022	2026	Concept	Offshore wind	0.26
49	Aquamarine	DEU	2021	2024	Feasibility study	Offshore wind	0.10
50	HyTechHafen - 1	DEU	2022	2027*	Feasibility study	Offshore wind	0.08
51	HyTechHafen - 2	DEU	2022	2030	Concept	Offshore wind	0.68
52	Esbjerg Green Ammonia plant	DNK	2021	2030	FEED	Offshore wind	0.75
53	REDDAP project	DNK	2021	2023	Under construction	Solar and Wind	0.01
54	Alfanar Green Ammonia - 1	EGY	2022	2025	Concept	Solar PV	0.25
55	Alfanar Green Ammonia - 2	EGY	2022	2032	Concept	Solar PV	0.25
56	AMEA - 1	EGY	2022	2030	FEED	Solar and Wind	0.40
57	AMEA - 2	EGY	2022	2029*	Concept	Solar and Wind	0.40
58	EDF Renewable - 1	EGY	2022	2026	Concept	Solar and Wind	0.14
59	EDF Renewable - 2	EGY	2022	2029*	Concept	Solar and Wind	0.21
60	Egypt Green Ammonia (Two plants)	EGY	2021	2024	FID	Solar and Wind	0.09
61	Green Ammonia in SCZone	EGY	2021	2030*	Concept	Solar and Wind	1.00
62	Masdar - 2	EGY	2022	2030	Concept	Various	2.30
63	MEP	EGY	2022	2029*	Feasibility study	Solar and Wind	0.13

#	Project name	Country	Announced Date	Date on-stream	Status	Type of renewable	Announced (MTPA)
64	ReNew Power - 1	EGY	2022	2025	Concept	Various	0.10
65	ReNew Power - 2	EGY	2022	2029	Concept	Various	0.90
66	Total - 1	EGY	2022	2029*	Concept	Unknown	0.30
67	Total - 2	EGY	2022	2030	Concept	Unknown	1.50
68	Catalina - 1	ESP	2022	2025	Under construction	Solar and Wind	0.20
69	Fertiberia/Iberdrola - Palos de la Frontera - 1	ESP	2021	2023	Feasibility study	Solar PV	0.17
70	Fertiberia/Iberdrola - Palos de la Frontera - 2	ESP	2021	2027	Feasibility study	Solar PV	0.28
71	Fertiberia/Iberdrola - Puertollano - 1	ESP	2020	2022	Under construction	Solar PV	0.02
72	Fertiberia/Iberdrola - Puertollano - 2	ESP	2020	2027	Feasibility study	Solar PV	0.16
73	HyDeal España	ESP	2022	2025	Under construction	Solar PV	0.17
74	Orkney Green Hydrogen/Ammonia plant	GBR	2021	2024*	Concept	Offshore wind	0.01
75	Green Hydrogen and Ammonia - 1	IDN	2022	2029*	Feasibility study	Geothermal	0.22
76	PT Panca Amara Utama Ammonia plant	IDN	2021	2028*	Feasibility study	Blue	0.70
77	Rajasthan Hydrogen & Ammonia plant	IND	2021	2021	Operational	Solar PV	0.00
78	Renewable Hydrogen & Ammonia	IND	2022	2027	Concept	Solar PV	1.20
79	EI-H2 - Aghada	IRL	2020	2028	Feasibility study	Offshore wind	0.38
80	Green Fuel Iceland - 1	ISL	2021	2023	Under construction	Geothermal	0.02
81	Green Fuel Iceland - 2	ISL	2021	2025	Under construction	Geothermal	0.05
82	Hyrasia One	KAZ	2021	2030	Concept	Solar and Wind	11.24
83	Green Ammonia and Fertilizer facilities - 1	KEN	2022	2025	Feasibility study	Geothermal	0.11
84	Green Ammonia and Fertilizer facilities - 2	KEN	2022	2030	Concept	Geothermal	9.55
85	Kenya Green Ammonia Plant	KEN	2021	2025	FEED	Geothermal/Solar	0.04
86	AMUN - 1	MAR	2022	2028	FID	Solar and wind	2.00
87	AMUN - 2	MAR	2022	2030	Concept	Solar and wind	2.00
88	Green H2A Green Ammonia Pilot	MAR	2022	2024	Under construction	Solar and wind	0.00
89	Green Investment plan for Renewable Ammonia	MAR	2022	2027	FID	Solar and wind	1.00
90	HEVO Ammonia - 1	MAR	2021	2022	FEED	Solar PV	0.00
91	HEVO Ammonia - 2	MAR	2021	2023	FEED	Solar PV	0.02
92	HEVO Ammonia - 3	MAR	2021	2024	FEED	Solar PV	0.04
93	HEVO Ammonia - 4	MAR	2021	2025	Feasibility study	Solar PV	0.06
94	HEVO Ammonia - 5	MAR	2021	2026	Feasibility study	Solar PV	0.06
95	Tarafert - 1	MEX	2022	2026	Under construction	Blue	1.00
96	Tarafert - 2	MEX	2022	2026	Under construction	Solar PV	0.50
97	AMAN - 1-2	MRT	2022	2029	Feasibility study	Solar and Wind	10.00
98	H2biscus - 1	MYS	2022	2029*	FEED	Hydropower	0.63
99	H2biscus - 2	MYS	2022	2029*	FEED	Blue	0.60
100	H2-Pilot Plant / Refueling Station - 1	NAM	2022	2024	FID	Solar PV	0.00
101	Hyphen Hydrogen Energy - 1	NAM	2021	2026	Feasibility study	Solar and Wind	0.70
102	Hyphen Hydrogen Energy - 2	NAM	2021	2030	Concept	Solar and Wind	1.00
103	Sluiskil	NLD	2020	2025	Feasibility study	Offshore wind	0.08
104	Barents Blue	NOR	2021	2025	Concept	Blue	1.00
105	Berlevåg Green Ammonia Value Chain	NOR	2020	2025	FID	Onshore wind	0.10
106	Finnmark P2XFloater	NOR	2022	2029*	Feasibility study	Offshore wind	0.23
107	Green Ammonia Production in Finnmark	NOR	2021	2026*	Concept	Wind/Green hydrogen	0.08
108	Herøya Green Ammonia (HEGRA) - Energy	NOR	2021	2029	FID	Hydropower	0.40
109	Herøya Green Ammonia (HEGRA) - Fertilizer	NOR	2021	2029	FID	Hydropower	0.02
110	North Ammonia Arendal	NOR	2021	2027	FEED	Hydropower	0.10
111	Project Sauda Iverson Efuels	NOR	2022	2026	Under construction	Hydropower	0.21
112	Slagen Terminal	NOR	2022	2029*	Feasibility study	Hydropower	0.10
113	Green Energy Oman (GEO)	OMN	2022	2038	Feasibility study	Solar and Wind	10.00
114	H2Oman	OMN	2021	2030*	Concept	Solar and Wind	1.00
115	HYPORT® Duqm Green Ammonia - 1	OMN	2021	2026	Feasibility study	Solar and Wind	0.38
116	Oman Green Ammonia - 1	OMN	2021	2027*	FID	Solar PV	0.10
117	Oman Green Ammonia - 2	OMN	2021	2030*	Concept	Solar and Wind	1.20
118	SalalaH2	OMN	2021	2028*	Feasibility study	Solar and Wind	0.35
119	Industrial Cachimayo	PER		1975	Operational	Hydropower	0.02
120	Papua New Guinea Projects Portfolio	PNG	2021	2030*	Feasibility study	Geothermal/Hydropower	11.50
121	Alto Parana plant	PRY	2021	2026	Feasibility study	Hydropower	0.22
122	ATOME - 1	PRY	2021	2025	FID	Hydropower	0.23
123	ATOME - 2	PRY	2021	2027	Concept	Hydropower	0.14
124	Ammonia-7	QAT	2022	2026	Under construction	Blue	1.20
125	HELIOS (NEOM)	SAU	2020	2025	Under construction	Solar and Wind	1.20
126	SAREH - 1	SAU	2021	2030	Concept	Unknown	15.00

#	Project name	Country	Announced Date	Date on-stream	Status	Type of renewable	Announced (MTPA)
127	SAREH - 2	SAU	2021	2035	Concept	Unknown	5.00
128	Green Wolverine	SWE	2021	2026	Concept	Wind/Hydropower	0.52
129	NewGen	TTO	2021	2024	Feasibility study	Solar PV	0.15
130	Khalifa Industrial Zone Abu Dhabi (KIZAD) - 1	UAE	2021	2024	Feasibility study	Solar PV	0.04
131	Khalifa Industrial Zone Abu Dhabi (KIZAD) - 2	UAE	2021	2026	Feasibility study	Solar PV	0.16
132	The TAQA-Abu Dhabi Ports	UAE	2021	2026	Concept	Solar PV	1.20
133	Ascension Clean Energy (ACE)	USA	2022	2027	FEED	Blue	7.20
134	Beaumont Blue Ammonia plant - 1	USA	2022	2025	Under construction	Blue	1.10
135	Beaumont Blue Ammonia plant - 2	USA	2022	2030	Under construction	Blue	1.10
136	Donaldsonville Blue Ammonia	USA	2022	2027	FEED	Blue	1.00
137	Donaldsonville Green Ammonia	USA		2023	Under construction	Grid	0.02
138	Garner Green Ammonia Plant	USA	2021	2026*	Feasibility study	Onshore wind	0.08
139	Geismar Clean Ammonia Plant	USA	2021	2027	Concept	Blue	1.20
140	Green Ammonia plant - 1	USA	2022	2025	FEED	Unknown	0.10
141	Green Ammonia plant - 2	USA	2022	2029*	Concept	Unknown	0.60
142	Olive Creek 2	USA		2029*	Feasibility study	Blue	0.28
143	Wabash CarbonSAFE	USA		2022	Under construction	Blue	0.57
144	Waggaman Ammonia plant	USA	2021	2026	FEED	Blue	0.80
145	Yazoo City Blue Ammonia	USA	2022	2024		Blue	0.25
146	Hive Hydrogen	ZAF	2022	2025	Feasibility study	Solar and Wind	0.80

*Date onstream has been estimated, see methodology