WHEN TRUST MATTERS

AVAILABILITY OF GREEN AND BLUE AMMONIA IN 2030 TO 2050

WHITEPAPER

Content

Authors

Hendrik Brinks, Oleksii Ivashenko, Bent Erik Bakken,
Tianyu Wang and Hans Anton Tvete

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Introduction

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. Almost all ammonia in use today is made from hydrocarbons, and as such confers no carbon abatement advantage. Hence new production capacity for green or blue ammonia needs to be added. There is, however, a risk related to sufficient supply of green/blue ammonia at key trading ports around the world, also taking into account competing end uses for ammonia, such as its use in power plants and for producing hydrogen and fertilizers. The present foresight study is conducted to assess the supply and demand of green and/or blue ammonia in the years 2030, 2040, and 2050.

Background

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, which defines the colour labelling of the ammonia. The colours may be simplified into brown from fossil sources (natural gas or coal), green produced by electrolysis powered by renewables or nuclear and blue for fossil sources with close to complete carbon capture and permanent storage (CCS). 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 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 fertilizer. In this report, we use the term 'clean ammonia' for both green and blue ammonia.

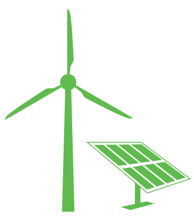
Today, about 80% of ammonia is used for fertilizers. The remainder is used variously for explosives, plastics, synthetic fibres and resins, refrigerants, and chemicals like nitric acid. Recently (liquid) ammonia has been suggested as an alternative for transporting hydrogen by ships, in addition to the other options of 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.

The fuel consumption of all ships was estimated to be 300 million tonnes (MT), which corresponds to 650 MT of ammonia on an energy basis. The global ammonia production today is close to 200 MT per annum (MTPA). To avoid maritime (for fuel) competing with food production for ammonia, new production capacity for 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. The feedstock can be natural gas that cannot be easily transported, or wind and solar/wind power with insufficient local demand. The produced ammonia may be transported by ship. Close to 20 MTPA of ammonia is traded internationally today. This is done by gas carriers designed for ammonia transportation, which are like LPG carriers. Typically, the ammonia shipments are done with gas carriers of up to 60 000 m^3 capacity, but 80 000 m^3 is also possible today.

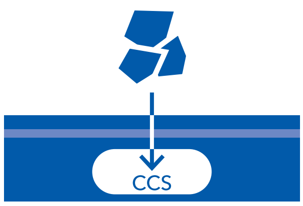
The cost of green ammonia would – with today's renewable electricity price level and capital expenditure – be about two to three times higher than for ammonia produced from natural gas, which has lately cost about the same as very-low sulfur fuel oil (VLSFO), on an energy basis. The green ammonia price will likely decrease in the future because of learning-curve effects leading to lower electrolyser prices and reduced costs of renewable electricity. In addition, fossil fuels are expected to be subject to taxes and regulations, which will alter the competition. With a CO_2 tax of 150 to 200 USD/tCO_2, green ammonia is competitive with oil-based fuels today.[1]

Commercial ammonia production started in the 1920s through the Haber-Bosch and related processes. In 1930, about 30% of the total ammonia production capacity was electricity-based, with the largest single plant, capable of producing 100 kTPA (kTPA = 1 000 metric tonnes of production per year), being at Rjukan in Norway.[2] The global production capacity of electrolyser-based ammonia peaked in the 1960s at about 650 kTPA, which at the time was about 4% of global ammonia production.[2] However, green ammonia was outcompeted by cheaper natural gas-based ammonia.

Green ammonia production is in principle scalable since it is produced from water, air and renewable electricity, which may be produced in regions with insufficient local electricity demand. The present study analyses the likely supply and demand of ammonia for the maritime sector.



Green ammonia
CO_2 emission-free
(from renewable electricity)



Blue ammonia
Fossil sources with carbon
capture and storage (CCS)

Brown ammonia
Fossil sources like natural
gas and coal

Approach

In the present work, supply and demand for the years 2030, 2040, and 2050 have been considered. A number of green and blue ammonia projects have been announced in recent years. These have been linked to several 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 timelines for the projects from announcement to full production can be substantial. 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. We have collected the announced projects up to June 2023 and used this pipeline to predict ammonia supply in 2030 based on a likelihood assessment.

For completed ammonia plants in 2040, however, most announcements are likely to 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 markets would at least be more mature in 2040 than in 2030. The demand for ammonia in the maritime market is estimated based, among other factors, on 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 DNV's previous work related to the Energy Transition Outlook and Maritime Forecast.

Approach for 2030 supply of ammonia

The 2030 supply of ammonia is based on projects announced up to June 2023 [Annex 1]. These were collated from all projects found from open sources. In particular, but not exclusively, the sources used for completeness are the Ammonia Energy Association website,[3] the IEA hydrogen database 2021, the European Maritime Safety Agency (EMSA) report Potential of Ammonia as Fuel in Shipping,[4] and the IRENA innovation outlook Renewable Ammonia.[5] The cut-off date was set to June 2023, and we have aimed to include all projects announced and still being considered. Certainly, more projects have been announced later in 2023 and beyond, that also may also be realized within 2030. This will most likely underestimate the 2030 ammonia supply. An ammonia plant could typically take three to four years to realize. In some cases, the production capacities for a project vary depending on which source is used, and the conservative value was chosen. When the date of operational 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.

Data consistency has been checked. 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 of 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 kTPA of ammonia. 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: shipping, fertilizers, and ammonia for energy purposes. The latter category can, for example, 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 separate 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 mention 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.

Probabilities were assigned based on both the status of the project (concept, feasibility study, front-end engineering design (FEED), final investment decision (FID), under construction or operational) and an additional evaluation of the project. The size of the project activity and the intended year of it going 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. The implemented probability assessment reflects the likelihood for all announced scope to be onstream in 2030, not the overall likelihood of the project's success.

Approach for 2040 and 2050 ammonia demand

For 2040 and 2050, the focus was on the demand side for ammonia, how much clean ammonia the market requires based on the regulations and financial aspects, instead of focusing on 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 has been used.[6] 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 comply 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 capital expenditure (capex) and fuel prices, are in general varied over time.

The capex, operating expenditure (opex), and fuel savings are used as input parameters in evaluating new technologies (hydrodynamics and machinery) that reduce the fuel consumption. The model also evaluates the operational measure of slow steaming. Furthermore, the model includes expected regulations from IMO in 2018 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 other factors, on the 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 operational profile is modelled using 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, since the model determines 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 ammonia demand for ship propulsion is calculated.

This has been done for several scenarios of input parameters, and selected scenarios were combined, resulting in the demand curve for ammonia shown in Figure 17, which is consistent with reference.[6] It should be noted that modelling of this is sensitive to, among other factors, fuel prices, which may lead to other outcomes, as demonstrated with a variety of scenarios in.[8] The options of nuclear power and onboard CO_2 capture have not been included, and this is also not within the IMO GHG strategy from 2023 that increases the GHG reduction goal from 50% in 2050 to 70–80% in 2040.

Clean ammonia supply in 2030

As of the first half of 2023, the global portfolio includes 161 blue and green ammonia projects, with some consisting of 2 to 4 phases, expanding into 206 unique project phases. The announcement boom occurred in 2021–2022, with more than 60 new project stages announced in each year. Many were also announced in the first half of 2023. Figure 1 shows the planned clean ammonia production is a global undertaking, involving 45 countries and 257 project partners across all continents. The total announced production capacity for clean ammonia is 244 MTPA, exceeding the current fossil-based production.

Development of clean ammonia projects

Project stages. Per Q2 2023, the announced projects have varying completion status (Figure 2). The majority (128 out of 206 project phases) and corresponding production of 164 MTPA are in the early stages of development (concept or feasibility), which introduces large uncertainties to 67% of the production. This is discussed further in the likelihood section below.

Date onstream. The majority of the projects (96%) plan to be onstream within 2030. The remaining nine projects are large and aim to become operational before 2045. However, it is likely that for these extra-large projects, a certain fraction, below the announced target, will be onstream and contributing to supply in 2030.

Completion time. Overall, announced projects have completion times of 2 to 24 years, averaging 13 years and peaking at 5 to 7 years. In general, the shorter construction duration is for the mature projects which are well underway or adding CCS to an existing natural gas-based plant. The majority of the projects (96%) aim to be completed within 10 years after the initial announcement of the intention to build the plant. The construction duration correlates somewhat with ammonia production capacity, even though the scatter in the data is large, especially for the faster projects. The indicative linear dependency can be roughly expressed as follows:

Planned Implementation Duration [years] = 3 [years] + 0.7 × announced output [MTPA]

FIGURE 1

Map of 161 green, blue, and mixed (light blue) announced ammonia projects, with count of project announcements for the past years. The bubble size indicates the announced production capacity.

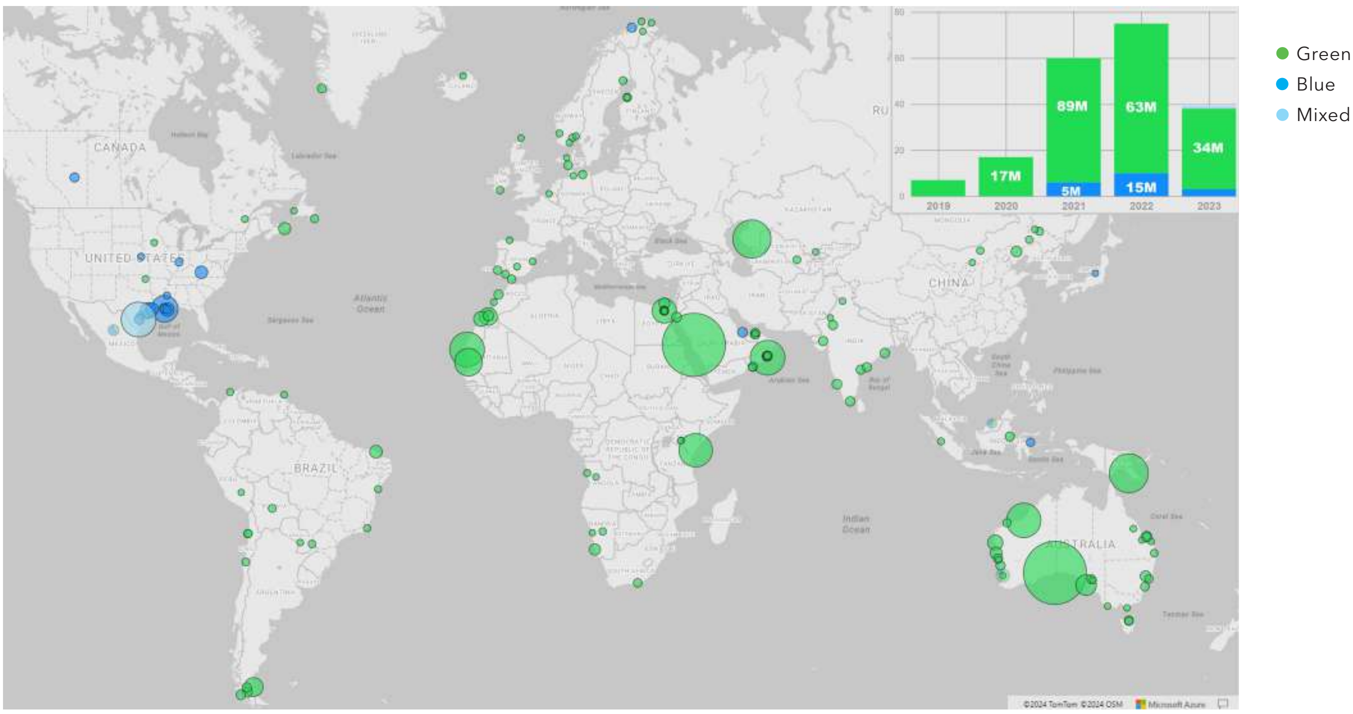
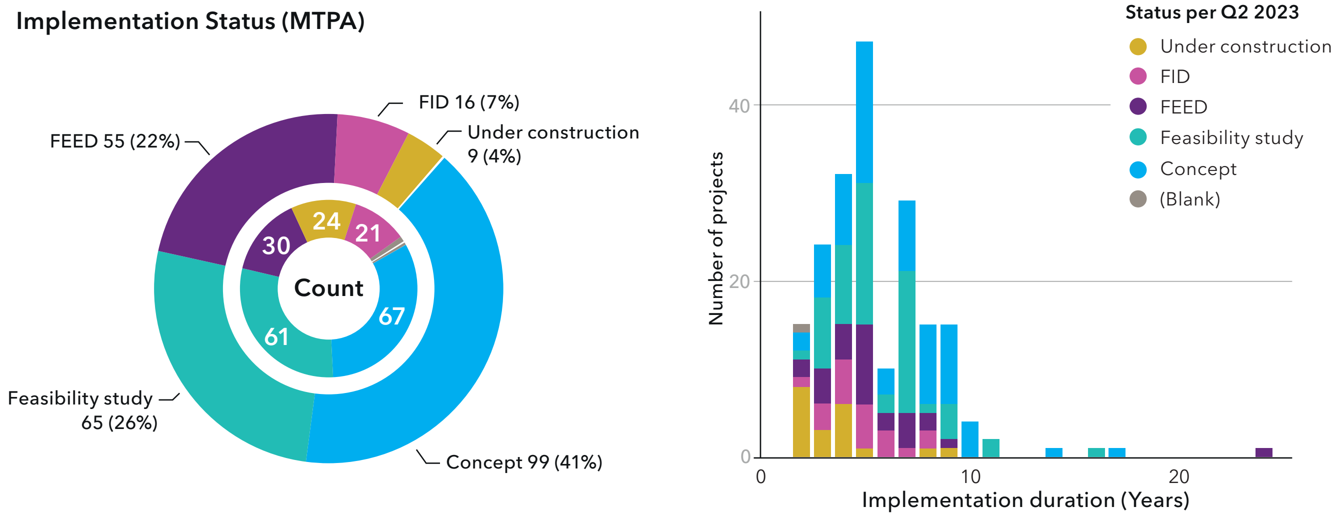


FIGURE 2

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



Additionally, there are differences in announcement strategies. Some risk-takers use early announcements of concepts to attract investors, while more established players tend to announce a project after it successfully passes a feasibility stage. This introduces differences in the perceived project implementation duration, and implies that some unannounced projects may already be in development.

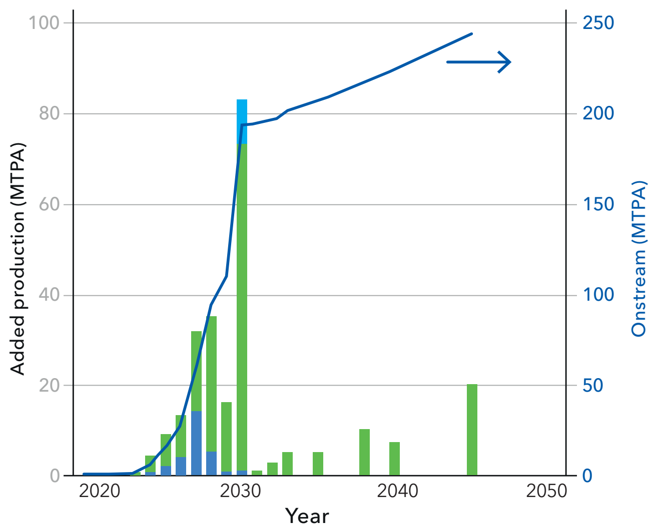
Finally, considering the likely duration for the project completion of about 5 to 7 years, new projects to be announced in 2023–2024 have a significant likelihood of contributing to the 2030 supply.

Production development. In 2023, about 10 green ammonia plants aim to be operational, producing 0.8 MTPA. From 2024, the announced production capacity increases significantly, roughly doubling every year. If all plants were to be completed on time, the production capacity in 2030 would be 193 MTPA, fulfilling 79% of the total announced capacity.

The apparent change in the production trend from rapid, exponential-like increase to a more monotonic growth (Figure 3) in 2030 is unlikely to happen for several reasons. The steadily growing number of announcements and increasing demand predicted after 2030[8] will together extend rapid

FIGURE 3

Annual and cumulative production capacity versus date onstream for the announced projects.



Onstream	New projects	Added (MTPA)	Added	Onstream (MTPA)	Onstream (% of 2045)
1975	1	0.02	0.0%	0.02	0.0%
2021	1	0.00	0.0%	0.02	0.0%
2022	3	0.58	0.2%	0.60	0.2%
2023	8	0.37	0.1%	0.97	0.4%
2024	19	4.23	1.7%	5.20	2.1%
2025	30	9.03	3.7%	14.23	5.8%
2026	31	13.20	5.4%	27.43	11.2%
2027	30	31.75	13.0%	59.17	24.2%
2028	28	35.03	14.3%	94.20	38.6%
2029	17	16.10	6.6%	110.30	45.2%
2030	29	83.09	34.0%	193.39	79.2%
2031	1	1.00	0.4%	194.39	79.6%
2032	3	2.60	1.1%	196.99	80.7%
2033	1	5.00	2.0%	201.99	82.7%
2035	1	5.00	2.0%	206.99	84.8%
2038	1	10.00	4.1%	216.99	88.9%
2040	1	7.20	2.9%	224.19	91.8%
2045	1	20.00	8.2%	244.19	100.0%
Total	**206**	**244.19**	**100.0%**	**244.19**	**100.0%**

growth beyond 2030. Furthermore, the likelihood analysis described below shows that the growth in the late 2020s will be less rapid than announced.

The compound annual growth rate (CAGR) of clean ammonia production between 2023 and 2030 is 112%, and even higher (134%) for green ammonia. For comparison, IEA estimates that to reach the 2050 net-zero goals,[9] green and blue hydrogen production should have a CAGR 66% between now and 2030. Only a fraction of the hydrogen production is envisioned to be green ammonia. From the announced projects, the commitment for annual production until 2030 exceeds the targets set for hydrogen up to 2030.

Geography of the announced projects

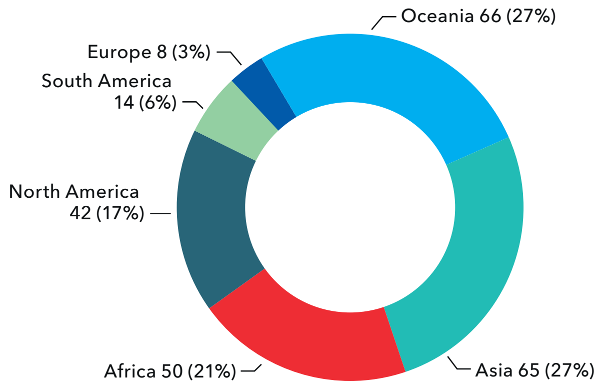
The location of a green ammonia project is a key factor in determining its success. The right location allows a project to benefit from: 1) access to renewable energy; 2) direct connection to a major maritime hub for export; 3) regional policy stimuli for renewable energy and derivatives.

The announced projects are distributed globally (Figure 4); 42 countries host the new production, with 96% of it located in the top 22 producer nations (from Australia to Malaysia). The top 10 producer countries host 80% of the production. For comparison, the existing fossil-based ammonia is produced in 64 countries.[10]

FIGURE 4

The distribution of production between the continents and countries.

Country	Share	Announced (MTPA)	Installed power (GW)	Green (MTPA)	Blue (MTPA)
Australia	22.17%	54.13	115.64	53.71	0.42
USA	14.38%	35.10	4.93	2.25	22.85
Saudi Arabia	8.68%	21.20	30.67	21.20	
Mauritania	7.17%	17.50	40.00	17.50	
Oman	6.09%	14.87	36.17	14.87	
Papua New Guinea	4.71%	11.50	15.33	11.50	
Kazakhstan	4.60%	11.24	20.00	11.24	
Egypt	4.24%	10.36	12.59	10.36	
Kenya	3.97%	9.70	25.37	9.70	
Morocco	3.92%	9.58	27.25	9.58	
Chile	3.87%	9.46	19.63	9.46	
India	3.07%	7.50	11.95	7.50	
Canada	1.59%	3.89	4.85	2.89	1.00
China	1.24%	3.04	4.92	3.04	
Brazil	1.10%	2.69	2.94	2.69	
Norway	0.92%	2.24	1.63	1.24	1.00
Namibia	0.84%	2.05	3.43	2.05	
United Arab Emirates	0.82%	2.00	3.10	2.00	
Indonesia	0.79%	1.92	1.40	1.22	0.70
Spain	0.71%	1.74	9.50	1.74	
Mexico	0.61%	1.50	0.67	0.50	1.00
Malaysia	0.50%	1.23	0.84	0.63	0.60
Qatar	0.49%	1.20			1.20
Finland	0.39%	0.96	1.35	0.96	
Greenland	0.37%	0.90	1.20	0.90	
Germany	0.35%	0.85	1.10	0.85	
South Africa	0.33%	0.80	1.07	0.80	
Denmark	0.31%	0.76	1.01	0.76	
Portugal	0.31%	0.75	1.00	0.75	
Paraguay	0.24%	0.58	0.75	0.58	
Sweden	0.21%	0.52	0.60	0.52	
Uzbekistan	0.21%	0.52	0.69	0.52	
Bolivia	0.20%	0.50	0.49	0.50	
Ireland	0.15%	0.38	0.50	0.38	
Angola	0.15%	0.36	0.47	0.36	
Colombia	0.11%	0.26	0.35	0.26	
Trinidad and Tobago	0.06%	0.15	0.13	0.15	
Netherlands	0.06%	0.15	0.20	0.15	
Iceland	0.03%	0.08	0.10	0.08	
Peru	0.01%	0.02	0.02	0.02	
United Kingdom	0.00%	0.01	0.01	0.01	
Japan	0.00%	0.00			0.00
Total	**100.00%**	**244.19**	**403.83**	**205.42**	**28.77**



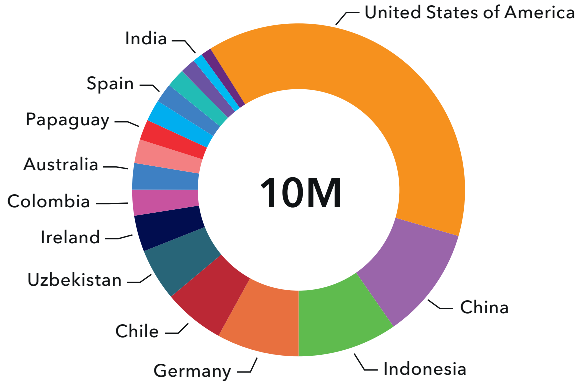
Australia may become the world's largest producer, with plans to produce about 22% of the global output of clean ammonia, a huge leap from today's production of less than 2 MTPA of fossil-derived ammonia. 79% of global blue ammonia production could possibly be concentrated in the United States, where blue (including a project with an undefined mixture of blue and green) ammonia constitutes 94% of the planned production. The USA already hosts the biggest (grey) ammonia plant in Donaldsonville, Louisiana, with production capacity of 4.3 MTPA. The new Ascension Clean Energy plant with 7.2 MTPA blue ammonia in the same location will be the biggest blue facility once operational in 2027, accompanied by a 10 MTPA mixed ammonia facility in Port of Corpus Christi, Texas.

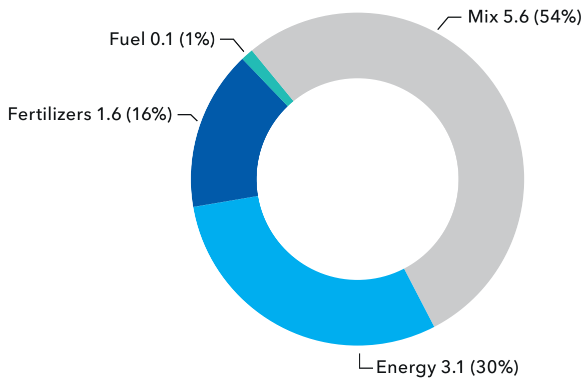
Egypt, Kazakhstan, Mauritania, Oman, Papua New Guinea, and Saudi Arabia are countries with production exceeding 10 MTPA and which focus exclusively on developing green ammonia. Additionally, it is notable to find the top producers of fossil-derived ammonia, such as China and India, ramping up efforts for clean ammonia as well. If a majority of the projects succeed, it will change which countries are the largest ammonia producers.

Today about 18.5 MTPA (10%) of ammonia is exported.[1] In contrast, the announced production of clean ammonia is predominantly export-oriented. Only 4.2% of the announced production capacity (43 projects) explicitly target the domestic market. These include several large blue ammonia facilities in the USA, and several smaller green projects across all continents (Figure 5). The highest fraction of local consumption is within the fertilizers market.

FIGURE 5

Clean ammonia production capacity targeted solely for local consumption, and its intended end use.





Size distribution of ammonia plants

In 2021, there were more than 490 active ammonia plants worldwide,[10] with an average production capacity of 0.38 MTPA. In contrast, green and blue ammonia projects are aiming for capacities averaging around 1.0-1.5 MTPA per facility, thereby achieving economies of scale. For analysis of the size distribution, the projects were categorized into four scales (Figure 6): 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).

The dominant portion (110 project phases, 53%) of the announced projects belongs to the large (L) category with production of 0.1-1.0 MTPA contributing a total of 54 MTPA and including 11 blue ammonia facilities. Green projects in this category use electrolysers with capacities in the range of 0.1–7.5 GW.

The largest existing (grey) ammonia facility produces 4.3 MTPA,[11] and 14 projects aim to break this record. Today, the upper limit for a single Haber-Bosch (HB) line is about 1 MTPA. If this size limitation remains, the minimum number of HB lines needed for the construction of all the announced projects is 348, including 188 single train HB lines for ≥1 MTPA projects and 160 for the smaller ones.

Production categorization by colour

Most of the energy consumption and hence the emissions in ammonia production arise from hydrogen production, and therefore the ammonia colour is equivalent to the colour of hydrogen used in the Haber-Bosch plant.

The announced 244 MTPA includes 29 MTPA of blue ammonia, 205 MTPA of green, and 10 MTPA of an undefined mix of blue and green. Quicker implementation of CCS renders a significant portion of blue ammonia available before 2030. Blue constitutes 36% of production capacity onstream in 2027 but its share decreases to 15% in 2030 (an 12% by 2045) as more green ammonia production become operational. There are plans for 21 blue and 1 mixed ammonia facilities (Figure 7).

More than three-quarters (79%, 22.85 MTPA) of the global blue ammonia production pipeline would be concentrated in the USA. The rest is planned to be produced by eight countries: Australia, Canada, Indonesia, Japan, Malaysia, Mexico, Norway, and Qatar. The only mixed production facility is the 10 MTPA Port of Corpus Christi ammonia facility in the USA.

The proportion of blue ammonia is likely to be higher, as pressure to decarbonize existing production is likely to 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, India, Indonesia, Russia, and the USA. In the USA, it can be expected that the Inflation Reduction Act (IRA) would further incentivize more blue ammonia projects in the coming years.[12, 13] Following the IRA requirement to begin the construction before 2026, these facilities are likely to be completed near 2030 and therefore contribute to the scope of clean ammonia supply in 2030.

FIGURE 6

Distribution of project production capacity (outer circle) and count (inner circle). Today's largest production facility with output of 4.3 MTPA is highlighted for reference.

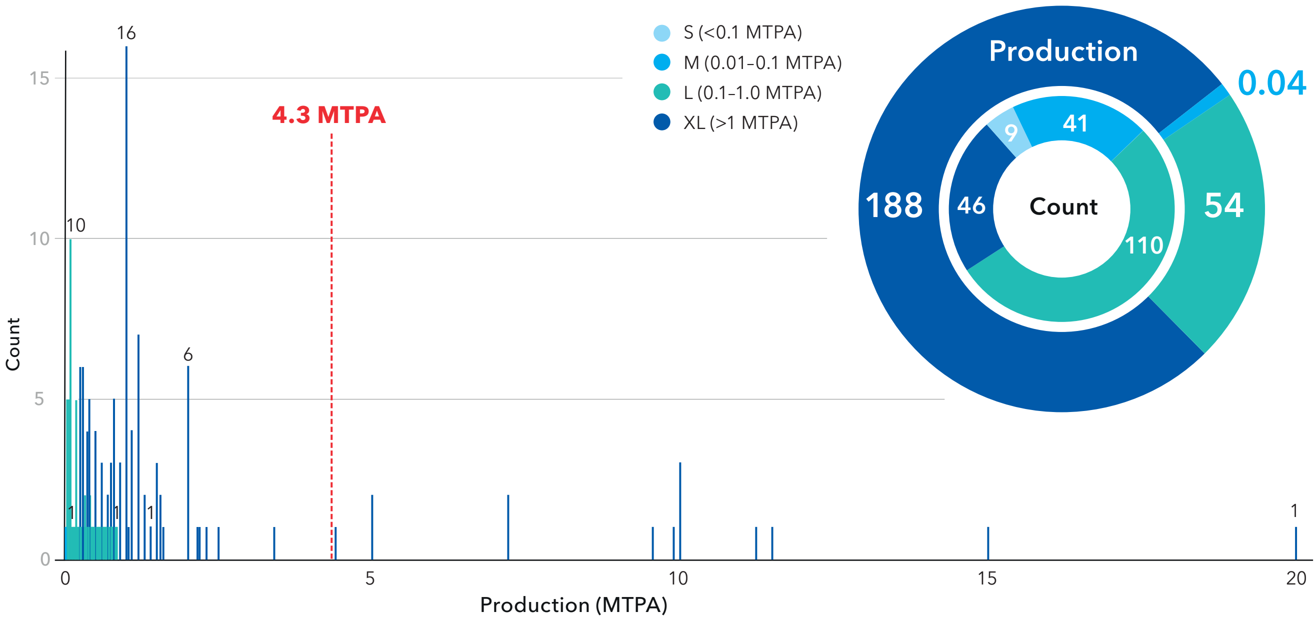
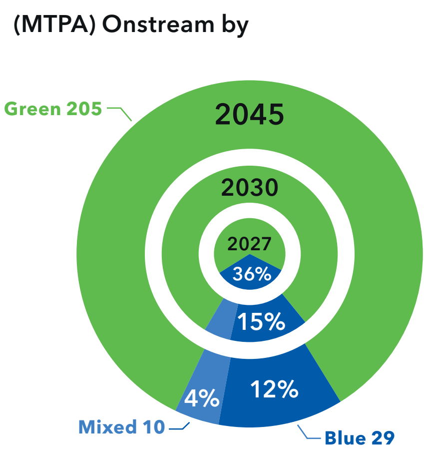


FIGURE 7

Projects focusing on production of blue and mixed ammonia (left) and the fraction of blue ammonia (right).

Project name	Announced (MTPA)	Country	Year onstream
Port of Corpus Christi Mixed Ammonia	10.00	USA	2030
Ascension Clean Energy (ACE)	7.20	USA	2027
Baytown Blue Ammonia	3.40	USA	2028
St. Charles Clean Fuels – 1-2	2.50	USA	2027
Adams Fork Energy Clean Ammonia	2.16	USA	2027
Enbridge Ingleside Energy Center	1.30	USA	2028
Ammonia-7	1.20	Qatar	2026
Geismar Clean Ammonia Plant	1.20	USA	2027
Beaumont Blue Ammonia Plant – 1	1.10	USA	2025
Beaumont Blue Ammonia Plant – 2	1.10	USA	2030
Blue Ammonia & Blue Methanol	1.00	Canada	2026
Tarafert – 1	1.00	Mexico	2026
Barents Blue	1.00	Norway	2025
Donaldsonville Blue Ammonia	1.00	USA	2027
Waggaman Ammonia Plant	0.80	USA	2026
PT Panca Amara Utama Ammonia Plant	0.70	Indonesia	2028
H2biscus – 2	0.60	Malaysia	2029
Wabash CarbonSAFE	0.57	USA	2022
H2Perth, 1 – blue	0.42	Australia	2024
Olive Creek 2	0.28	USA	2029
Yazoo City Blue Ammonia	0.25	USA	2024
INPEX-led	0.00	Japan	2025
Total	**38.77**		



Magnitude of investments

Ammonia production benefits from economy of scale, with investment cost per production unit decreasing as ammonia production grows.[14] 97 of the announced project stages have advertised their intended investment size. Cumulatively, they plan to invest USD 506 billion to produce 111 MTPA.

Investment information is available only for a selection of the projects, corresponding to about half of the announced scope. The total investment extrapolates to about USD 1 112 billion, with annual investments up to 2030 in the USD 40–90 billion range. For comparison, DNV's Maritime Forecast to 2050 estimates USD 28–90 billion annual investment to scale up all alternative fuels production, distribution, and bunkering infrastructure, depending on decarbonization scenarios and targets.[8]

Indicatively, an average USD 4.6 billion is required per MTPA ammonia production capacity. There is a large data scatter for the projects below 3 MTPA. This implies that smaller projects can deviate significantly from the USD 4.6 billion average.

Types of renewable energy used for green ammonia

For every tonne of green ammonia, 10 MWh of electricity is typically needed[1], of which about 90% is used for electrolysis. Therefore, to produce all the announced 205 MTPA of green ammonia it would require about 2 050 TWh of renewable power, amounting to 6.8% of global renewable electricity production and exceeding the annual electricity production of India. Thus, the renewable energy supply is a critical part of the green ammonia production facilities.

Almost all possible renewable energy sources are represented in the announced projects, including solar PV, wind, hydropower, geothermal power, and their combinations.

Most of the announced projects (63 in total, representing 52% of the green ammonia production capacity) rely on a complementary combination of solar and wind power generation. In contrast, only solar energy is used in 35 projects, which corresponds to approximately 5% of the total announced capacity. Hydropower is used in 15 projects, contributing 2% to the overall production. Onshore and offshore wind are each expected to contribute approximately 2% to 3%.

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

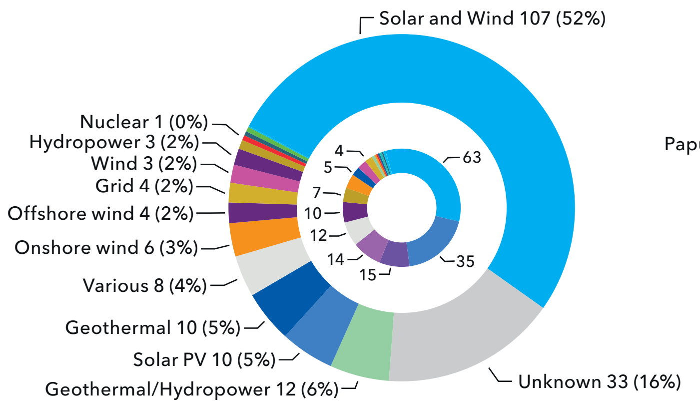
Overall, the dominance of wind and solar power generation is in line with DNV's Hydrogen Forecast to 2050,[15] which indicates an expected 40% reduction in costs of solar panels and 27% reduction in wind turbine costs this decade.

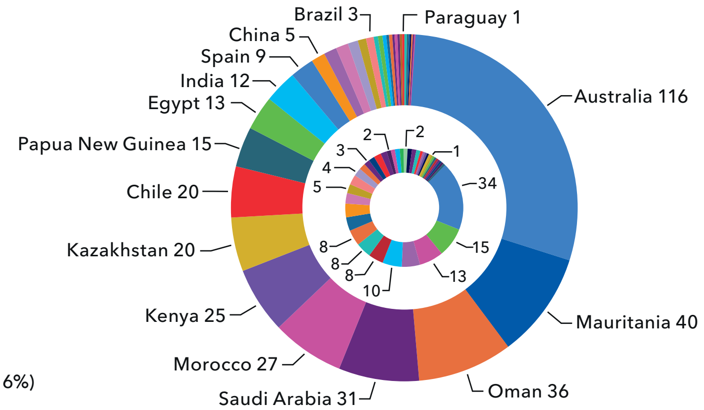
Grid electricity – whose use sometimes leads to the produced hydrogen and ammonia being labelled 'yellow' – is used in 1.8% of the announced capacity. This percentage is expected to grow after 2030, when more variable renewable energy sources (VRES) will be connected to power grids, supplying cheap or even free surplus energy for 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 for hydrogen production in 2050.[15] Notably, the origin of grid electricity plays a key role to ensure truly clean ammonia production. The 17–40 $kgCO_2/kgH_2$ emitted when hydrogen is produced by electrolysis from grid electricity derived from fossil fuel can be more than double the carbon intensity (9 $kgCO_2/kgH_2$) of hydrogen produced from steam reforming of natural gas.[16]

Despite a significant portion of electricity being produced by nuclear power, only one project, in Indonesia, is associated with the use of nuclear energy. Announcements from locations with multiple planned reactors (e.g. China, EU, India, Japan, Saudi Arabia, and UAE) may come in the coming years. Despite low emissions and mature technology, DNV forecasts that only 1% of H_2 will be produced via the nuclear route by 2050, primarily in China.[15]

FIGURE 8

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





Clean ammonia projects by end use

Currently, the fertilizers market consumes about 80% of existing ammonia production[1]. There is significant uncertainty over which market segments will take up clean ammonia. The announcements and project descriptions refer to applications such as fertilizers, shipping fuel, and energy. The Venn diagram (Figure 9) visualizes the distribution of the targeted 244 MTPA ammonia among the targeted applications for these projects. Surprisingly, fertilizers is the smallest end-use application mentioned (11 MTPA), with significantly greater planned production dedicated to more novel applications such as fuel (21 MTPA) and energy (33 MTPA).

The remaining 180 MTPA production is divided among four mixed applications; 'energy and fertilizers' (6 MTPA), 'fertilizers and fuel' (7 MTPA), 'energy, fuel, fertilizers' (59 MTPA); and 'energy or fuel' (109 MTPA). Clearly, the developers prefer to cater to multiple applications, with the overall mixed end use of 180 MTPA being nearly three times the 64 MTPA total for specific, dedicated end uses. The large ammonia scope targeting mixed applications results in a wide availability range for fuel, fertilizers, and energy. This reflects the future dynamic distribution of ammonia, which will depend on drivers of decarbonization in the sectors. Further, it is likely that as the projects mature, they will more clearly define the end uses for their output.

The top 10 countries (Figure 9), covering 80% of production from announced projects, focus markedly on mixed applications.

The map of dedicated and mixed end-use projects in Figure 10 shows the locations of the planned facilities.

Shipping fuel

Ammonia for shipping fuel is targeted by 30 projects across 10 countries with combined output of 20.8 MTPA. Almost all these projects plan for green ammonia. The leading

FIGURE 9

Left – Venn diagram schematically showing distribution of 244 MTPA of clean ammonia and overlap between the three end-use sectors 'fuel', 'fertilizer', and 'energy'.
Right – Distribution of ammonia by the targeted market sector in the top 10 producing countries (80% of total).

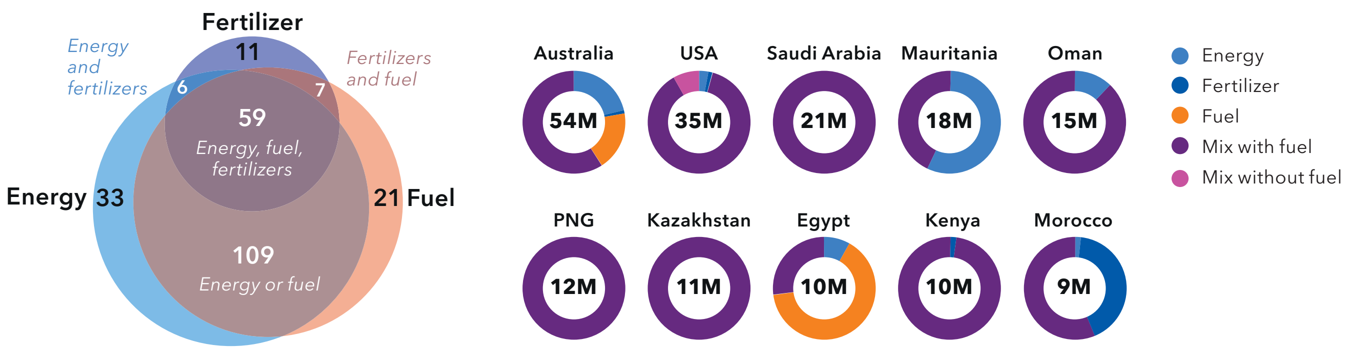
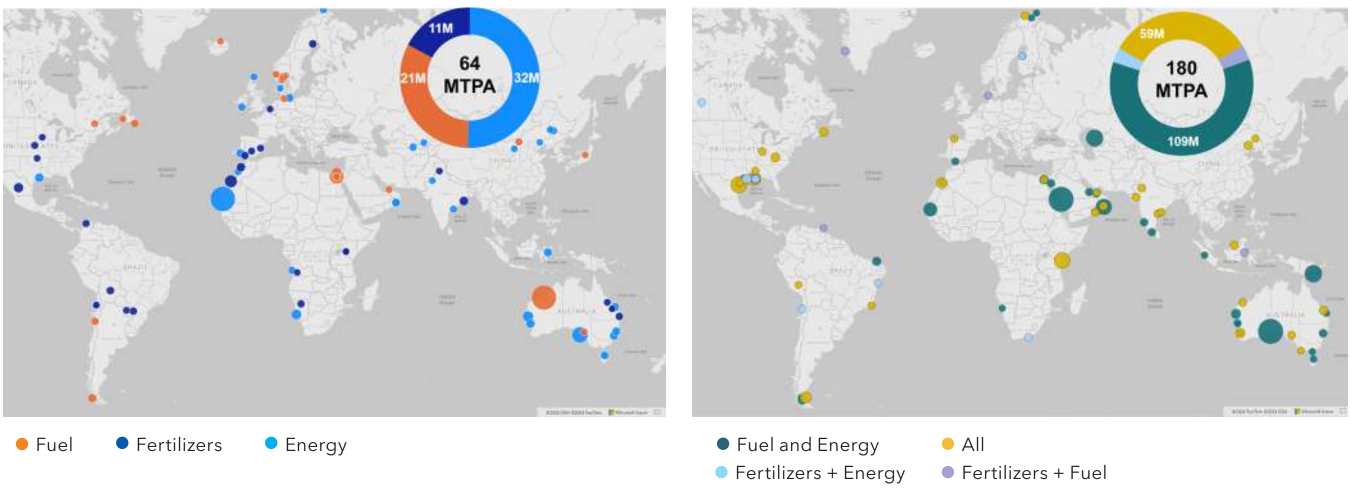


FIGURE 10

Left – Map of production with dedicated end use. Right – Map of production with mixed end use.



countries are Australia (49% share) and Egypt (33 % share). In addition, 93 other projects have announced end-use combinations of fuel and either fertilizer, energy, or both, with combined production amounting to 174 MTPA. If all the announced projects are successful according to their planned onstream date, the possible supply of ammonia for shipping fuel would be in the range 21–195 MTPA, with 21–151 MTPA available in 2030.

Fertilizer
33 ammonia-for-fertilizer projects are located across 16 countries (Table 2). Notable examples include two Moroccan projects, Tarfaya Renewable Ammonia and Green Investment Plan for Renewable Ammonia, together contributing more than a third of all dedicated fertilizer production. It is notable that in Australia, which aims to produce nearly 54 MTPA of ammonia, there are just three ammonia-for-fertilizer projects with combined production of 0.55 MTPA.

In addition to the dedicated renewable fertilizer projects, several mixed-end-use projects target combinations of fertilizers and either fuel or energy, with combined production of 71 MTPA. In this category 'mix including fertilizers' the leaders are the USA (18.2 MTPA blue and 10 MTPA mixed), Kenya (9.7 MTPA), Morocco (8.0 MTPA), Australia (6.7 MTPA), and Chile (5.1 MTPA). The overall fraction of blue ammonia in the potential (dedicated + uncertain mix) fertilizer segment is 27–39%, higher than the overall average of 12–16 %.

TABLE 1

Projects committed to the development of clean ammonia projects for fuel market.

Project name	Country	Announced (MTPA)	Share	Date onstream
AREH	Australia	9.9	47.7%	2028
Ra	Egypt	1.6	7.7%	2028
Total – 2	Egypt	1.5	7.2%	2030
Green Ammonia in SCZone	Egypt	1.0	4.8%	2030
Magallanes Wind to Ammonia	Chile	1.0	4.8%	2027
ReNew Power – 2	Egypt	0.9	4.3%	2029
Argentina Renewables – 2	Canada	0.5	2.5%	2027
Green Pegasus	Chile	0.5	2.2%	2027
AMEA – 1	Egypt	0.4	1.9%	2030
AMEA – 2	Egypt	0.4	1.9%	2029
Herøya Green Ammonia (HEGRA) – Energy	Norway	0.4	1.9%	2029
Baotou Renewable Ammonia	China	0.4	1.9%	2025
Total – 1	Egypt	0.3	1.4%	2029
The Port Pirie Green Hydrogen	Australia	0.2	1.0%	2028
EDF Renewable – 2	Egypt	0.2	1.0%	2029
Project Sauda Iverson Efuels	Norway	0.2	1.0%	2026
Courant	Canada	0.2	0.8%	2026
Khalifa Industrial Zone Abu Dhabi (KIZAD) – 2	United Arab Emirates	0.2	0.8%	2026
EDF Renewable – 1	Egypt	0.1	0.7%	2026
MEP	Egypt	0.1	0.6%	2029
Aquamarine	Germany	0.1	0.5%	2024
North Ammonia Arendal	Norway	0.1	0.5%	2027
Nujio'qonik – 1	Canada	0.1	0.5%	2026
ReNew Power – 1	Egypt	0.1	0.5%	2025
Slagen Terminal	Norway	0.1	0.5%	2029
Egypt Green Ammonia (Two plants)	Egypt	0.1	0.4%	2024
Argentina Renewables – 1	Canada	0.1	0.4%	2025
Green Fuel Iceland – 2	Iceland	0.1	0.3%	2025
Green Fuel Iceland – 1	Iceland	0.0	0.1%	2023
INPEX-led	Japan	0.0	0.0%	2025
Total		**20.8**	**100%**	

TABLE 2

Projects committed to the development of clean ammonia projects for fertilizer market.

Project name	Country	Announced (MTPA)	Share	Green (MTPA)	Blue (MTPA)
Tarfaya Renewable Ammonia –3	Morocco	2.00	18.07%	2.00	
Odish Ammonia	India	1.10	9.94%	1.10	
Tarafert – 1	Mexico	1.00	9.03%		1.00
Green Investment plan for Renewable Ammonia	Morocco	1.00	9.03%	1.00	
Tarfaya Renewable Ammonia – 2	Morocco	0.80	7.23%	0.80	
Green Wolverine	Sweden	0.52	4.69%	0.52	
Oruro Plant	Bolivia	0.50	4,52%	0.50	
Tarafert – 2	Mexico	0.50	4.52%	0.50	
Gibson Island Green Ammonia	Australia	0.40	3.61%	0.40	
Daures Green Hydrogen Vilage	Namibia	0.35	3.16%	0.35	
Fertiberia/Iberdrola – Palos de la Frontera – 2	Spain	0.28	2.51%	0.28	
Olive Creek 2	USA	0.28	2.48%		0.28
Barranquilla Offshore Wind Farm to Ammonia	Colombia	0.26	2.37%	0.26	
ATOME – 1	Paraguay	0.23	2.03%	0.23	
Alto Parana Plant	Paraguay	0.22	1.98%	0.22	
Tarfaya Renewable Ammonia – 1	Morocco	0.20	1.81%	0.20	
Catalina – 1	Spain	0.20	1.81%	0.20	
Fertiberia/Iberdrola – Palos de la Frontera – 1	Spain	0.17	1.56%	0.17	
Fertiberia/Iberdrola – Puertollano – 2	Spain	0.16	1.42%	0.16	
ATOME – 2	Paraguay	0.14	1.22%	0.14	
Dyno Nobel Renewable Hydrogen	Australia	0.12	1.08%	0.12	
Green Ammonia and Fertilizer facilities – 1	Kenya	0.11	0.99%	0.11	
Himachal Pradesh	India	0.10	0.90%	0.10	
Verdigris Complex Ammonia	USA	0.10	0.90%	0.10	
Garner Green Ammonia Plant	USA	0.08	0.75%	0.08	
Minbos Resources Green Ammonia Nitrogen Fertilizer Facility	Angola	0.08	0.68%	0.08	
Sluiskil	Netherlands	0.08	0.68%	0.08	
Kenya Green Ammonia Plant	Kenya	0.04	0.36%	0.04	
Herøya Green Ammonia (HEGRA) – Energy	Norway	0.02	0.19%	0.02	
Queensland Nitrates Renewable Hydrogen and Ammonia	Australia	0.02	0.18%	0.02	
HyEx – 1	Chile	0.02	0.16%	0.02	
Fertiberia/Iberdrola – Puertollano – 1	Spain	0.02	0.14%	0.02	
Green H2A Green Ammonia Pilot	Morocco	0.00	0.01%	0.00	
Total		**11.07**	**100%**	**9.80**	**1.28**

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 the avoidance of a large proportion 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 meet a large share of 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.[6]

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 coming years, the projects that plan to serve this market are already in development.

41 projects specifically target ammonia as an energy carrier, with the total output of 32.5 MTPA, 98% of which is green ammonia. Countries leading production of ammonia for energy are Australia (11.6 MTPA), and Mauritania (10 MTPA). In this sector, AMAN in Mauritania is an outstanding project with 10 MTPA with a 31% share. The fraction of blue ammonia in the scope is 2.2% 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 173 MTPA.

What is the likely supply of clean ammonia in 2030?

Successful implementation of the projects in the pipeline could result in the doubling of global ammonia production. To provide several likely, risk-aware scenarios for ammonia supply by 2030, we consider how uncertainties in the assessed projects' implementation could lead to production lower than announced. Most risks that affect project likelihood are related to its implementation, with early-stage projects having the largest risks. Furthermore, the project features such as size, location, technology, maturity and date onstream were evaluated and assigned three probabilities of success. The probabilities describe degrees of likelihood that a project will achieve its announced targets by 2030, and lead to the 'high', 'balanced', and 'low' scenarios that we apply.

Production estimates by scenario are 51 MTPA (high), 43 MTPA (balanced), and 34 MTPA (low). All production scenarios conclude that the likely supply of clean ammonia will be four to six times less than the 193 MTPA announced for 2030. This is not very surprising since the majority (67%) of the projects are in the earliest stages of their development. Moreover, only a fraction of the additional 51 MTPA planned to be onstream after 2030 may contribute to 2030 supply.

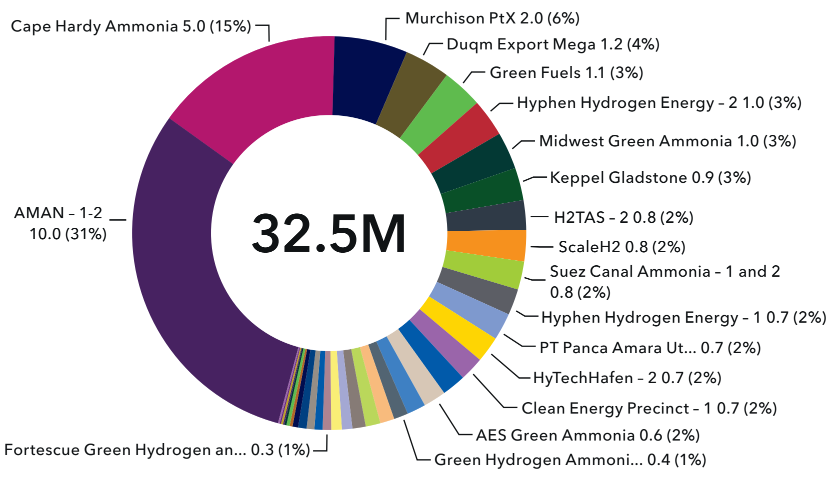
Blue and green plants pose distinct risks and technological challenges. For example, retrofitting CCS to an established brown ammonia facility to produce blue ammonia requires a smaller scope for technical implementation than development of a new green ammonia plant, thereby posing lower risks and having a higher likelihood. This increases the fraction of blue ammonia in the scope from 12% to about 32% consistently for all scenarios. More than half (55%) of the blue production is to be developed by 2027, and the rest by 2030. The likely range for blue (including mixed) ammonia is 13–16 MTPA in 2030, and for green ammonia 21–35 MTPA. In the balanced scenario, almost all (39 MTPA, 92%) the produced ammonia will be for export.

The distribution of ammonia by end-use category is unevenly altered by the likelihoods. In the balanced scenario, for example, production for fuel decreases 76%, for fertilizers by 58%, and for energy by 83%. A moderate decrease in

FIGURE 11

Countries and projects committed to development of clean ammonia projects for energy market.

Country	Announced (MTPA)	Share	Green (MTPA)	Blue (MTPA)
Australia	11.56	35.62%	11.56	
Mauritania	10.00	30.81%	10.00	
Oman	1.85	5.70%	1.85	
Namibia	1.70	5.24%	1.70	
USA	1.05	3.24%	1.05	
China	0.85	2.62%	0.85	
Egypt	0.79	2.44%	0.79	
Germany	0.75	2.31%	0.75	
Portugal	0.75	2.31%	0.75	
Indonesia	0.70	2.16%		0.70
Chile	0.60	1.85%	0.60	
Uzbekistan	0.52	1.59%	0.52	
Ireland	0.38	1.16%	0.38	
Angola	0.28	0.86%	0.28	
India	0.25	0.78%	0.25	
Norway	0.23	0.71%	0.23	
Morocco	0.18	0.56%	0.18	
United Kingdom	0.01	0.03%	0.01	
Denmark	0.01	0.02%	0.01	
Total	**32.45**	**100.00%**	**31.75**	**0.70**



the fertilizers category is mainly due to the significant fraction of blue ammonia projects present in this application.

Focusing on the availability of ammonia as a low carbon shipping fuel in 2030, the announced capacity targets the range 21–151 MTPA, which includes 21 MTPA specifically dedicated to fuel and 131 MTPA with an uncertain fraction of ammonia for fuel. After assessing success probability, our scenario analysis provides three likely ranges: a) Low, 4.3–25.0 MTPA; b) Balanced, 5.0–32.2 MTPA; c) High, 7.1–38.6 MTPA.

In the balanced scenario, the lower limit of the fuel-dedicated amount of 5.0 MTPA can be considered a minimum realistic supply of ammonia for fuel. Correspondingly, the upper limit, which can be regarded as a maximum realistic supply of ammonia for fuel, also includes mix with fuel (27.2 MTPA), resulting in 32.2 MTPA.

The future demand for clean ammonia will be driven by the market demand, and thus the distribution of mixed end-use category will be dynamic. If an equal share between the three end-use sectors is assumed, this results in an indicative fuel availability in the range of 11–18 MTPA.

Notably, all the 5.0 MTPA of dedicated fuel supply is green. It is critical that the development of green and blue ammonia for fuels proceeds in parallel with development of ammonia engines, such that by near to 2030 the ammonia-capable vessels contribute to decarbonization of maritime transportation.

FIGURE 12

Left – Annual added production for the balanced scenario (bars with distribution of ammonia colours) and total production capacity in high (dashed), balanced (solid), and low (dotted) scenarios. Announced production capacity in dark blue line. Right – Comparison of distribution of ammonia end use according to the announced and balanced scenario in 2030. The pie charts show the fraction of green, mixed, and blue ammonia for balanced vs. announced production capacities.

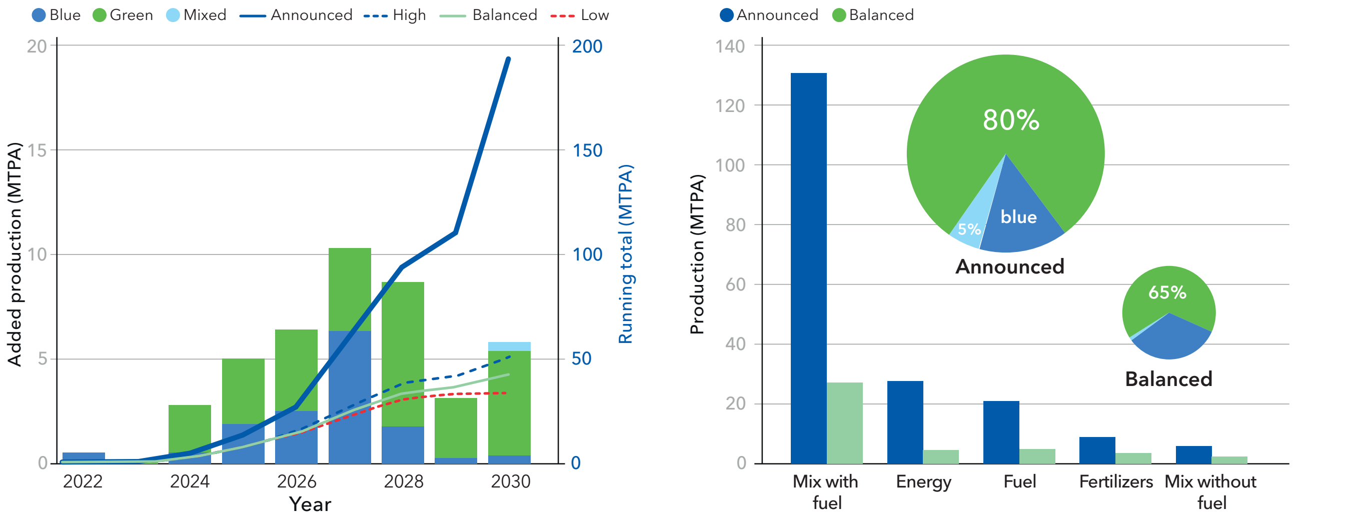
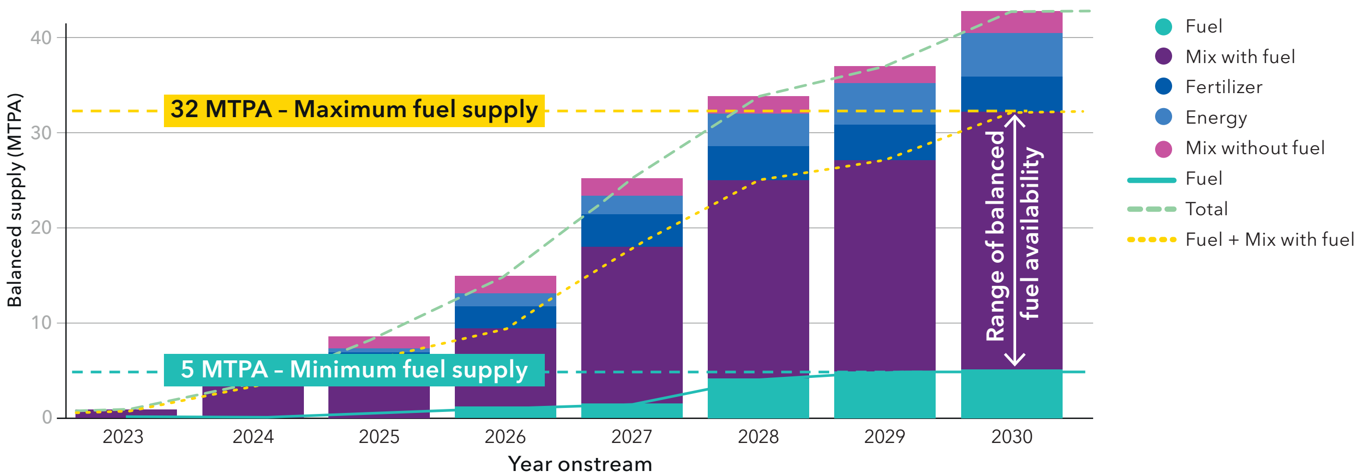


FIGURE 13

Evolution of balanced production of clean ammonia by end-use category.



Will there be enough electrolysers?

When reflecting on the materials and components required to realize the visions of clean ammonia production, and in particular the announced production capacity, the question arises whether production of electrolysers can be a limiting factor for development of green ammonia production. The current global installed capacity of electrolysers is 7–10 GW/yr, and electrolysers will also be used for hydrogen production.

Announced electrolyser capacity
Electrolyser capacities were announced for the majority of the ammonia projects, and the missing values were derived from the announced green ammonia production using a conversion factor of 0.75 ktNH_3/MW. Overall announced total electrolyser capacity is close to 404 GW. The largest announced installed electrolyser capacity is in countries with the largest green ammonia production capacity; Australia, Kenya, Mauritania, Morocco, Oman, and Saudi Arabia. Only 51 projects announced the electrolyser technology. Among these, alkaline and PEM technology have comparable shares of around 40%, the remaining being SOEC. This aligns with patenting trends for electrolyser technologies, with PEM having a 41% share, SOEC (32%), alkaline (22%) and AEM (5%).[16]

The installed electrolyser power is projected to exceed gigawatt level for the first time in 2024, with 4.8 GW. The Ammonia in Pecém Complex in Brazil, with a 2.5 GW electrolyser capacity could be the first to reach the GW milestone, with announced production of 2.2 MTPA.

Between 2025 and 2030, the yearly installations are projected to be consistently high, in the range 17–126 GW. Since many developers aim for completion by 2030, this results in a record 126 GW electrolyser power capacity installed in a single year if all projects are implemented as announced. However, as noted in the above discussion on likelihoods of project success, delays and cancellations may occur.

Several projects indicated a producer of the electrolyser units. However, most leave this information unspecified. The final choice of electrolyser supplier and type of technology is often taken after FEED stage, with the FEED package serving as a basis for the bidding for execution-phase contracts. According to Figure 2, 89% of the projects have not completed FEED stage, which is consistent with the 92% of unallocated electrolysers supply in Figure 14.

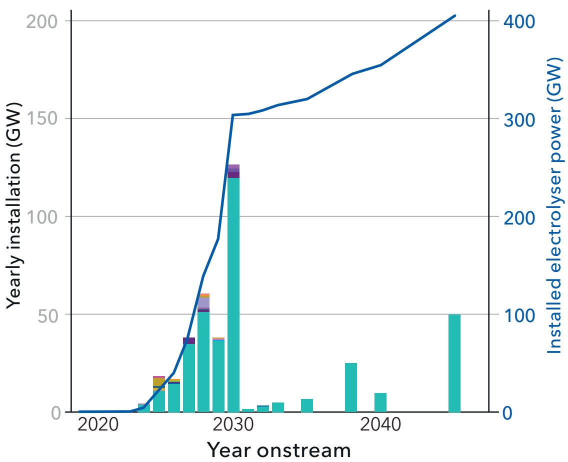
Demand for electrolysers and predicted upscaling
Production of the 155 MTPA ammonia in 2030 would require about 299 GW electrolyser capacity. In the balanced scenario, the green ammonia production is lower (28 MTPA), requiring 61 GW of electrolyser capacity. In this case, the yearly installations would vary in the range 4–12 GW, with an average value of 8 GW/year. This requires substantial efforts on upscaling electrolyser manufacturing.

Several predictions exist for the expected manufacturing capacity and cumulative installed electrolyser power towards 2030. When comparing these, 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 a 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.[17]

FIGURE 14

Announced yearly installation of electrolysers, and selected producers of the electrolysers for the 32 GW where this is defined.



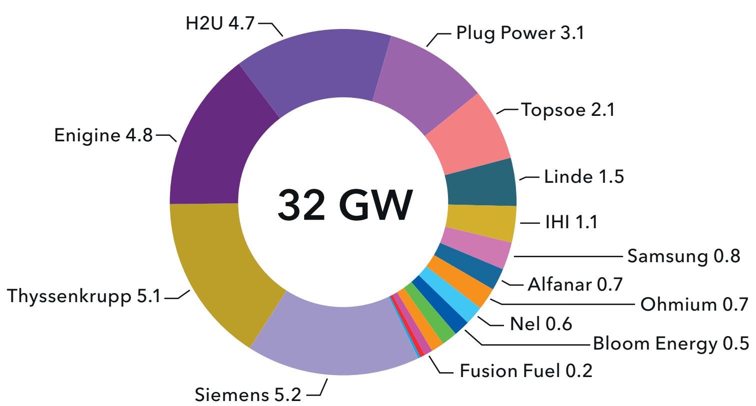
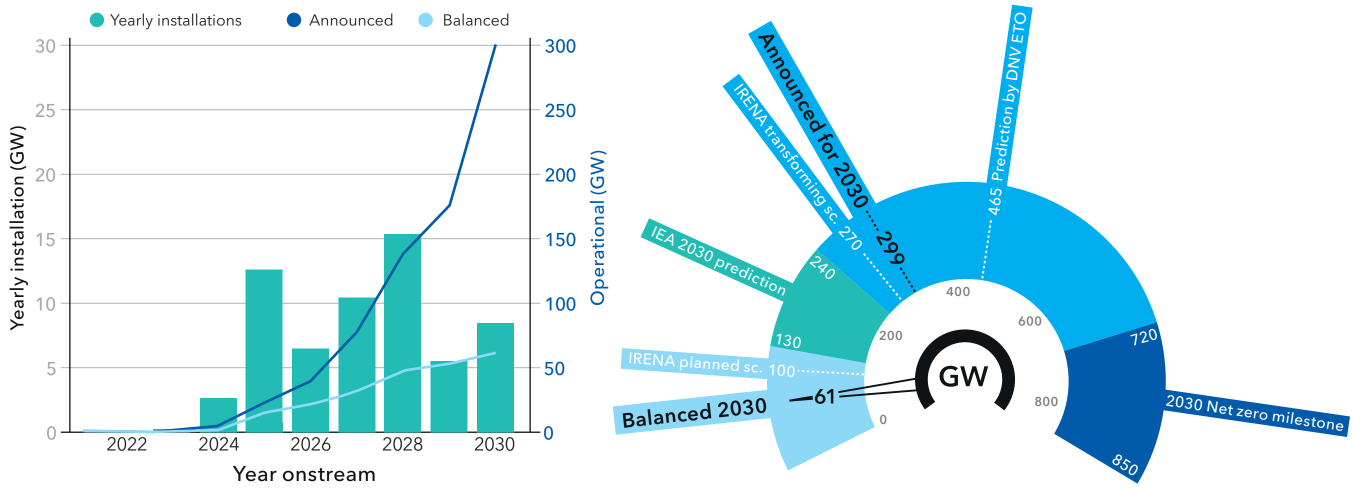


FIGURE 15

Yearly electrolyser deployment according to the balanced scenario (bars) and total installed electrolyser capacity for balanced scenario and announced (lines). Right – Gauge graph showing the present estimate for the balanced scenario and all announced projects for 2030, compared with literature projections from IRENA,[17] IEA,[9] and DNV ETO forecast.[6]



In 2022, IEA predicted 130–240 GW to be installed by 2030.[16] DNV's ETO forecast in the same year was higher, with 465 GW electrolysers to be deployed by 2030.[6] All these predictions are significantly lower than IEA's estimate that 720–850 GW will be necessary in 2030 to be on track to net zero by 2050.[9]

The announced electrolyser capacity of 299 GW exceeds IEA and IRENA (planned scenario) predictions, but aligns somewhat with both DNV's prediction (64% of all electrolysers are for ammonia) and net-zero pathway (<41% is for ammonia production). On the other hand, the balanced scenario requires 61 GW, which seems reasonable from many perspectives. It is about a quarter of the IEA and IRENA predictions of all electrolyser capacity, and 13% of the DNV ETO forecast. To account for new announcements to appear within 2023–2024, the possible electrolyser installations may realistically total up to 80–90 GW by 2030.

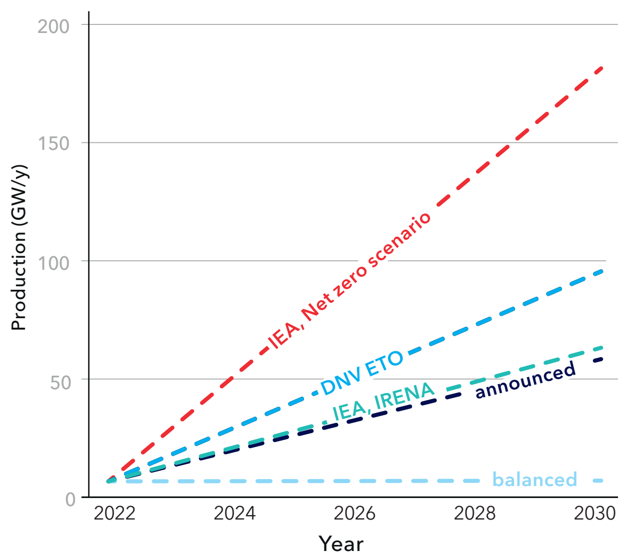
Several predictions outline how upscaling could evolve to accommodate the growing market demand. IRENA's scenarios foresee ramping up manufacturing to 10–60 GW/year by 2030.[17] IEA's patenting review similarly predicts reaching yearly production of 65 GW by 2030,[16] which would include gigawatt fabrication lines for alkaline, PEM, and solid oxide electrolysers.

To derive at the installation rate needed to reach the announced and realistic production levels, a rough estimation was made using a linear increase in manufacturing capacity (Figure 16). For reaching the 61 GW of installed capacity in 2030 needed in the balanced scenario, a constant yearly manufacturing capacity of 7 GW over the next eight years will be sufficient.

However, for the announced ammonia production capacity, the electrolyser industry needs an additional increase of 6.3 GW every year, thereby reaching 58 GW/year in 2030. While such a manufacturing rate and upscaling are feasible in principle, it is unlikely to be dedicated only to the green ammonia production industry. In comparison, for fulfilment of the DNV scenario of 465 GW in 2030, the electrolysers industry needs to expand by an additional 11 GW each year, which leaves ample capacity available for dedicated hydrogen production with the balanced scenario. To be on track for IEA's net zero in 2050 scenario, an additional 22 GW must be introduced each year.

FIGURE 16

Electrolyser manufacturing required to fulfil the 2030 predictions (IRENA, DNV ETO, and IEA) compared with announced and balanced electrolyser installations.



Notably, only a fraction of the upscaled manufacturing capacity can be of PEM type due to the limited availability of iridium. 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.

Factors relevant to upscaling the electrolysers manufacturing
Upscaling of electrolyser manufacturing allows for significant reduction of the manufacturing costs. IRENA's 'Scaling up the electrolysers' report[17] concludes that advancing from a typical 1 MW electrolyser produced in 2020 to 1 GW-sized units could lead to 70% reduction in the stack cost. The strategies to achieve such a reduction include switching to more automated stack assembly, standardization, and using advanced coating technologies to optimize the use of precious metals. Overall, a 1 GW/year manufacturing plant should benefit from the economy of scale. Multiple producers (Thyssenkrupp, NEL, ITM, Siemens) have either reached this milestone or target it within the next couple of years.

From the manufacturer perspective, to facilitate the needed upscaling of production, risks need to be considered. According to IRENA, factors such as land area, water purification, desalination, deionization and saltwater availability are not limiting the needed ramp-up of manufacturing.[17]

In contrast, one of the crucial limiting factors for upscaling PEM electrolyser manufacturing is availability of precious metals. Two precious metals are used in the electrolysers, platinum and iridium. While platinum appears in both PEM and some designs of alkaline, iridium is primarily used in PEM. Even though there is significant pressure to reduce their amount in electrolysers, to advance efficiency, and to increase lifetime and recycle, mining 200 tonnes of platinum per year would allow for quite aggressive upscaling in the order of hundreds of gigawatts. In contrast, iridium is 10 times less abundant than platinum, and the 7 or so tonnes mined per year set a hypothetical upper limit of 30–75 GW PEM capacity by 2030.[17]

Finally, DNV's Hydrogen Forecast to 2050 highlights 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. Based on the number of green ammonia projects reviewed in the present work as well as dedicated hydrogen projects, the demand for electrolysers is large. In the balanced scenario, the yearly electrolyser installation would match the current production capacity, and the capacity of the announced projects are more than 5 times higher.

Results for the years 2040 and 2050

Using the DNV Pathway model as described above, demand for ammonia as a maritime fuel is modelled to grow from 2.3 MTPA in 2030 to 62 MTPA in 2040, and 245 MTPA in 2050. The demand for each year is shown in Figure 17, with both green and blue ammonia included.

In addition to the DNV Pathway model for the maritime sector, another model used in the DNV Energy Transition Outlook (ETO) 2022[6] has modelled the entire energy system. In the ETO 2022 model, demand for ammonia as a feedstock, particularly for fertilizers and explosives, shows moderate growth from about 186 MTPA in 2021 to about 200 MTPA in 2050. The robust growth is for ammonia as a maritime fuel from zero today to surpass its use for feedstock by 2046 and then reach 245 MTPA in 2050.

In addition to these final demand uses, there will be growth in intermediate demand, where ammonia is used for deep-sea transport of hydrogen and cracked back to hydrogen at the destination. This trade will emerge in 2030 and grow to more than 150 MTPA in 2050, 90 of it from the region Northeast Eurasia (includes Russia, Ukraine, and other former Soviet republics). Interestingly, differential costs and distance to final use means supply chains vary by end-use category. The ETO analysis finds that the case for using ammonia in electricity production, either alone or in co-firing with coal or natural gas, requires unrealistic cost assumption: Ammonia was not considered to be used for that purpose.

While over 30% of production used for feedstock in 2050 will still be unabated ammonia from methane reforming, maritime energy use can be entirely abated. Indeed, the only reason ammonia will be used in shipping will be the ability to declare it as 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, still be the largest source (39%) in 2050, followed by blue (35%) and green (26%). For ammonia as energy carrier, i.e. for marine fuel, blue ammonia dominates by 76%, cf. Figure 18.

FIGURE 17

Demand for ammonia as a maritime fuel according to the DNV Pathway model; for both green and blue ammonia contributions.[6] The supply approach for 2030 is compared to how the demand is modelled to pick up (from a selection of scenarios as described under Approach).

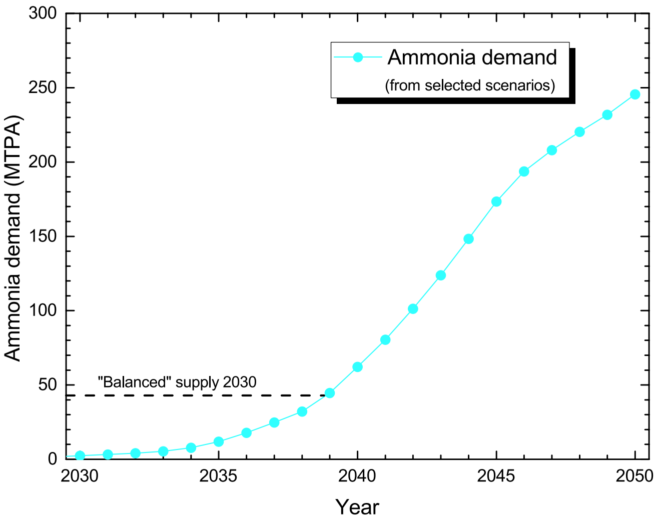
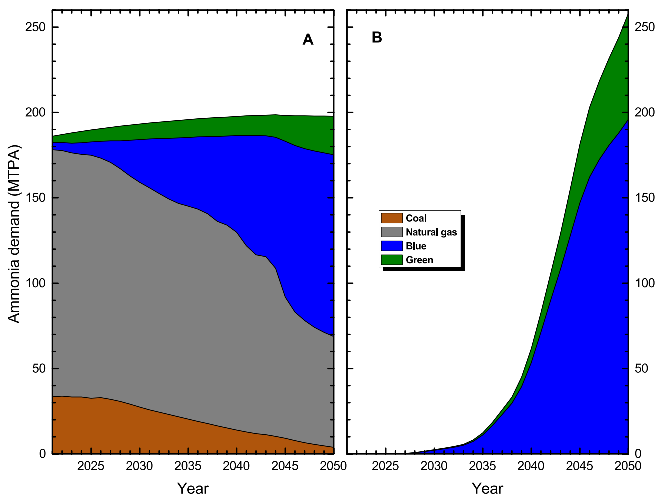


FIGURE 18

Global ammonia demand for A) Feedstock and B) Energy demand (marine fuel). Green consists of ammonia made using solar PV, wind, and nuclear power. Blue consists of ammonia made from both natural gas and coal with CCS.[6]



Market dynamics

Up to 2023, ammonia has been an industrial feedstock used primarily in fertilizer production. The future 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. Ammonia's potential growth a major shipping fuel is promoted by the development of wider demand for hydrogen and ammonia in other energy sectors as well. As shown in Figure 19, ammonia is a nascent marine fuel, and will most likely make up 35% of all shipping fuels in 2050.[6] Yet even this spectacular growth must be seen in a broader context of hydrogen use quadrupling to 2050: 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.[15]

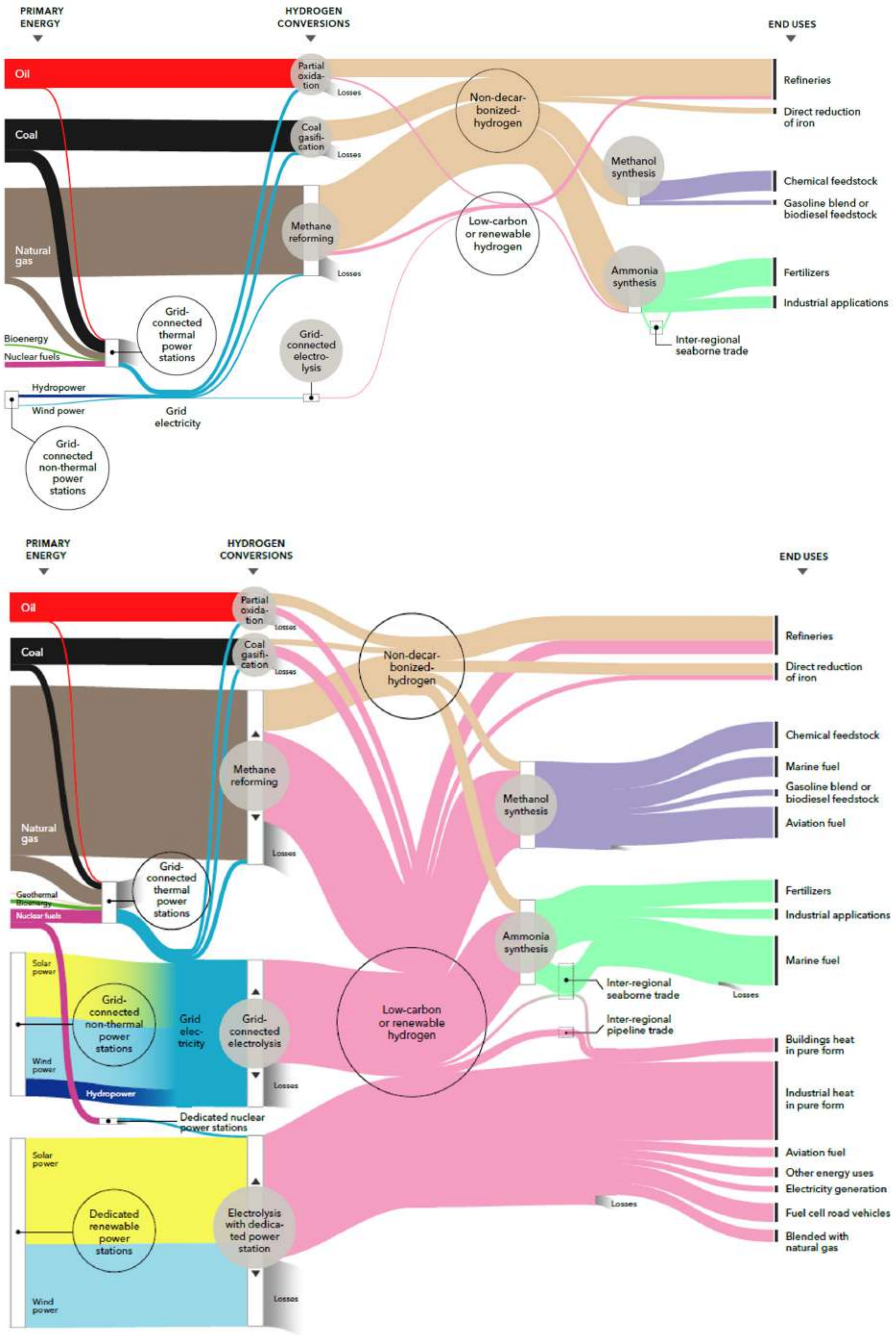
The need for zero-emission fuels arises because of societal demand for reducing GHG emissions. In recognition of the need to create the above self-reinforcing loop to get the 'snowball rolling'[18] and increase its speed and size, there are numerous support programmes to help the ammonia market take off. As an example, the IRA programme in the USA covers more than half the cost of green and blue hydrogen.[19] This will be reflected in lower prices to final customers and thereby accelerate demand and 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 20.

Lower price is not the only driver for demand to develop. 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 the maritime sector a demand driver. But as has been seen, shipping is also an important part of the ammonia supply chain. It is likely that hydrogen will also be transported on keel as ammonia, as this avenue will be less costly; converting hydrogen to ammonia and back is less energy intensive and therefore less expensive than liquefying hydrogen.[15]

It must be noted, however, that all zero-emission fuels are in their infancy. There are several contenders to ammonia: hydrogen, methanol, other e-fuels, and biofuels. Each will compete for market share in the zero-emission ship fuel market, and the zero-emission fuel market is again competing for share in the total maritime fuel market. It is a given that this market share will increase, but the DNV ETO 'most likely future' estimates ammonia will still supply only about 35% of all maritime fuels in 2050,[6] or 50% of all clean fuels, shares which will combine to make up 70% of the shipping fuel market. In a less likely Paris-compliant net-zero emissions by 2050 future, the clean ship fuel market share reaches 85% in 2050, of which 60% will be ammonia, 6% biofuels, 24% methanol, and 10% electricity.[6]

FIGURE 19

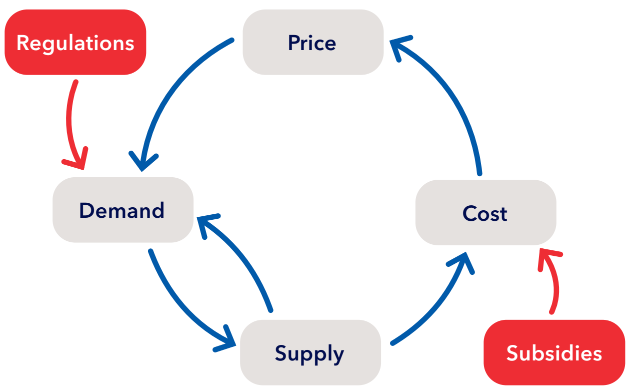
Sankey diagram of hydrogen production and end uses in 2020 (top) and 2050 (bottom) in line with a most likely future (from reference 15).



As indicated in Figure 21, the clean ammonia market consists of three interconnected self-reinforcing feedback loops. The fact that the loops are self-reinforcing implies strong first mover advantages, because of path dependencies[20] and technology lock-ins: an early zero-emission entrant fuel might become dominant, as a well-developed supply chain might lock actors into this fuel and consequently leave others out in the cold forever. But the finding that the ammonia share of the maritime clean fuel market will be 50–60% depending on the scenario also implies that there are local and regional contexts that prevents a winner-takes-all future.

FIGURE 20

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



Compared with biofuels and methanol (as 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 (brown) ammonia is already shipped on keel today, there is a supply chain in the form of pipelines, ports, and terminals. Moreover, as many liquefied petroleum gas (LPG) ships can accommodate ammonia, this part of the supply chain also exists. However, the 'most likely future' and 'pathway to net zero' that DNV models still forecast that methanol, biofuels, and ammonia will split the market share. This is because cost differentials will be small, cost learning rates similar, and local supply-chain fits will differ.

The Haber-Bosch process has already accumulated 100 years of experience, and steam methane reforming (SMR) has been the dominant production technology behind hydrogen for almost as long. In contrast, CCS to make blue hydrogen and electrolysers to create green hydrogen are each in their infancy. To become cost-competitive, their costs must come down. Cost learning through both local and global accumulation of experience is required. In Figure 21 parlance, this means that the upper-left loop, (in which the combined demand is less than 10% of the bottom-right loop) is totally dependent on the dynamics of the global production processes (including CCS and electrolysers) for green, blue, and grey ammonia.

Regulations

Economists typically favour GHG emission prices as the most cost-effective way to ensure emissions reduction. To ensure temperature rises below 1.5°C, analysts typically require CO_2 prices greater than 160 USD/tCO_2 by 2030.[21] As no one predicts such high price levels, emission reductions will additionally require emission regulations. Such regulations will partly be at the technology level (e.g. banning coal-fired power stations and the sale of new internal combustion engine cars), and partly through mandated emission limits in various sectors.

For the maritime industry, IMO has already in 2020 shown its influence by mandating sulfur emission limitations in parts of the world,[22] requiring reductions by a factor of seven. Similarly, the 70% reduction in GHG intensity in maritime transport to 2050[23] will require national and international regulations to help ensure that goal is achieved.

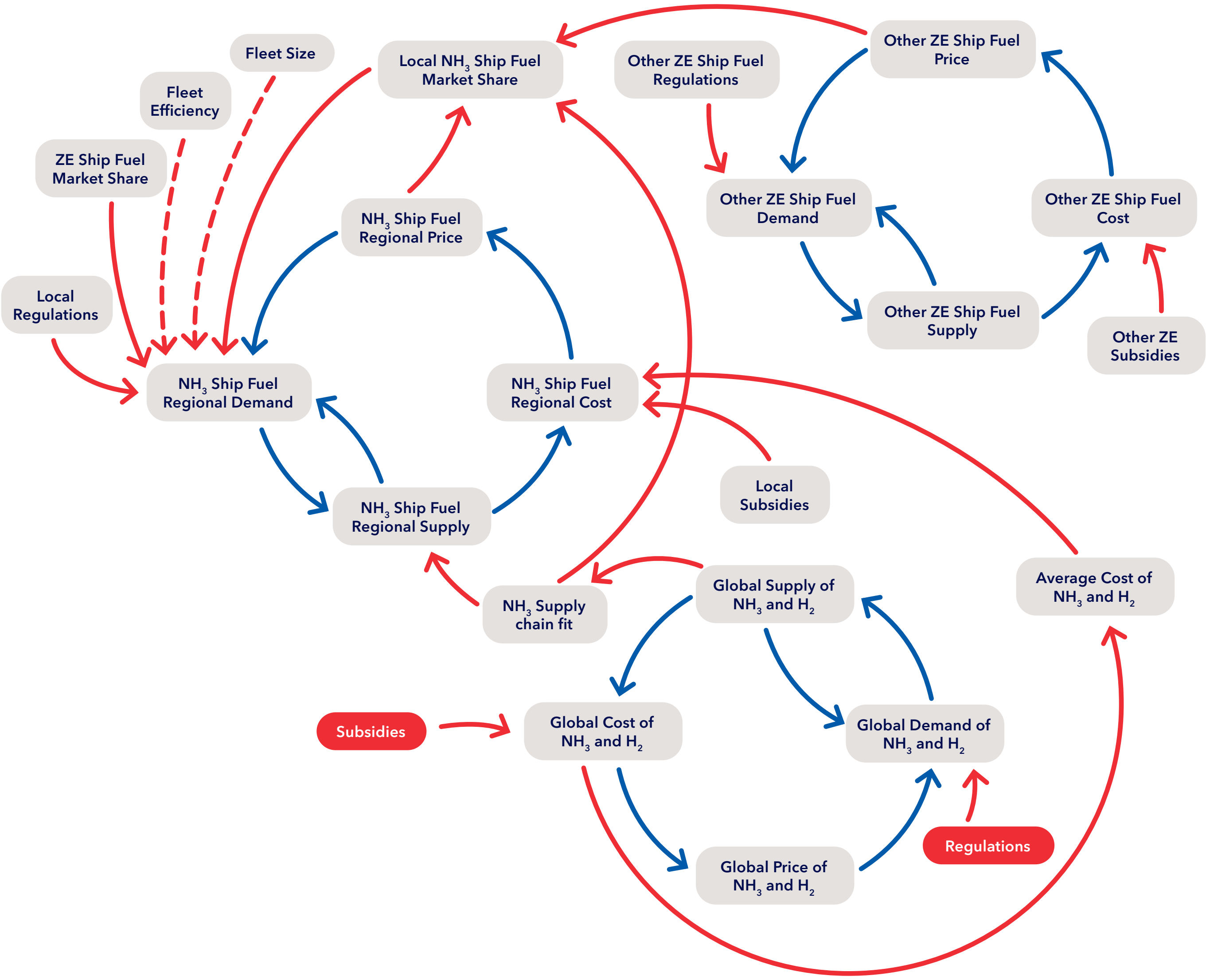
As indicated by Figure 19 and the interlocked feedback loops, regulations in other parts of the hydrogen and ammonia value chains will also play a role. Regulations in various parts of the world are working in tandem with subsidy schemes to enable emission targets to be met.

The USA's IRA policy portfolio is mainly a financial support package that will run until 2032.[24] Yet, it also contains regulations, the best-known being 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 advantages of battery electric vehicle technologies will abort FCEV for the light-duty sector.[15] However, requirements that 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 ammonia, hydrogen regulations will increase H_2 production and hence reduce costs. This will also benefit ammonia.

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 its derivates will also benefit from this.

FIGURE 21

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. Exogenous forces (in red) are regulations and subsidies.



In Europe, the European Green Deal[25] focuses not so much on financial support as on 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.

Regulations will 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.

In Asia, Japan is set to mandatory closure of coal-fired power plants in the 2040s. Instead of stranding such assets, Japan plans for the plants to soon be co-fired with ammonia with minimal update costs.[26] It aims to increase ammonia's share in fuel for these plants to 100% within 20 years. Japan's goal is to use 30 MTPA ammonia for power generation by 2050.[5] Similar policy initiatives are underway to use hydrogen for electricity generation and home heating. Though Japan's fuel cell use in homes and use of ammonia in power plants both benefits from regulations, such use suffers from much greater energy losses than direct use of renewable electricity. DNV foresees ammonia energy inefficiencies impairing coal co-firing in a 'most likely' future where only 6% of buildings' energy will come from hydrogen and ammonia. But in a Pathway to Net Zero Emissions future, regulations would follow, and hard-to-abate elements of buildings' energy use would be decarbonized, leading to 25% of such energy use coming from hydrogen. Using hydrogen and ammonia for power generation will not take off, even in a net-zero future. The alternatives, notably renewable electricity and storage combinations, are typically twice as energy efficient, and for extreme dunkelflaute situations, other and less energy-wasteful storage options will suffice.

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

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 subsidized (or both). Second, and as with other aspects of the energy transition, national and regional economies such as China, EU, and the USA understand pathway dependence, first mover advantages, and barriers to entry. Therefore, support for hydrogen and ammonia is interlinked with industrial policy and support. Using a global and regional framework, and integrating industrial and climate policy forces, the tables below show subsidy levels. Note that they were developed in spring 2022 before the US IRA and the EU and Chinese responses to it; and have since risen. Regional support mechanisms are already in full swing and, in a 'most likely' future, will remain at current levels for the reminder of the present decade.[6] Then they will linearly taper off to reach half of current levels in 2050. The combination of financial muscle, climate ambitions, and industrial policy means half of all capital investment in hydrogen plants will come from taxpayers in OECD countries and China through 2030. Similarly, governments in the Middle East, North Africa, and India will foot 15% of the investment bills on 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.

Table 3 shows investment support to all hydrogen facilities for both a 'most likely future' and a plausible 'pathway to net zero'. In addition, variable renewable electricity dedicated to hydrogen is initially the most costly production pathway, though the most desirable from a climate perspective. 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 quarter of all operating costs. Other regions will in our estimate foot 4–10% of the bill. Note that 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

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 4

Production cost support levels for dedicated hydrogen.

	OECD	CHN	LAM+MEA+NEE	IND	SSA
2030 – 2050	25%	4%	10%	7.5%	5%

Who will the clean ammonia players be?

Companies and governments worldwide 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.

Governments will support clean ammonia projects for the foreseeable future as indicated in Table 3, covering half of all investment costs in China and OECD member states until 2030, a support level that will only be halved by 2050. Other regions – except Sub-Saharan Africa, which cannot support it, and Northeast Eurasia, which is less concerned with climate change – will have lower support levels, though 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 brown, and supply chains enabling ammonia trading currently exist. Players in these supply chains have experience and knowledge of SMR production and the handling and transportation of ammonia. They are already positioning themselves for cleaning up GHG emissions from SMR through retrofitting CCS 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 as 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,[6] where current feedstock production will remain stable while H_2 used for energy purposes comes to dominate, increasing from zero today to 75% of global production, representing 240 MtH_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 these 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 lacking electrolyser competence, renewables companies often partner with electrolyser technology specialists such as IHI Corporation.

The two latter sets 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 it 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 function as a storage and transport element of energy. As it can easily replace coal in power production, Japan in particular is developing plans to acquire, produce, and use ammonia for this purpose, with current coal handlers planning to handle ammonia and extend their activities into operating other parts of the ammonia value chain. As with natural gas, which is purchased for conversion to ammonia used predominantly as feedstock today, ammonia for energy will be a commodity. Traded ammonia is forecasted[15] to expand from only a marginal share of global ammonia produced now to account for most ammonia output in mid-century as it becomes a traded commodity par excellence. The value chains will therefore also include activities such as cracking ammonia to hydrogen, with players being either horizontally or vertically integrated. But there will also be potential room for niche players specializing in smaller segments such as ammonia-to-hydrogen cracking and -trade.

As indicated in Table 5, the various player classes all have strength and face challenges. Oil companies such as Equinor and BP are also increasingly active in renewable energies, where they say they will spend the majority of their 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 is a hybrid project where steam methane reforming and green technologies will be developed in parallel.

Summing up, there are no showstoppers for any player class. 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 some can benefit from cooperation with players from other classes. Indeed, such cooperation appears to be the norm for most future projects.

TABLE 5

Clean ammonia players.

Player class	Player type	Examples	Projects	Strengths	Challenges
Grey ammonia/ Fertilizer	Ammonia user	• Yara • Nutrien Ltd	• Yuri • Geismar	Knowledge of feedstock market, production technology, value chain. Significant internal customer.	Limited knowledge of ammonia energy market
Heavy industry	Ammonia equipment	IHI Corporation	H2TAS	As clean ammonia involves emergent technologies, solving and fielding new technology will be core of the new business.	Core competence on a small part of value chain
Natural gas	Ammonia manufacturer	• Equinor • BP • Chevron	• H2M Eemshaven • Nord-West Oelleitung (NWO) • Clean Ammonia/ Indonesia	Ample access to natural gas and energy markets. The only way to prevent methane becoming stranded assets in a GHG-free future.	Limited knowledge of ammonia feedstock market
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

Price elasticity

The fact that grey 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 SMR process to make blue hydrogen will of course add cost and requires additional energy. Though green ammonia may well become cheaper, forecasters typically estimate that cost learning potential for green ammonia, though substantial, will lead only to a similar cost to blue ammonia once both technologies' cost learning curves flatten after 2040.

As is evident from recent press releases, many sectors foresee a hydrogen economy in the shift to a decarbonized future. Two price elasticities of demand are of importance. One is the price elasticity of clean ammonia in the maritime sector relative to the price elasticity of other sectors. The other elasticity is that of ammonia as opposed to other zero-emission fuels.

One way of assessing the first of these elasticities is to contrast the additional fraction of (operating) costs that switching from traditional to ammonia fuels represents for various sectors. According to Stopford 2009,[27] fuel costs are 30% of total ship transportation costs. According to IEA,[28] clean ammonia is 215% more expensive than diesel. This means that switching to clean ammonia as fuel increases the 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.[6] Ammonia is the main cost of producing fertilizer, and clean ammonia will double its cost compared with production via methane reforming without CCS.[29,1] If total costs nearly double for fertilizer producers, but only increase by two-thirds for shipowners by using clean ammonia instead of diesel, one could conclude that shipping industry ammonia demand would be less price-sensitive and so crowd out fertilizer demand. But Yara's perspective is different. For the fertilizer final user, such as a US Midwest corn producer, fertilizer represents only 18% of total costs. This means that the total cost for the farmer for clean ammonia use would increase by 30%. Therefore, the fertilizer producer would easily crowd out shipowners for the clean ammonia.

With respect to clean ammonia's demand elasticity versus other fuels, 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.

Discussion

Export and the nearest major maritime hub

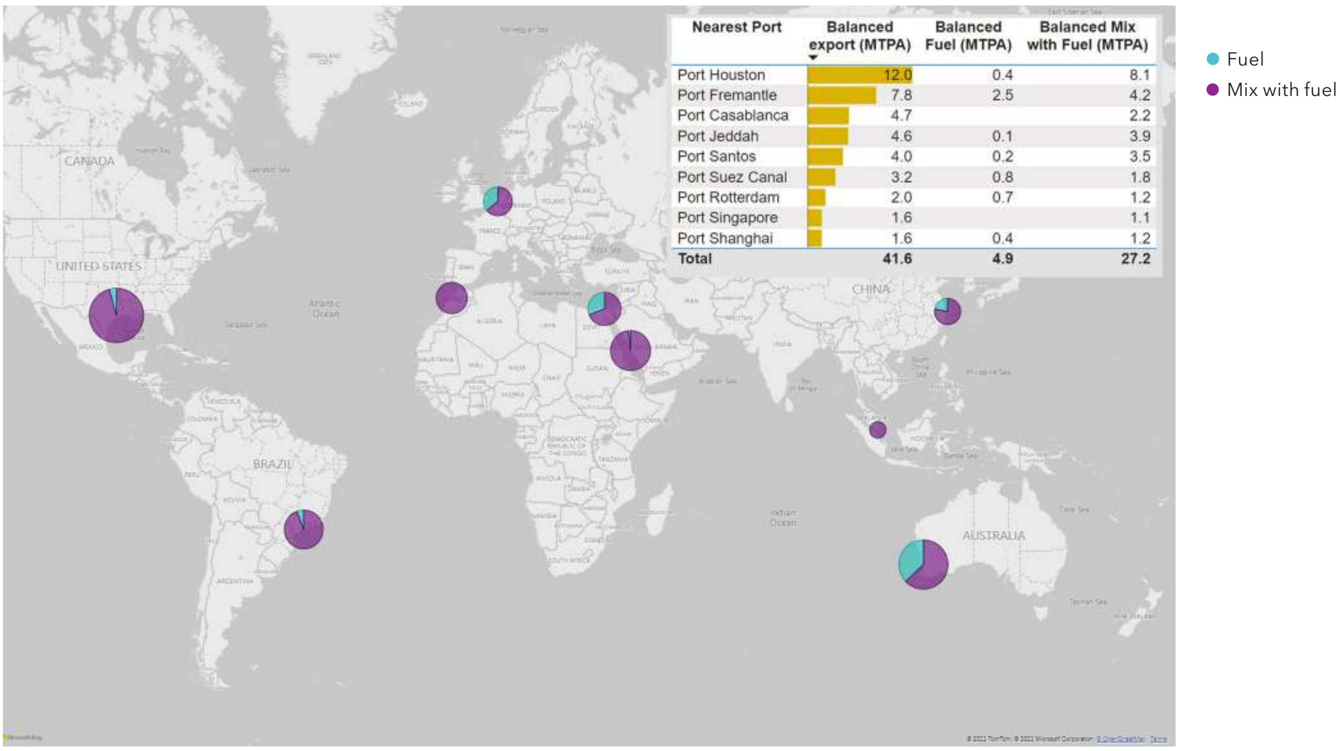
The project developers plan to produce about 234 MTPA for international export by 2045. If all the projects were realized on time, the load on the existing ammonia transportation infrastructure in 2030 would increase nearly 10-fold compared with today to reach 183 MTPA. In the balanced scenario, the export volume is 41.6 MTPA. That would also require more vessels being available for shipments. For transportation by sea, a Large Gas Carrier (LGC) can carry up to about 40 000 tonnes of ammonia, whereas the largest ships, for example Very Large Gas Carrier (VLGC), may carry up to 54 000 tonnes of ammonia. If all the clean ammonia produced for export in 2030 was to be shipped by sea, it would require 1 040 individual LGC voyages to transport the 'balanced' scope of ammonia.

Ammonia to be transported by deep-sea shipping will rely closely on ports, which offer infrastructure for storing and fuelling ships with alternative fuels such as ammonia. In line with this, a notable feature of almost all production facilities is that they are within a few kilometres of a nearby port, which facilitates easy transportation by sea. To describe ammonia export traffic, we chose nine major maritime hubs (Casablanca, Fremantle, Houston, Jeddah, Rotterdam, Santos, Shanghai, Singapore, and Suez Canal) and identified which is closest to a project location. Note that this approach allows for an indicative export-traffic picture showing the regional origin of the produced ammonia. Choosing a larger number of ports can provide a more realistic scenario, but is beyond the scope of this study.

Based on the nearby production facilities, the busiest port exporting clean ammonia in the balanced scenario could be Houston (USA), followed by Fremantle (Australia). This distribution of ammonia export does not strictly reflect the actual availability of ammonia in that port but indicates the amount of produced ammonia in the vicinity. In reality (e.g. in South America), multiple export hubs would be participating in ammonia transportation, further sharing the scope among the multiple ports. Similarly, Port of Singapore is at the forefront of the development of bunkering infrastructure and will play a major role in ammonia fuel trade.

FIGURE 22

Map showing the scope of balanced fuel and mix with fuel in the vicinity of nine major maritime ports.

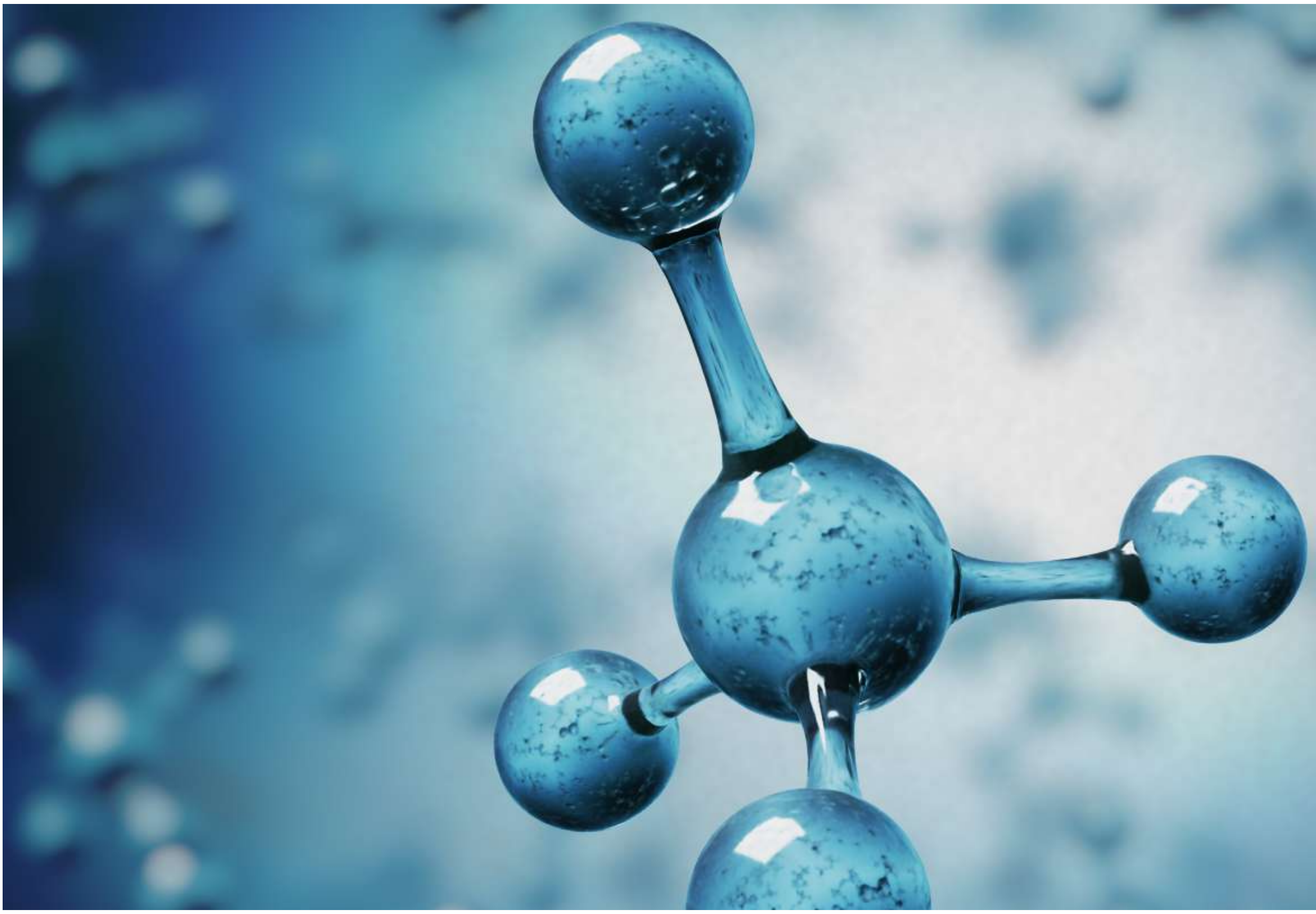


Nearest Port	Balanced export (MTPA)	Balanced Fuel (MTPA)	Balanced Mix with Fuel (MTPA)
Port Houston	12.0	0.4	8.1
Port Fremantle	7.8	2.5	4.2
Port Casablanca	4.7		2.2
Port Jeddah	4.6	0.1	3.9
Port Santos	4.0	0.2	3.5
Port Suez Canal	3.2	0.8	1.8
Port Rotterdam	2.0	0.7	1.2
Port Singapore	1.6		1.1
Port Shanghai	1.6	0.4	1.2
Total	**41.6**	**4.9**	**27.2**

On the competition between clean ammonia types

Until 2021, green ammonia production was very small with about 20 kt produced per year in Peru and no known production of blue ammonia (i.e. without enhanced oil recovery).[1] Since 2021, some smaller green ammonia plants have started producing. A number of factors determine the shares of green and 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 copious natural gas. This may be distributed in the country and region for consumption and might be the most efficient use of the gas. However, there are a number of countries where the population or established industries are unable 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 facilitates its transport. Conversion to these liquids involves energy losses of 10% for LNG, 30% for methanol, and 36% for ammonia. All three natural gas derivates are produced globally at large scale – 372 MTPA LNG,[31] 100 MTPA methanol,[32] and 186 MTPA ammonia. The choice of derivate is likely to depend on market conditions for the derivates and their end uses. Ammonia is the only one of the three that comes without carbon. With LNG and methanol, the CO_2 has to be removed by the consumer, whereas for ammonia the CO_2 can be captured and stored 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 more likely to choose blue ammonia for export than to establish 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 – from existing SMR plants retrofitted with CCS and greenfield developments with built-in carbon capture – for using natural gas resources in the USA, which is also supported by the US Government.



For green ammonia, there are several regions globally that have large potential for wind and/or solar power, but where local demand for renewable electricity is limited due, for example, to low population density. There is also a limit to how much intermittent renewable power can be used in a grid without significant storage possibilities. This potential may be exploited with green ammonia, which is in principle scalable[1] because it requires only renewable electricity, water (including sea water), and air. Hence, if regions are found with good solar or wind power potential, and 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 are not a barrier, but good, stable framework conditions are important to realize the projects.

Production costs are another major factor. If costs for green or blue ammonia are too high to compete in the international market, they will not be produced even though the presence of resources point to a project being the right choice. The competition will be between green ammonia, blue ammonia, and the alternatives in various markets (e.g. maritime fuel, fertilizers, power production and hydrogen production). This will certainly also depend on market regulations and GHG taxes, and probably and increasingly on stakeholder expectations. For example, natural gas-derived ammonia in 2019 was similarly priced per energy unit as low-sulfur fuel oil (LSFO), but without having any GHG benefits. Green ammonia has significant GHG benefits but costs at least twice as much as LFSO[1] and will see limited uptake before sufficiently supportive regulations, GHG taxes, and/or stakeholder's expectations. This will be alleviated by renewable electricity becoming cheaper[33] and by learning-curve effects reducing electrolyser 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 for the two reasons mentioned above.[15]

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, blue ammonia production is likely to be larger than the announced number of blue and green ammonia projects in the pipeline indicates.

One of the pending questions for green ammonia production is on the source of CO_2 for fertilizers and on AdBlue, the control agent for NO_x emissions, 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 fertilizer compounds other than urea. The alternative would be to produce urea from CO_2 sources that can withstand the test of time for being carbon neutral.

Assuming global carbon prices of 50 USD/tCO_2 by 2030, the Arkwright 2021 market study predicts that blue ammonia will be cost competitive with grey ammonia between 2030 and 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 Australia, Middle East, North America, and South America offer good potential for development of new blue ammonia projects.

There will also be competition for green ammonia between markets such as 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 in turn will depend on taxes, regulation, and stakeholder requirements.

Conclusion

Before 2021, green ammonia production was exceedingly 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 with captured CO_2). Now, as per Q2 2023, the global green and blue ammonia production industry has announced 161 clean ammonia projects with a total production capacity of 244 MTPA. From the steady stream of project announcements in 2021–2023, it is expected that significant 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.

They are distributed globally but with a large share of green ammonia projects in Australia and the majority of blue ammonia projects in the USA. Most are in very early stages of development with inherently large uncertainty over their implementation. Nevertheless, 79% of the production capacity is announced to be available in 2030. Only 12–16% of the announced production capacity is of the blue variety.

Several factors determine the relative shares of green and blue ammonia in a country. An important one is access to resources – for example, natural gas and renewable electricity potential – and their consumption in the local market. Excess natural gas can be exported as the liquids LNG, methanol, or ammonia. Ammonia is the only one of the three that comes without carbon. For LNG and methanol, CO_2 must be removed by the consumer, whereas for ammonia the CO_2 can be removed centrally by the producer of blue ammonia if permanent CO_2 storage sites are available. For green ammonia, several regions globally have large potential for wind and/or solar power, where local demand for renewable electricity is limited and with good framework conditions, such that this potential can be exploited for the export of green ammonia. Green ammonia is in principle scalable, since it only requires 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 market regulations, GHG taxes, and increasingly (probably) on stakeholder expectations. Even though there will be 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 current ammonia production, which is mostly consumed 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 14 clean ammonia plants aim for production capacities larger than the largest ammonia facility today.

Today's ammonia market is dominated by the fertilizer market (80% of the ammonia demand), but clean ammonia aims at new applications such as shipping fuel, power plants, and as a hydrogen carrier. Most of the producers aim to sell ammonia to multiple sectors, with only 26% production capacity committing to a single end use. Many possible offtakers will contribute to drive up clean ammonia production.

Likelihoods of implementation were evaluated in this report, and this leads to less final ammonia output in 2030 than published details of announced projects might otherwise suggest. Of the announced 244 MTPA, little over a sixth (43 MTPA) is estimated to be available in the balanced scenario. From this, about 14 MTPA is projected to be blue. Green ammonia dedicated to shipping may be in the range of 4–7 MTPA, and 21–31 MTPA will potentially be available across fertilizers, energy, and fuel markets.

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

The demand for ammonia as a maritime fuel in 2030 is estimated to be 2.3 MTPA, increasing rapidly to 62 MTPA in 2040 and 245 MTPA in 2050. The maritime sector will use only green and blue ammonia.

The total amount of green and blue ammonia available in the balanced scenario is estimated to be more than an order of magnitude higher than the anticipated demand from the maritime sector in 2030. If the announced ammonia production goes where initially stated, there will be sufficient availability for the maritime sector; comparing the supply of 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 ammonia demand in the sector becomes possible. The ammonia producers appear to be hedging, and the main approach is a mixture of offtakers. The risks are clearly reduced when, instead of only maritime fuel, an investor has three to four distinct end uses in an open market. However, this may also lead to competition from other offtakers if they have greater purchasing power. From our investigation, green ammonia production growth does not appear to be limited by electrolyser production capacity, as the estimated 61 GW by 2030 is likely to be achievable. However, the demand growth after 2030 is steep and accelerating and the supply-demand balance may change rapidly 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.

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Appendix

#	Project name	Country	Onstream	MTPA
1	Minbos Resources Green Ammonia Nitrogen Fertilizer Facility	AGO	2026	0.08
2	The Barra do Dande	AGO	2024	0.28
3	AREH	AUS	2028	9.90
4	Cape Hardy Ammonia	AUS	2033	5.00
5	Clean Energy Precinct – 1	AUS	2028	0.66
6	Dyno Nobel Renewable Hydrogen	AUS	2026	0.12
7	Eyre Peninsula Gateway – 1	AUS	2026	0.04
8	Eyre Peninsula Gateway – 2	AUS	2030	0.83
9	Fortescue Green Hydrogen and Ammonia Plant	AUS	2028	0.25
10	GERI – 1	AUS	2025	0.02
11	GERI – 2	AUS	2031	1.00
12	Gibson Island Green Ammonia	AUS	2025	0.40
13	H2-hub Gladstone – 1	AUS	2025	0.11
14	H2-hub Gladstone – 2-3	AUS	2027	1.50
15	H2Kwinana	AUS	2025	0.04
16	H2Perth, 1 – blue	AUS	2024	0.42
17	H2Perth, 1 – green	AUS	2024	0.18
18	H2Perth, 2 – green	AUS	2030	2.00
19	H2TAS – 1	AUS	2025	0.20
20	H2TAS – 2	AUS	2025	0.80
21	Hunter Energy Hub	AUS	2030	1.50
22	Hydrogen Portland	AUS	2030	0.01
23	HyEnergy – 1	AUS	2030	1.55
24	HyEnergy – 2	AUS	2030	1.55
25	Keppel Gladstone	AUS	2028	0.85
26	Midwest Green Ammonia	AUS	2027	1.00
27	Murchison PtX	AUS	2028	2.00
28	Origin Green Hydrogen and Ammonia Plant	AUS	2027	0.42
29	QLD Bundaberg	AUS	2023	0.03
30	Queensland Nitrates Renewable Hydrogen and Ammonia	AUS	2024	0.02
31	ScaleH2	AUS	2027	0.80
32	The Port Pirie Green Hydrogen	AUS	2028	0.21
33	VIC Port Anthony	AUS	2023	0.08
34	Western Green Energy Hub	AUS	2045	20.00
35	Yuri – 1	AUS	2024	0.00
36	Yuri – 2	AUS	2026	0.11
37	Yuri – 3	AUS	2028	0.35
38	Yuri – 4	AUS	2030	0.18
39	Oruro Plant	BOL	2025	0.50
40	Ammonia in Pecém Complex	BRA	2024	2.20
41	Porto do Acu Fortescue Ammonia	BRA	2028	0.25
42	Unigel Brazil – 1	BRA	2027	0.06
43	Unigel Brazil – 2	BRA	2029	0.18
44	Argentia Renewables – 1	CAN	2025	0.09
45	Argentia Renewables – 2	CAN	2027	0.53
46	Blue Ammonia & Blue Methanol	CAN	2026	1.00
47	Courant	CAN	2026	0.17
48	Hydrogen & Ammonia Export	CAN	2028	2.00
49	Nujio'qonik – 1	CAN	2026	0.10
50	AES Green Ammonia	CHL	2028	0.60
51	Gente Grande	CHL	2026	1.30
52	Green Pegasus	CHL	2027	0.46
53	H2 Magallanes	CHL	2027	4.40
54	HNH	CHL	2026	1.00
55	HyEx – 1	CHL	2024	0.02
56	HyEx – 2	CHL	2030	0.68
57	Magallanes Wind to Ammonia	CHL	2027	1.00
58	Baotou Renewable Ammonia	CHN	2025	0.39
59	Chifeng Ammonia – 0	CHN	2023	0.02
60	Chifeng Ammonia – 1	CHN	2024	0.30
61	Chifeng Ammonia – 2	CHN	2026	0.30
62	Chifeng Ammonia – 3	CHN	2029	0.90
63	Da´an Project	CHN	2026	0.18
64	Green Hydrogen Ammonia Alcohol Integration – 1	CHN	2026	0.20
65	Green Hydrogen Ammonia Alcohol Integration – 2	CHN	2027	0.40
66	Inner Mongolia Ammonia	CHN	2025	0.05

#	Project name	Country	Onstream	MTPA
67	Tongliao Joint Venture	CHN	2025	0.30
68	Barranquilla Offshore Wind Farm to Ammonia	COL	2026	0.26
69	Aquamarine	DEU	2024	0.10
70	HyTechHafen – 1	DEU	2027	0.08
71	HyTechHafen – 2	DEU	2030	0.68
72	Esbjerg Green Ammonia Plant	DNK	2030	0.75
73	REDDAP	DNK	2023	0.01
74	Alfanar Green Ammonia – 1	EGY	2025	0.25
75	Alfanar Green Ammonia – 2	EGY	2032	0.25
76	AMEA – 1	EGY	2030	0.40
77	AMEA – 2	EGY	2029	0.40
78	EDF Renewable – 1	EGY	2026	0.14
79	EDF Renewable – 2	EGY	2029	0.21
80	Egypt Green Ammonia (Two Plants)	EGY	2024	0.09
81	Green Ammonia in SCZone	EGY	2030	1.00
82	Masdar – 2	EGY	2030	2.30
83	MEP	EGY	2029	0.13
84	Ra	EGY	2028	1.60
85	ReNew Power – 1	EGY	2025	0.10
86	ReNew Power – 2	EGY	2029	0.90
87	Suez Canal Ammonia – 1 and 2	EGY	2026	0.79
88	Total – 1	EGY	2029	0.30
89	Total – 2	EGY	2030	1.50
90	Catalina – 1	ESP	2025	0.20
91	Fertiberia/Iberdrola – Palos de la Frontera – 1	ESP	2023	0.17
92	Fertiberia/Iberdrola – Palos de la Frontera – 2	ESP	2027	0.28
93	Fertiberia/Iberdrola – Puertollano – 1	ESP	2022	0.02
94	Fertiberia/Iberdrola – Puertollano – 2	ESP	2027	0.16
95	HyDeal España	ESP	2025	0.17
96	San Roque Ammonia	ESP	2027	0.75
97	Flexens Kokkola	FIN	2027	0.20
98	Kokkola Renewable Ammonia	FIN	2028	0.76
99	Orkney Green Hydrogen/Ammonia Plant	GBR	2024	0.01
100	Greenland P2XFloater	GRL	2028	0.90
101	Green Hydrogen and Ammonia – 1	IDN	2029	0.22
102	Nuclear-Powered Ammonia	IDN	2028	1.00

#	Project name	Country	Onstream	MTPA
103	PT Panca Amara Utama Ammonia Plant	IDN	2028	0.70
104	Andhra Pradesh Project – 1	IND	2025	0.25
105	Andhra Pradesh Project – 2	IND	2027	0.75
106	Andhra Pradesh Renewable Ammonia	IND	2030	1.00
107	Gujarat Renewable Ammonia – 1 and 2	IND	2030	1.00
108	Himachal Pradesh	IND	2024	0.10
109	Odish Ammonia	IND	2028	1.10
110	Rajasthan Green Ammonia	IND	2030	1.00
111	Rajasthan Hydrogen & Ammonia Plant	IND	2021	0.00
112	Renewable Hydrogen & Ammonia	IND	2027	1.20
113	Thoothukundi Green Ammonia	IND	2027	1.10
114	EI-H2 – Aghada	IRL	2028	0.38
115	Green Fuel Iceland – 1	ISL	2023	0.02
116	Green Fuel Iceland – 2	ISL	2025	0.05
117	INPEX-led	JPN	2025	0.00
118	Hyrasia One	KAZ	2030	11.24
119	Green Ammonia and Fertilizer facilities – 1	KEN	2025	0.11
120	Green Ammonia and Fertilizer facilities – 2	KEN	2030	9.55
121	Kenya Green Ammonia Plant	KEN	2025	0.04
122	AMUN – 1	MAR	2028	2.00
123	AMUN – 2	MAR	2030	2.00
124	Green H2A Green Ammonia Pilot	MAR	2024	0.00
125	Green Investment plan for Renewable Ammonia	MAR	2027	1.00
126	HEVO Ammonia – 1	MAR	2022	0.00
127	HEVO Ammonia – 2	MAR	2023	0.02
128	HEVO Ammonia – 3	MAR	2024	0.04
129	HEVO Ammonia – 4	MAR	2025	0.06
130	HEVO Ammonia – 5	MAR	2026	0.06
131	Morocco Renewable Ammonia	MAR	2028	1.40
132	Tarfaya Renewable Ammonia – 1	MAR	2026	0.20
133	Tarfaya Renewable Ammonia – 2	MAR	2027	0.80
134	Tarfaya Renewable Ammonia – 3	MAR	2032	2.00
135	Tarafert – 1	MEX	2026	1.00

#	Project name	Country	Onstream	MTPA
136	Tarafert – 2	MEX	2026	0.50
137	AMAN – 1-2	MRT	2029	10.00
138	Masdar Joint Venture – 1	MRT	2028	0.30
139	Masdar Joint Venture – 2-4	MRT	2040	7.20
140	H2biscus – 2	MYS	2029	0.60
141	H2biscus – 1	MYS	2029	0.63
142	Daures Green Hydrogen Vilage	NAM	2032	0.35
143	H2-Pilot Plant / Refueling Station – 1	NAM	2024	0.00
144	Hyphen Hydrogen Energy – 1	NAM	2026	0.70
145	Hyphen Hydrogen Energy – 2	NAM	2030	1.00
146	NH3 FPSO	NLD	2028	0.08
147	Sluiskil	NLD	2025	0.08
148	Barents Blue	NOR	2025	1.00
149	Berlevåg Green Ammonia Value Chain	NOR	2025	0.10
150	Finnmark P2XFloater	NOR	2029	0.23
151	Green Ammonia Production in Finnmark	NOR	2026	0.08
152	Herøya Green Ammonia (HEGRA) – Energy	NOR	2029	0.40
153	Herøya Green Ammonia (HEGRA) – Fertilizer	NOR	2029	0.02
154	North Ammonia Arendal	NOR	2027	0.10
155	Project Sauda Iverson Efuels	NOR	2026	0.21
156	Slagen Terminal	NOR	2029	0.10
157	Duqm Export Mega	OMN	2030	1.20
158	Green Energy Oman (GEO)	OMN	2038	10.00
159	H2Oman	OMN	2030	1.00
160	HYPORT® Duqm Green Ammonia – 1	OMN	2026	0.38
161	HYPORT® Duqm Green Ammonia – 2	OMN	2028	0.65
162	Oman Green Ammonia – 1	OMN	2027	0.10
163	Oman Green Ammonia – 2	OMN	2030	1.20
164	SalalaH2	OMN	2028	0.35
165	Industrial Cachimayo	PER	1975	0.02
166	Papua New Guinea Projects Portfolio	PNG	2030	11.50
167	MadoquaPower2X – 1	PRT	2027	0.38
168	MadoquaPower2X – 2	PRT	2030	0.38
169	Alto Parana Plant	PRY	2026	0.22
170	ATOME – 1	PRY	2025	0.23
171	ATOME – 2	PRY	2027	0.14

#	Project name	Country	Onstream	MTPA
172	Ammonia-7	QAT	2026	1.20
173	HELIOS (NEOM)	SAU	2025	1.20
174	SAREH – 1	SAU	2030	15.00
175	SAREH – 2	SAU	2035	5.00
176	Green Wolverine	SWE	2026	0.52
177	NewGen	TTO	2024	0.15
178	Green Ammonia in Abu Dhabi – 1	UAE	2026	0.10
179	Green Ammonia in Abu Dhabi – 2	UAE	2028	0.50
180	Khalifa Industrial Zone Abu Dhabi (KIZAD) – 1	UAE	2024	0.04
181	Khalifa Industrial Zone Abu Dhabi (KIZAD) – 2	UAE	2026	0.16
182	The TAQA-Abu Dhabi Ports	UAE	2026	1.20
183	Adams Fork Energy Clean Ammonia	USA	2027	2.16
184	Ascension Clean Energy (ACE)	USA	2027	7.20
185	Baytown Blue Ammonia	USA	2028	3.40
186	Beaumont Blue Ammonia Plant – 1	USA	2025	1.10
187	Beaumont Blue Ammonia Plant – 2	USA	2030	1.10
188	Donaldsonville Blue Ammonia	USA	2027	1.00
189	Donaldsonville Green Ammonia	USA	2023	0.02
190	Enbridge Ingleside Energy Center	USA	2028	1.30
191	Garner Green Ammonia Plant	USA	2026	0.08
192	Geismar Clean Ammonia Plant	USA	2027	1.20
193	Green Ammonia Plant – 1	USA	2025	0.10
194	Green Ammonia Plant – 2	USA	2029	0.60
195	Green Fuels	USA	2028	1.05
196	Olive Creek 2	USA	2029	0.28
197	Port of Corpus Christi Mixed Ammonia	USA	2030	10.00
198	Port of Victoria Ammonia	USA	2025	0.30
199	St. Charles Clean Fuels – 1-2	USA	2027	2.50
200	Verdigris Complex Ammonia	USA	2027	0.10
201	Wabash CarbonSAFE	USA	2022	0.57
202	Waggaman Ammonia Plant	USA	2026	0.80
203	Yazoo City Blue Ammonia	USA	2024	0.25
204	Uzbekistan Renewable Ammonia Pilot	UZB	2024	0.02
205	Uzbekistan Green Ammonia	UZB	2028	0.50
206	Hive Hydrogen	ZAF	2025	0.80

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DNV AS
NO-1322 Høvik
Norway
Phone +47 67 57 99 00
www.dnv.com

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