International
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Turning Hydrogen Demand Into Reality: Which Sectors Come First?

Identifying hydrogen demand sectors, demand locations and the demand-pull timeline

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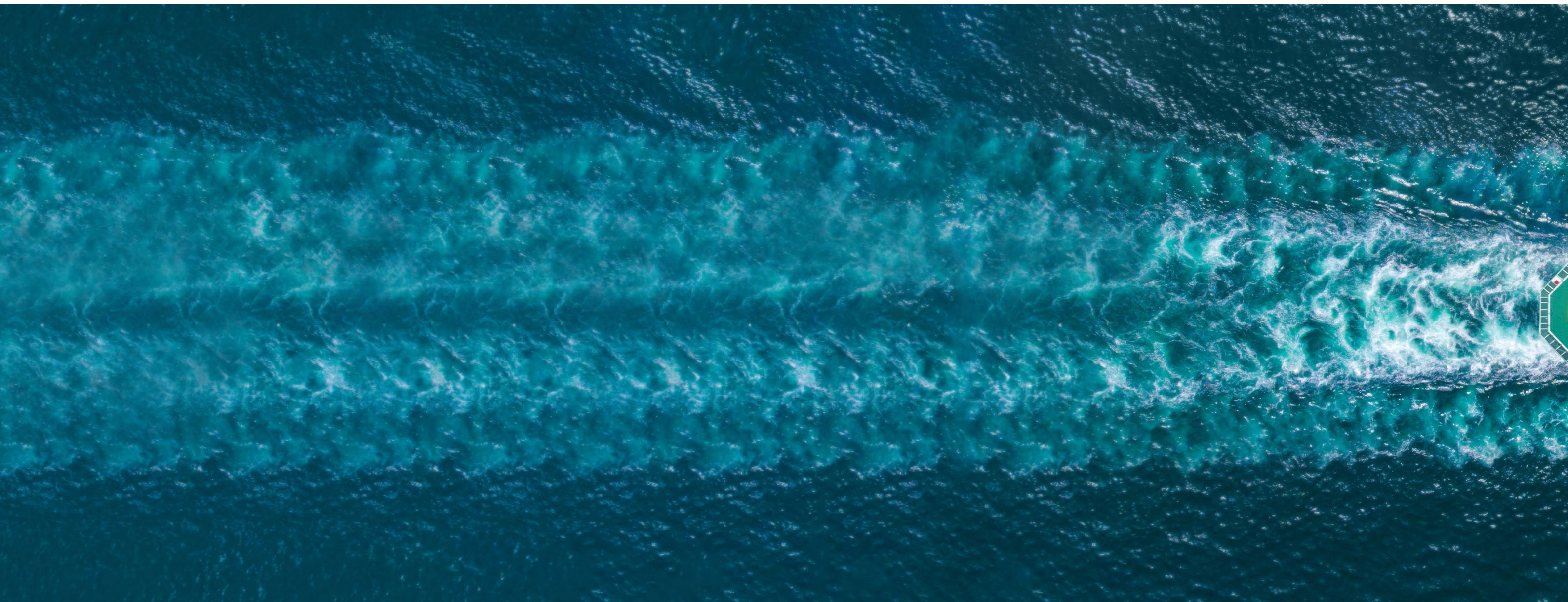


Abbreviations

APS	Announced Pledges Scenario
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture use and storage
CO_2	Carbon dioxide
FC	Fuel cell
FCEV	Fuel cell electric vehicle
GDP	Gross domestic product
GW	Gigawatt
ICS	International Chamber of Shipping
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LHV	Lower heating value
LCOE	Levelised cost of electricity
LOHC	Liquid organic hydrogen carriers
LNG	Liquefied natural gas
Mt	Millions of tonnes
NG	Natural gas
OECD	Organisation for Economic Co-operation and Development
PtX	Power-to-X
PV	Photovoltaic
SPS	States Policies Scenario
TWh	Terawatt hour

Definitions

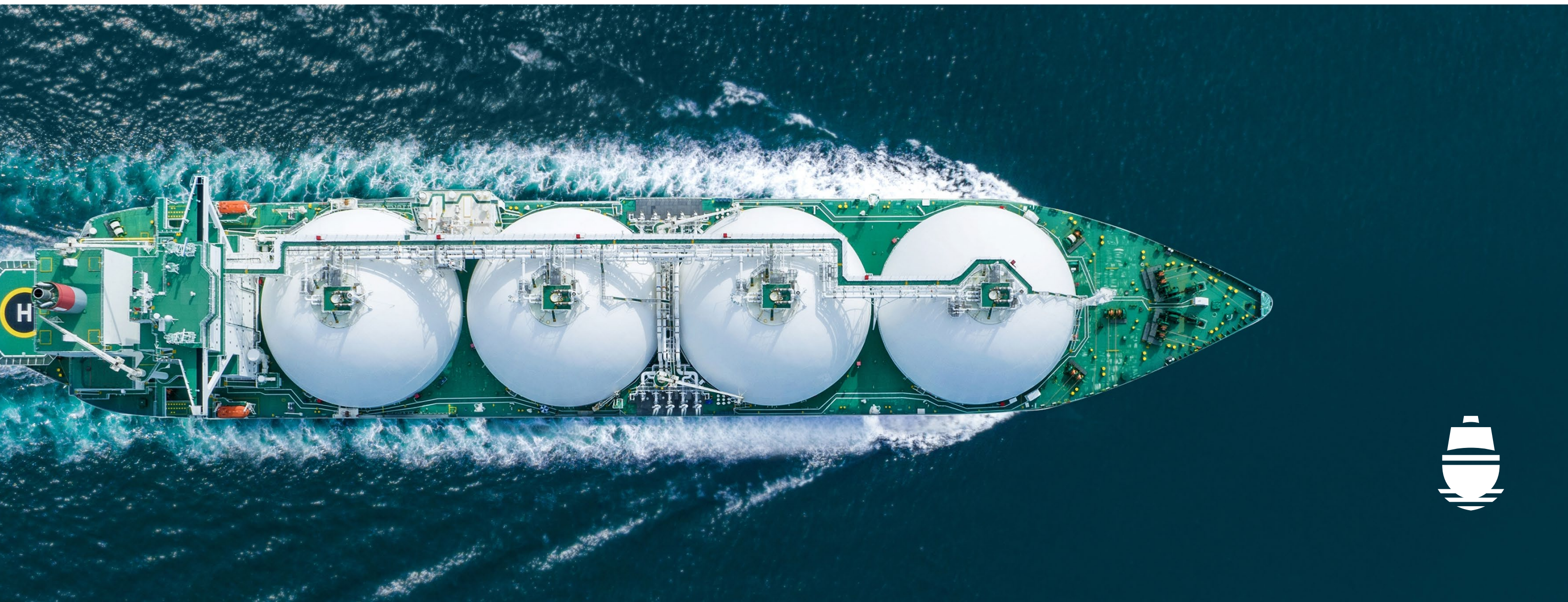
Blue hydrogen Produced from natural gas, with CO_2 emissions captured by carbon capture, utilisation and storage (CCUS).

Green hydrogen Produced from green electricity and water, with no CO_2 emissions.

Grey hydrogen Produced from natural gas, with CO_2 emissions to atmosphere.

Hydrogen trade In this publication hydrogen trade refers to trading hydrogen (liquefied, LOHC and others), but also includes methanol and ammonia trade, where the latter two fuels are produced from hydrogen.

Red hydrogen Produced from nuclear electricity and water, with no CO_2 emissions to atmosphere. Sometimes also called pink hydrogen.



Executive summary

Clean hydrogen has the potential to function as an energy carrier and feedstock to decarbonise multiple sectors (especially hard-to-abate sectors) and support global decarbonisation efforts by 2050 and beyond. The main driver for hydrogen demand in multiple sectors is the target of abatement of emissions. Making hydrogen from clean sources, its infrastructure and transportation available at scale in various regions would be key to secure a diversified supply and contribute to a global low-carbon energy security.

Currently, ¾ of hydrogen use is concentrated in refining operations and chemical processes (such as the production of ammonia, fertilizers and desulphuration of fuels), it is mainly produced on-site and based almost entirely on fossil fuels. Current methods of global hydrogen production led to more than 900Mt of CO_2 emissions in 2022[1], i.e. slightly higher than current maritime emissions of 706Mt in 2022[2]. For hydrogen increase to support decarbonisation, it would need to be developed from clean sources.

According to the International Energy Agency (IEA) hydrogen use is expected to remain almost stagnant and within current industrial use cases into 2030. **Hydrogen demand scenarios for 2050 see demand for hydrogen growing in multiple sectors, although the rate and timeline of uptake of hydrogen varies between sectors due to infrastructure and regulatory challenges and is likely to take place in stages.** Not all sectors will require the same degree of transformation and infrastructure to be built to incorporate hydrogen as a replacement for fossil fuels. To go beyond the existing hydrogen demand by existing sectors – predominantly refining and chemical processes – infrastructure and power access barriers need to be addressed for new sectors to begin uptake of hydrogen. Hydrogen demand could double by 2040, with most of the additional demand coming from industrial sectors – as it is easier to uptake – acting as a baseload, the rest coming from new industrial uses and a small share of the total (less than 5%) from transport sectors.

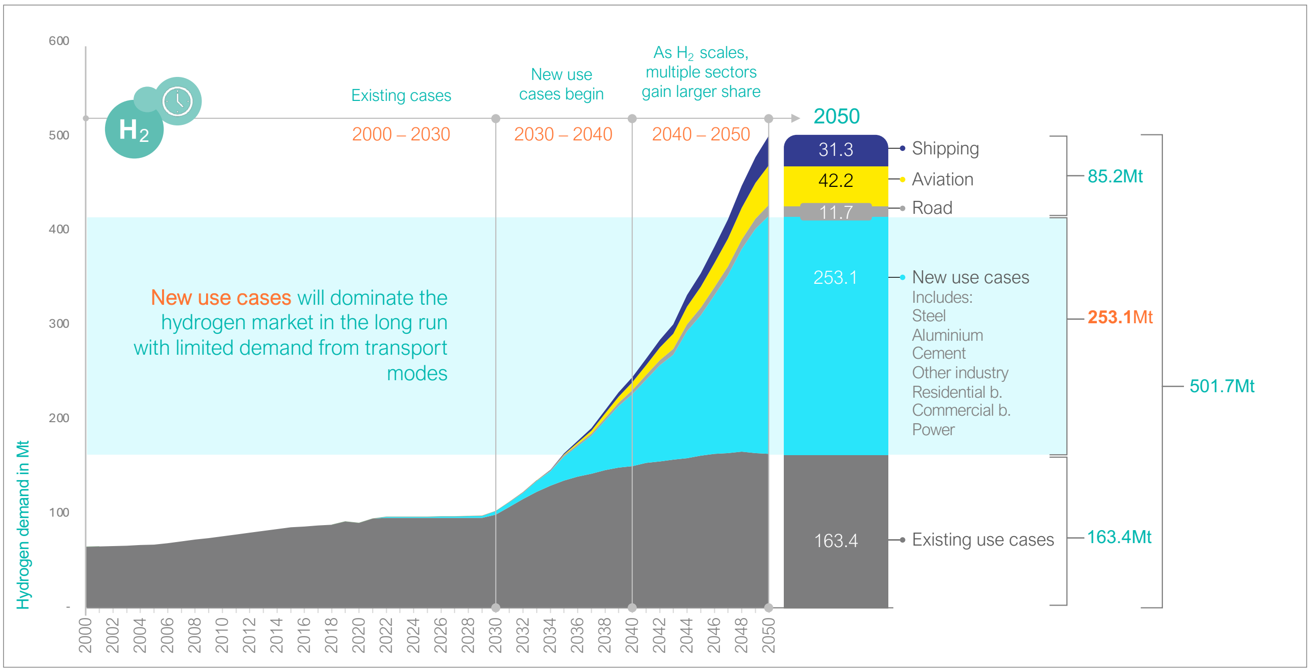
For global hydrogen demand to keep the net-zero by 2050 scenario within reach, demand would need to scale five times from current levels to reach nearly 500 million tonnes from 2030 to 2050. Additional multiple sectors and their regulatory conditions, infrastructure and ecosystems would need to be prepared to uptake hydrogen to scale up hydrogen use. Road, shipping and aviation sectors are expected to increase their share of total hydrogen demand from 2034 onwards, potentially reaching 17% of total hydrogen demand from all transport sectors by 2050. **However, the report finds that by 2050 industrial demand, and not transport, will dominate hydrogen demand.**

As the IEA sets out, the overall contribution of hydrogen in the energy sector could increase from 1.8% in 2022 to 5.7% in 2050 under the IEA Announced Pledges Scenario and reach 14% of global final energy demand by 2050 according to the International Renewable Energy Agency (IRENA). IRENA expects 90% of future hydrogen production to come from renewable sources, making electrification the pathway for production of hydrogen.

South Korea, Japan and the EU are the main markets to initially drive hydrogen demand. These two Asian economies have a projected combined hydrogen demand of 30 million tonnes per year by 2050 (a 10x increase for Japan and 177x for South Korea respectively from current levels), with more than half of hydrogen to come by imports. Europe has a target of 20 million tonnes per year by 2030 with half of that volume to come from imported sources. **The development of port infrastructure and readiness to facilitate the transportation of hydrogen and its derivatives through the establishment of clean energy marine hubs will be essential for the maritime sector to become an enabler of the hydrogen economy.**

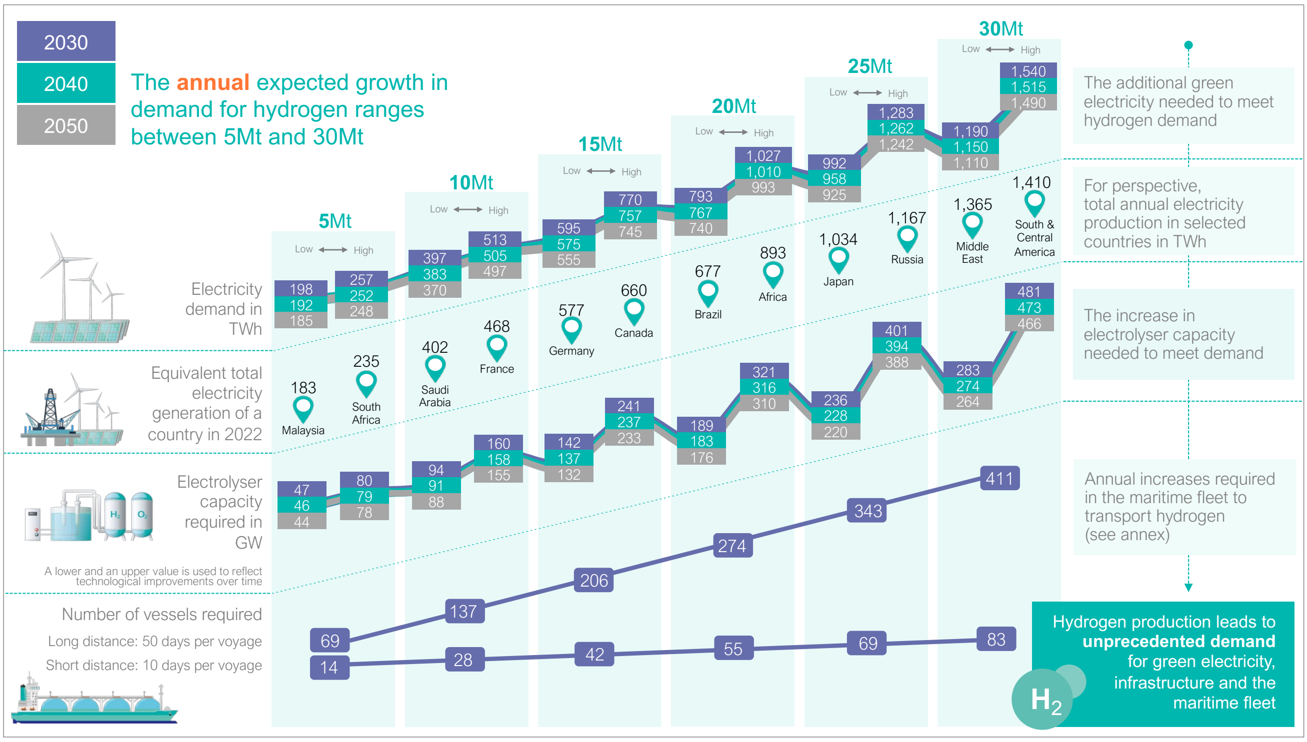
1 IEA, *Global Hydrogen Review 2023*, Paris (September 2023)

2 IEA, *International Shipping* (www.iea.org/energy-system/transport/international-shipping, retrieved 31 March 2024)



Source: Bloomberg NEF

There are 443 vessels currently transporting ammonia worldwide, but to meet the expected demand of 20 million tonnes of hydrogen of the EU , the fleet will need to increase by up to 300 vessels for the EU 2030 target, and **to meet 33 million tonnes of hydrogen the current shipping ammonia fleet would need to more than double and reach up to 500 additional ammonia vessels for Japan and Korea's demand alone [3].** Thirty million hydrogen tonnes would represent only 5% of the global demand expected in 2050 and to meet that demand the world would require the equivalent production of the total South and Central America electricity production (if all production comes from renewable sources).

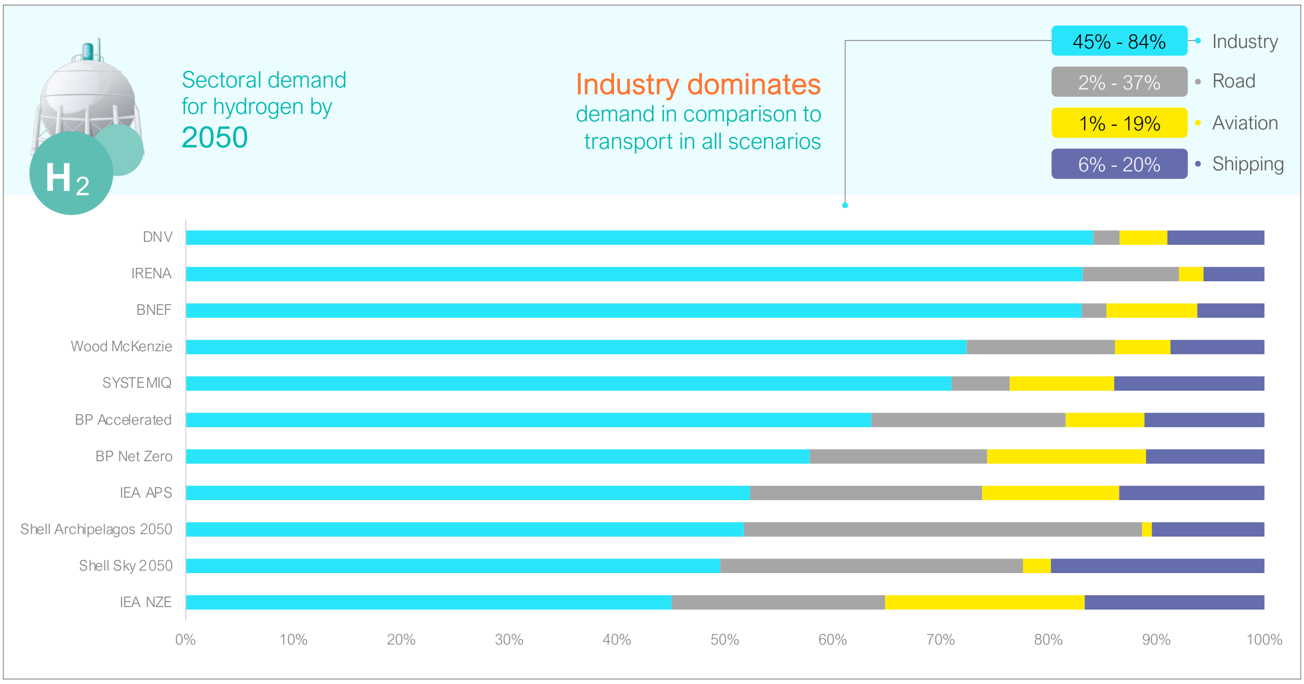


3 In the figure above it is shown a smaller number of vessels since in the figure hydrogen carriers are assumed in contrast to ammonia carriers. Hydrogen transported as ammonia would require a slightly larger number of vessels (considering current vessel sizes), please see appendix for details.

The electrification of hydrogen production and its derivatives is expected to grow. **To meet future hydrogen demand, the scale of electricity demand for green hydrogen production is unprecedented and leads to once-in-a-generation opportunities and challenges.** Renewable electricity is considered a cornerstone for achieving a climate-neutral energy system and hence an essential solution for transport and heating/cooling. However, this also leads to competition for green electricity that is also needed to produce green hydrogen. Since the power demand for hydrogen electrolysis is enormous (reaching up to 25,000 TWh in the most optimistic scenario), the global power system would need to grow more than the tripling of renewable energy commitment announced at COP28 to make a hydrogen economy a reality. Without this, the transition to a hydrogen economy will be stifled and will not deliver on the objectives of the EU and the leading Asian governments.

Governments and industry should increase efforts in innovation and R&D to bring down the cost for hydrogen to improve affordability. They should also explore new forms of clean generation to meet the global hydrogen demand at scale and in a form that facilitates alignment of production, transportation and distribution from production centres to demand centres. In essence, support the energy trilemma to improve affordability, security of supply and sustainability.

Furthermore, **current hydrogen growth demand scenarios show tremendous variability with respect to the share of hydrogen demand by sector,** fuelling uncertainty for businesses and adding barriers to potential investments. Expected hydrogen demand ranges from 90Mt to 600Mt by 2050, equivalent to 4% and 11% of total global energy supply by 2050. Efforts are needed to clarify that demand and reduce uncertainty to unlock further investment opportunities and offtake agreements. To unlock investment, governments should focus their attention on supporting demand side derisking over supply side subsidy. Without this, the transition to a hydrogen economy will be stifled and will not deliver on the decarbonisation objectives set by governments and industry.



Sources: IEA, BP, Shell, DNV, McKinsey, IRENA, Bloomberg NEF, Wood McKenzie, Hydrogen Council Kearney, SystemIQ, Deloitte

Acknowledgement

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1 Introduction

Hydrogen is often mentioned as being an inevitable part of achieving climate neutrality by the middle of this century[4]. With an estimated abatement potential of 7Gt CO_2 in 2050, hydrogen could contribute up to 20% of the total global abatement needed in that year[5]. Global demand for hydrogen is expected to grow at an average rate of 4–6% per year between 2020 and 2030, accelerating to 6–8% per year between 2030 and 2050.

The main bottleneck for the scaling up of a green hydrogen economy is the availability of local clean electricity. Renewable energy capacity might not be able to meet the domestic demand for both electrification and hydrogen production. Additionally, local green hydrogen production could face high costs. Hence, importers might rely on other climate-neutral hydrogen sources, such as e.g. blue or red hydrogen. Consequently, global trade in hydrogen may offer benefits for countries with import needs, with regard to both security of supply and affordability.

Countries might use hydrogen at a scale that exceeds their domestic production capabilities[6]. Consequently, it is possible that Japan, South Korea and Northwest Europe become net importers of hydrogen, while Australia and New Zealand, Chile, the Middle East and North Africa are likely to be net exporters. The potential importers are densely populated and highly industrialised regions with the prospect of high demand for hydrogen but limited space to meet this demand with local production. Their aggregated demand could stimulate global hydrogen trade, since hydrogen imports are part of their national hydrogen strategies[7]. Accordingly, new or adapted trade infrastructure is needed covering not only the maritime fleet, but also sea ports and pipeline systems, to enable delivery to the final consumers.

Global trade in hydrogen could enhance the availability of low-cost hydrogen. Combined with incentives, policies, international collaboration and the learning curve from innovation, this would increase the number of use cases for clean hydrogen. Current hydrogen scenarios for the coming decades depict the main use cases for hydrogen (and its derivatives) in the early stages being in energy-intensive industry (chemicals, fertiliser, steel and cement), followed by the transport sector (road, aviation) and finally the buildings sector. A recent analysis concludes that by 2050 about one quarter of total global hydrogen demand could be satisfied through international trade[8].

The maritime sector, in particular, could play an important role in a global hydrogen economy as an enabler of hydrogen demand growth by transporting the hydrogen-based fuels from supply centres to demand centres – and as a consumer to meet its own sectoral climate targets[9].

4 The HYPAT meta-analysis concluded that when reaching a threshold of 80% greenhouse gas reductions compared with 1990, the use of hydrogen becomes unavoidable.

5 Hydrogen Council, *Hydrogen for Net Zero: A critical cost-competitive energy vector*, November 2021.

6 WTO members notified 44 hydrogen-related policies between 2009 and 2021 and more than 30 countries around the globe have national strategies for low-carbon hydrogen. Source: WTO and IRENA (2023).

7 By 2030, EU states to import 10Mt, Japan 3Mt and South Korea 2Mt. The IEA states in its Global Hydrogen Review 2023 that annual production of low-emission hydrogen could reach 38Mt in 2030, if all announced projects are realised, i.e. the three markets account for 40% of this production capacity.

8 WTO and IRENA, *International trade and green hydrogen: Supporting the global transition to a low-carbon economy*, Geneva/Abu Dhabi, December 2023.

9 International Chamber of Shipping, *Fuelling the Fourth Propulsion Revolution*, May 2022

2 The global picture

2.1 Current hydrogen demand and the need for decarbonisation

Currently, hydrogen corresponds to 1.8% of global final energy consumption (mainly used as feedstock), only a very small fraction of it from renewables. Hydrogen is consumed in several industries, including oil refining and the production of ammonia, methanol and other chemicals. As a feedstock, hydrogen can be used in high-grade heat applications in the iron, steel, cement and chemical industries. Compared with the consumption of energy as fossil fuels, the energy content of hydrogen used as a feedstock is rather small.

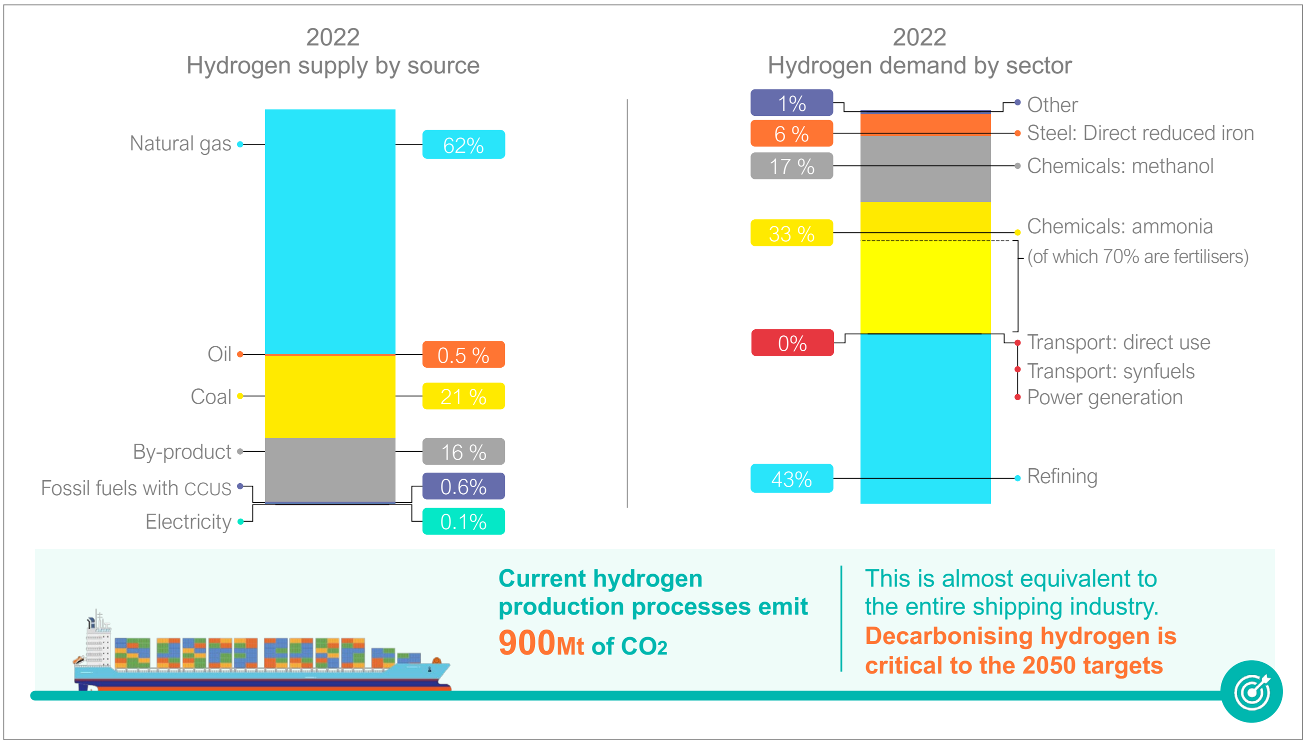

Figure 2.1: Structure of current hydrogen supply and demand

Source: IEA, Global Hydrogen Review 2023

> Replacing fossil-based hydrogen with climate-neutral hydrogen creates a baseload and indicates the first consuming sectors.

The energy content of the 95Mt of hydrogen consumption in 2022 is vastly outweighed by the scale of primary energy demand (Figure 2.2): the energy content of total oil consumption is 16 times greater, coal 15 times greater and natural gas 13 times greater. Producing all 95Mt of the hydrogen consumed in 2022 via electrolysis would need up to 5,700TWh of electricity – total global power production in 2022 was 29,165TWh. Optimistic scenarios assume hydrogen consumption of 600Mt by 2050, i.e. roughly six times higher than current. Hydrogen production based on electricity will also compete with electrification ambitions for transport and heating.

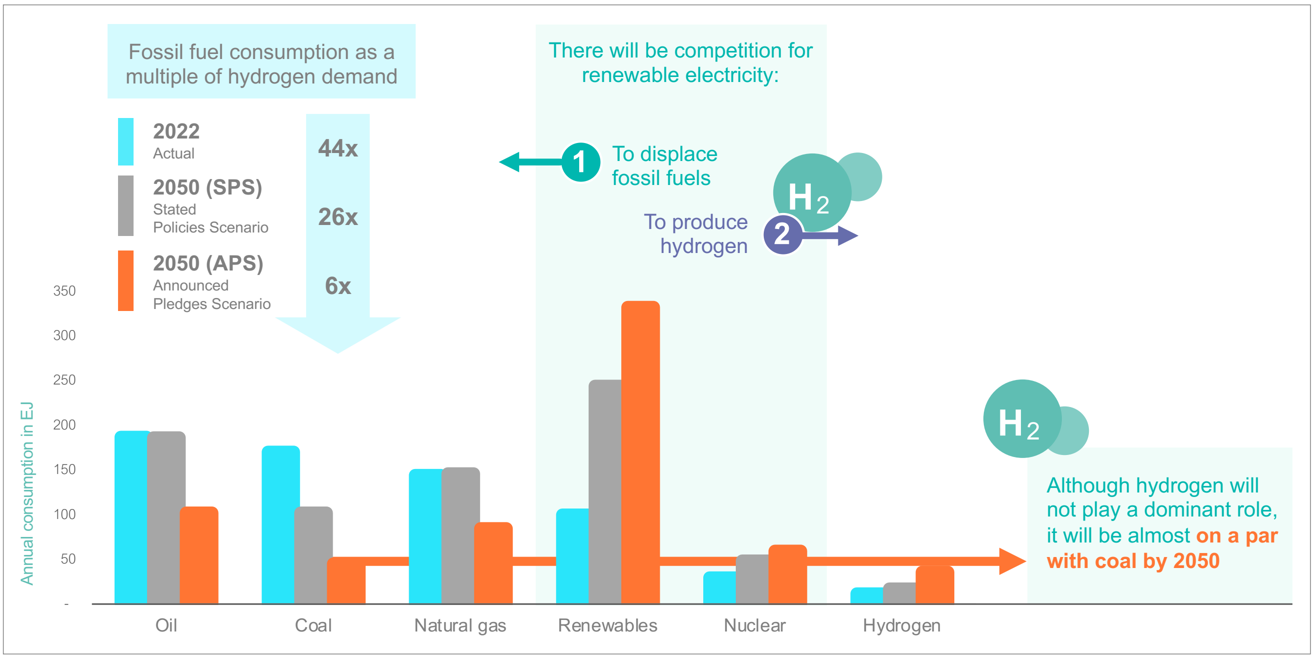

Figure 2.2: Primary fuel consumption versus current hydrogen demand

Notes: The States Policies Scenario (SPS) assumes business-as-usual; the Announced Pledges Scenario (APS) assumes that the countries will fulfil their climate pledges.
Source: IEA, World Energy Outlook 2023

Currently, hydrogen is mainly produced on-site and based almost entirely on fossil fuels. Small amounts of hydrogen and very small amounts of green hydrogen are distributed by pipeline. Global hydrogen production led to more than 900Mt of CO_2 emissions in 2022 [10], i.e. slightly higher than current maritime emissions of 706Mt in 2022 [11]. Consequently, hydrogen emissions must be addressed to reach carbon neutrality. Additionally, the recent price hikes in the global natural gas markets increased interest in alternative production methods for hydrogen and consequently also in merchant hydrogen, since a climate-neutral adaptation of on-site production is not always possible.

Comparing its energy content with primary fuels, the relative importance of hydrogen is set to grow. Strictly speaking, this comparison is not fully correct and should only serve as a means to set a benchmark, since hydrogen could mainly be used as feedstock – which is also the case for the fossil fuels, albeit to a lesser extent. This ratio occupies a broad range, as already indicated in Figure 2.2, where the business-as-usual scenario SPS shows a slight increase from 1.8% to 2.3%, whereas the climate-ambitious APS leads to 5.7%. Consequently, hydrogen becomes more relevant than today, but still not a dominant player in comparison with primary fuels. Nonetheless, in the hard-to-abate sectors, there might be limited alternatives to hydrogen as a means for decarbonisation.

10 IEA, *Global Hydrogen Review 2023*, Paris (September 2023)

11 IEA, *International Shipping* (www.iea.org/energy-system/transport/international-shipping, retrieved 31 March 2024)

2.2 Climate targets as fuel for hydrogen demand growth

The primary driver for future hydrogen demand is hydrogen's potential to reduce greenhouse gas emissions in different economic sectors and applications. Hydrogen can be used in industrial applications as feedstock or fuel – and replace fossil fuels. As feedstock, fossil fuels are often used for chemical processes; for example, in steel production, coal is used to remove oxygen from iron ore. As fuel, kerosene and diesel dominate aviation and heavy-duty road transport.

For all the above-mentioned and additional hydrogen applications, hydrogen or hydrogen-based products will be needed and in many cases imported, since local hydrogen production has limited potential in highly industrialised and densely populated areas.

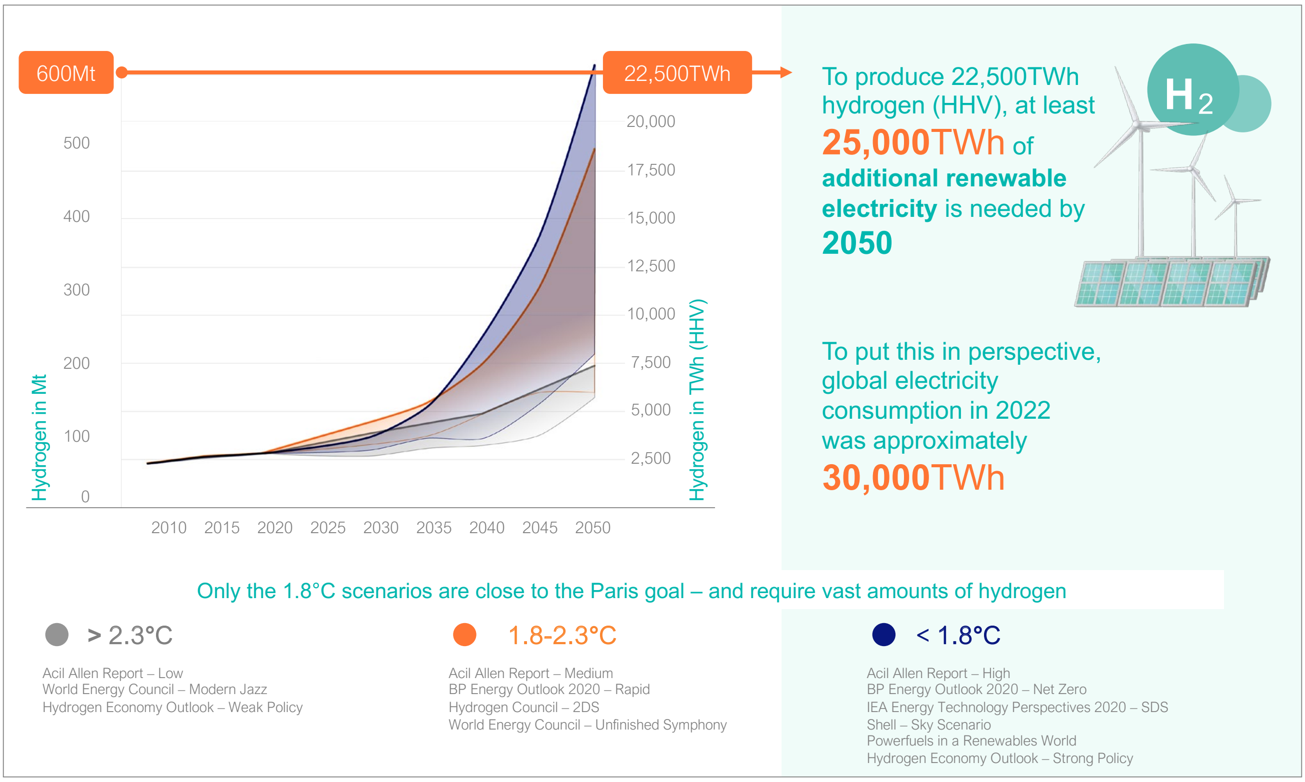

Figure 2.3: Hydrogen demand estimates by 2050
Source: World Energy Council, Hydrogen On The Horizon: Ready, Almost Set, Go?, September 2021

> The more ambitious the climate targets, the higher the hydrogen demand; some hard-to-abate sectors need hydrogen as feedstock on their way to climate-neutrality.

Future demand for hydrogen depends strongly on the level of ambition of climate targets, as can be seen in Figure 2.3: the lower the expected global temperature increase by 2050 in the scenarios, the higher the hydrogen demand. As previously mentioned, decarbonising current hydrogen production is a challenge given the level of demand for electricity connected with electrolytic hydrogen. Access to hydrogen that is produced without greenhouse gas emissions is key to meeting climate neutrality and the Paris goal of limiting global temperature rise[12].

12 According to the HYPAT meta-study, a scenario in which greenhouse gas reductions exceed 80% by 2050 would require between 4,000TWh and 15,000TWh of hydrogen and any synthesis products such as ammonia and methanol (figure corresponds to the LHV).

Again, hydrogen demand varies strongly between slightly higher than current demand and up to more than six times current demand. The hydrogen optimistic scenarios with demand of roughly 600Mt per year would necessitate electricity approximately equal to current global power production, if this volume of hydrogen were produced via electrolysis. And equally as important, these amounts of electricity would need to come from renewable sources for green hydrogen.

It should be noted that the requirement for climate neutrality establishes security of demand for exporting regions, since the decarbonisation of current hydrogen production will either lead to demand for hydrogen imports or products built on hydrogen, such as ammonia and fertilisers. The increasing demand to achieve deep decarbonisation will enhance the security of demand yet further.

2.3 Multiple sectors set to boost hydrogen demand, but which sector comes first?

Hydrogen production will be driven by multi-sectoral demand, albeit under a variable timeline, as some sectors are expected to drive early hydrogen demand (e.g. the steel and cement industry with highly ambitious targets) followed by heavy-duty road transport for those cases where electrification will not work as a solution. This is in line with the hydrogen ladder created by Michael Liebreich[13], where it states that for some processes (e.g. fertiliser production) there are no realistic alternatives to hydrogen. Consequently, an ongoing task in parallel with exploring new use cases is to meet existing demand with climate-neutral hydrogen. Consequently, most scenarios expect an increase in hydrogen consumption of between 20% and 40% between now and 2030, and a strong increase between 2030 and 2050 (by a factor of up to five). The main consuming regions by 2050 are identified by several studies as Northern America, China and the Middle East.

2.3.1 A high degree of uncertainty and a wide range for future hydrogen demand

In September 2022 an analysis known as "HYPAT" was published[14], which compared multiple scenarios describing the potential development of global hydrogen demand. The report was based on 43 scenarios from 25 studies ("focus scenarios") and the IPCC scenarios of the 6th Assessment Report ("IPCC scenarios"). It showed a wide range of volumes for hydrogen demand scenarios. However, it concluded that hydrogen is needed to reach climate neutrality. The wide range of hydrogen demand indicates a high level of uncertainty in the ramp-up of hydrogen markets, hindering investment in hydrogen production, transport and usage. Consequently, the compound annual growth rate between 2030 and 2050 ranged between 6% and 13%.

A comparison between scenarios needs to aggregate various use cases, since the scenarios consider different applications. In Figure 2.4 only the three transport modes (maritime, aviation and road) are considered – industrial and other hydrogen use cases are aggregated as others. However, this simplification already shows that in almost all scenarios industrial hydrogen consumption dominates transport by a factor of 2:1, and for maritime transport by a factor of at least 4:1.

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13 Michael Liebreich, *Hydrogen Ladder*, Version 5.0, October 2023

14 Riemer, M.; Zheng, L.; Pieton, N.; Eckstein, J.; Kunze, R.; Wietschel, M., *Future hydrogen demand: A cross-sectoral, multiregional meta-analysis,* HYPAT Working Paper 04/2022, Karlsruhe: Fraunhofer ISI (ed.), 2022

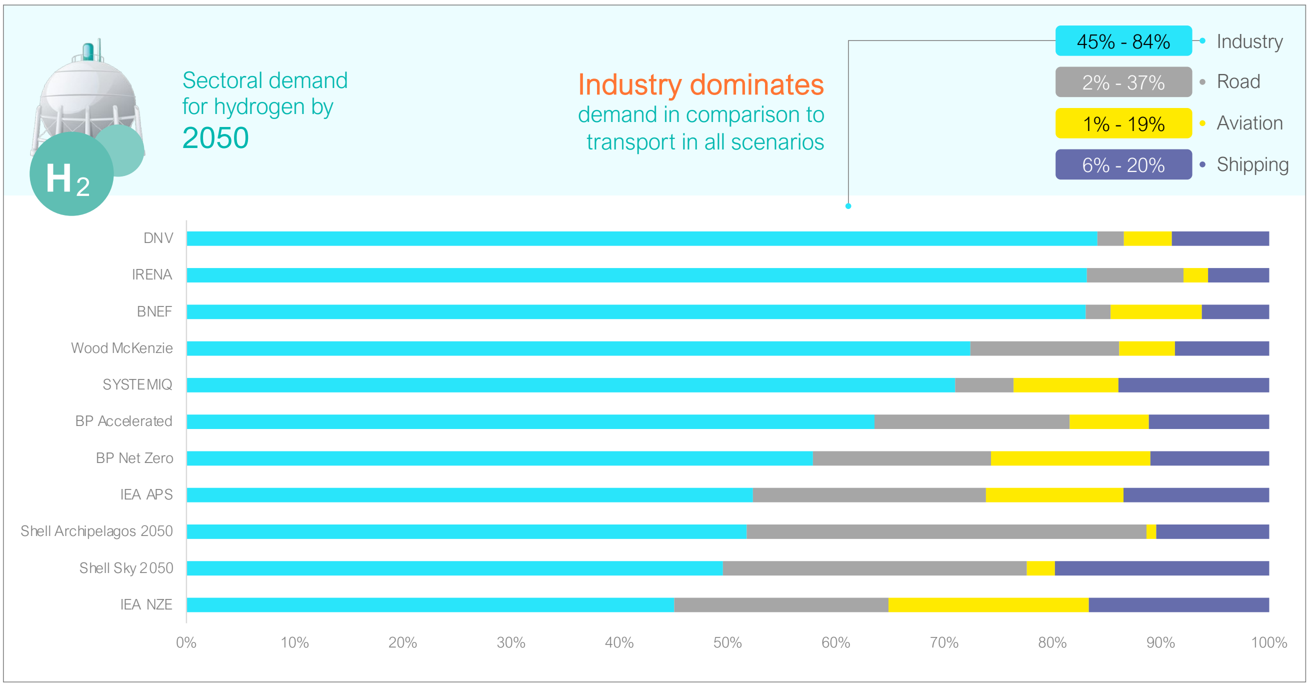


Figure 2.4: Sectoral demand for hydrogen and the variability of various scenarios

Sources: IEA, BP, Shell, DNV, McKinsey, IRENA, BloombergNEF, Wood McKenzie, Hydrogen Council, Kearney, SystemIQ, Deloitte

Industry dominates demand in comparison to transport by 2050.

2.3.2 Industry the dominant and priority hydrogen user of the coming decades

Industry is expected to maintain its position as the main consumer of hydrogen. Shifting existing consumption from the current fossil-based to climate-friendly production methods would be a relatively easy transformation, since industrial processes would mainly have to procure feedstock from another source, typically leaving the industrial facilities unchanged (e.g. fertiliser production based on ammonia). For the iron and steel sector, the processes and hence production facilities need a more significant change to shift from coal to hydrogen – and consequently the time for implementation is longer. For transport applications, not only would the engines and storage systems on board the aircraft, ship or truck need to be different, but the fuel logistics would also need to change.

Apart from these transformative considerations, economic factors associated with greenhouse gas abatement opportunities based on hydrogen are driving demand in these scenarios – and since most studies assume that the lowest hanging fruit is found in industrial applications, the hydrogen economy will be driven by industrial demand. In addition to this economic merit order, there is also an ecological merit order: 1TWh of green electricity leads to different amounts of abated greenhouse gases[15]. Typically, direct electrification is preferred to hydrogen use cases, mainly driven by the efficiency of the underlying processes. This again leads to a preference to use climate-neutral electricity for electromobility and heat pumps in comparison to maritime fuels.

15 Michael Liebreich, *Emission reduction using 1TWh of renewable energy*, 31 August 2023

Furthermore – as already mentioned with reference to the Liebreich ladder – for some applications there are no realistic alternatives. These applications will create what could be considered "baseload hydrogen demand", which could incentivise hydrogen exporters to build production and export facilities. Alternatives are available for maritime shipping and aviation (e.g. biofuels), which might perhaps not lead to a full decarbonisation, but will still be part of the solution and might be used earlier due to economic competitiveness.

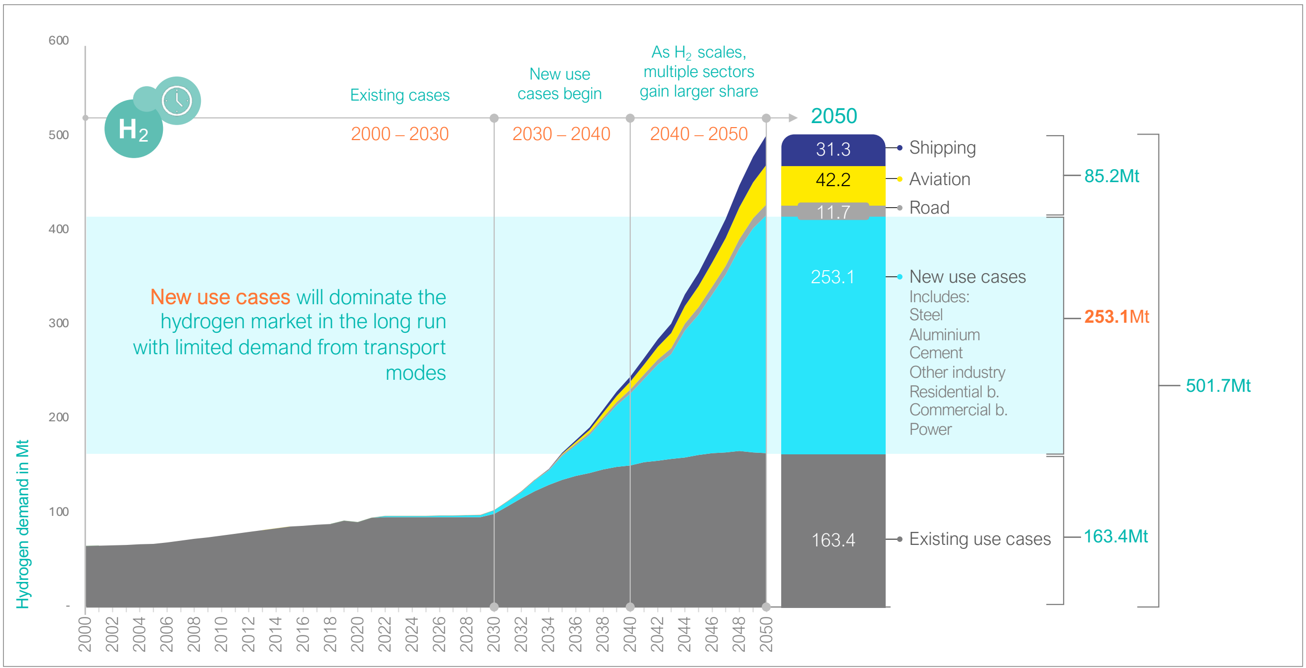


Figure 2.5: Sectoral development of hydrogen over time

Source: BloombergNEF

Existing demand is the primary target, followed by steel, power and other industrial use cases.

3 Unlocking barriers and scaling opportunity

3.1 Unprecedented electricity growth needed for expected green hydrogen demand

One of the main bottlenecks in meeting the expected levels of green hydrogen demand is the potential available electricity. Climate-friendly renewable electricity generation is already needed to replace existing conventional fossil-fired power plants. And the advancing electrification of transport and heating/cooling devices – which also replaces fossil fuels – is increasing the demand for electricity generation. Hydrogen production leads to an additional demand for electricity. Meeting this overall additional demand with, for example, wind and solar PV based generation can represent challenges in densely populated areas with less abundant renewable resources, such as Northwest Europe and Japan. Additionally, local renewable production might face higher costs than in other geographies. Hence, global trade in hydrogen offers benefits on both counts, offering adequate volumes for security of supply and affordability.

The expected growth in demand for hydrogen, as presented in the multi-scenario HYPAT analysis for 2050, ranges between 5Mt (LHV 167TWh) and 30Mt (LHV 1,000TWh) per year. Technological improvements could reduce electricity demand for hydrogen production (see Figure 3.1). The table shows for the expected range of electrolyser efficiency the necessary amount of green electricity to meet the anticipated yearly increase of hydrogen demand. To meet 5Mt per year, for example, this would correspond to the current annual electricity production of Malaysia in the best case of technology development, or up to the current annual electricity production of South Africa by 2050 in a less optimal case. These amounts would become smaller if other hydrogen sources (e.g. based on CCS or nuclear) were used. Whether the hydrogen is traded as liquefied hydrogen, ammonia or methanol does not have a significant impact on the amount of energy that is traded by a typical vessel. This allows a rough calculation of the annual increase in the maritime fleet to allow the trade to take place, assuming all hydrogen produced is traded by maritime transport[16]. Potential pipeline trade reduces the number of vessels accordingly.

16 There is an approximate 10% difference between hydrogen and ammonia carriers. With current vessel sizes considered for ammonia, the total number of vessels required would be higher than if hydrogen was transported.

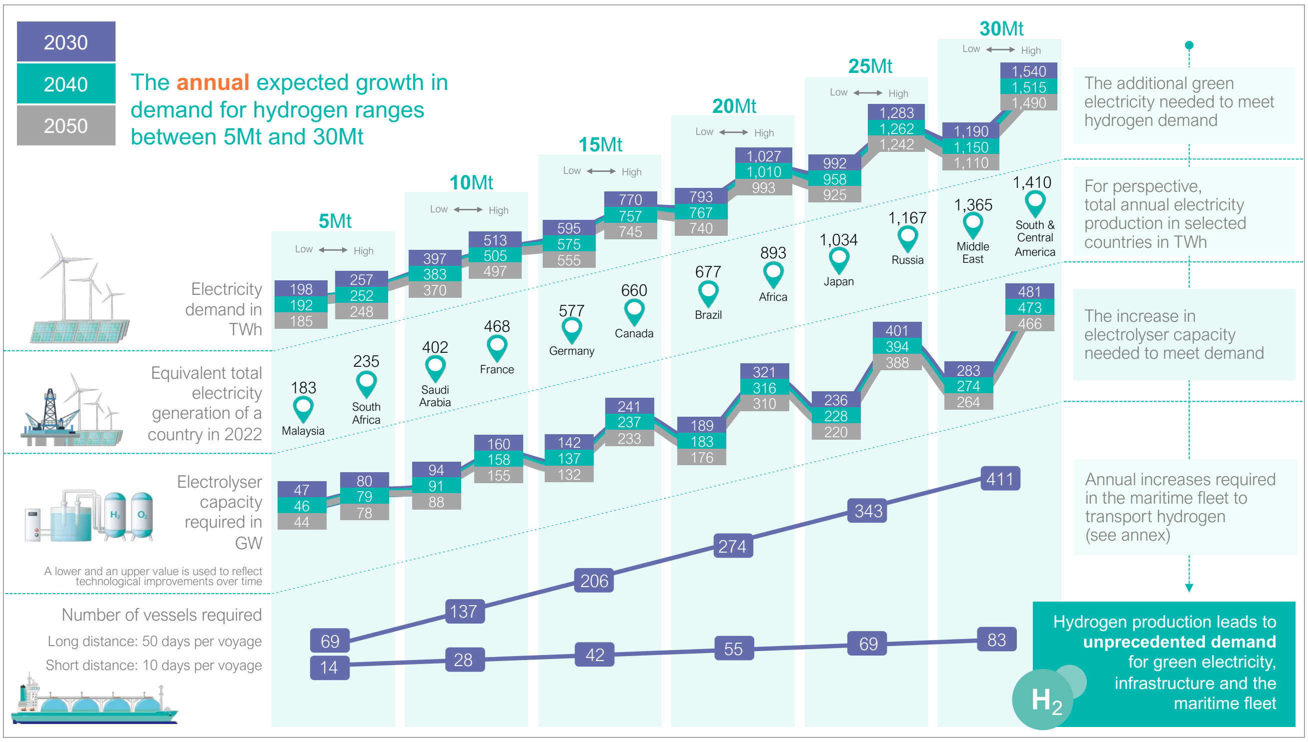


Figure 3.1: Unprecedented electricity demand from green hydrogen scaling up

Note: For electrolyser efficiency a lower and an upper value is used to reflect technological improvements over time.

Global renewable electricity generation shows annual growth of ca. 250TWh on average in the last ten years[17]. Consequently, building renewable electricity sources dedicated to replacing current hydrogen production only would lead to a construction period of roughly 15 years[18]. In a recent report IRENA provides a range of between 3,200 and 4,200 full load hours per year for onshore wind as worst and best cases[19]. Hence, globally between 850GW and 1,125GW of electrolyser capacity is needed. The IEA states that today's electrolyser manufacturing capacity is at nearly 8GW per year, but with industry announcements this would increase to 60GW per year[20]. With the latter value, it would take 20 years to build 1,200GW.

Hydrogen production will face strong competition for climate-neutral electricity from the need to replace existing greenhouse gas-emitting power production and from the conversion of transport and heating/cooling to electricity from fossil fuels. The latter two are inevitably grid-connected, whereas hydrogen may also be produced without grid connection and then imported. The COP28 pledge to triple renewable power capacity by 2030 and to use other non-zero technologies is mainly targeted at replacing existing unabated fossil-based generation to reduce greenhouse gas emissions. Additionally, some countries might prioritise the electrification of their economy vs hydrogen generation and exports.

17 Averaging over several years is reasonable for renewable production due to weather-related production fluctuations of e.g. wind, solar and hydro. Note that the swings might be substantial – for example, between 2020 and 2021 renewable production grew globally by 511TWh.

18 The simple calculation 3,600TWh/250TWh leads to an upper limit of the necessary time. Technology and process improvements might lead to a lower time requirement, but within the same order of magnitude.

19 IRENA, *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal,* Abu Dhabi, 2020

20 IEA, *Global Hydrogen Review 2022,* September 2022

3.2 Addressing the challenge of global infrastructure modifications and upgrades

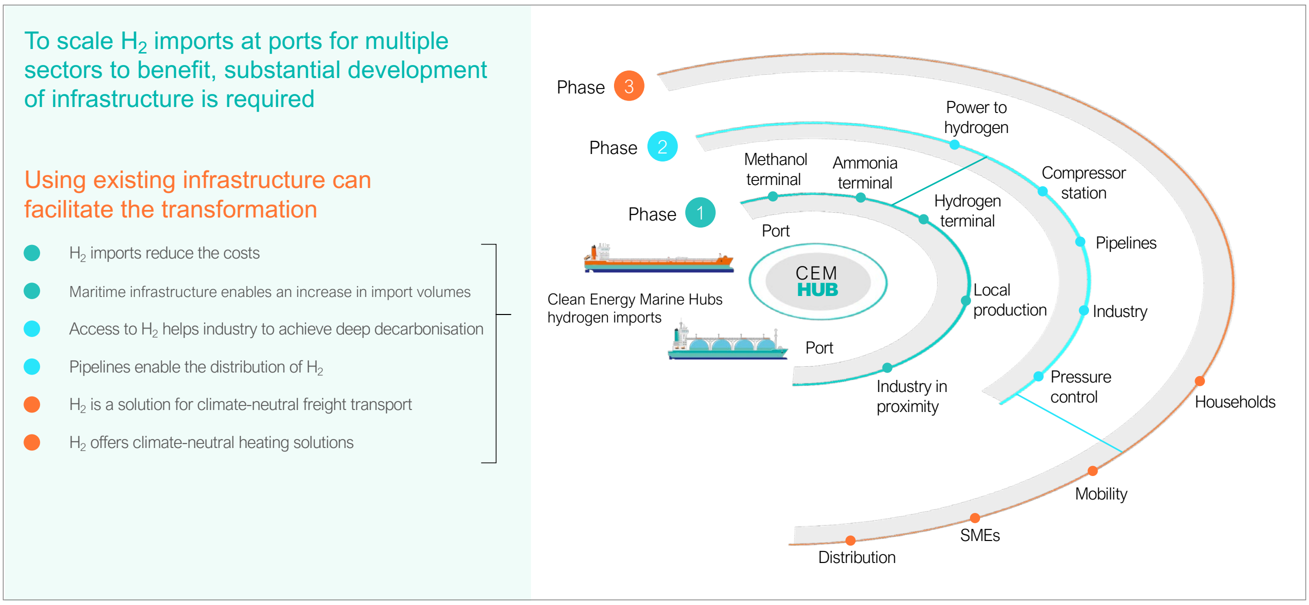


Figure 3.2: Clean energy marine hubs and the complex hydrogen infrastructure ecosystem

> Clean energy marine hubs can act as key elements of global hydrogen infrastructure; maritime infrastructure will help to scale up the supply of hydrogen for all relevant use cases.

A well-established supply chain for hydrogen and hydrogen-based fuels (e.g. ammonia and methanol) relies on infrastructure: transport and distribution infrastructure are needed for the physical delivery from producer to consumer. In part, existing infrastructure for natural gas might be used, supplementing new infrastructure that needs to be built. The design and implementation of such infrastructure is a major challenge since various actors and projects needs to be co-ordinated.

The hydrogen ecosystem is typically a system of various power generation units supplying electricity via a power grid to various electrolysers. These electrolysers feed the produced hydrogen either into a hydrogen pipeline system (or other transport system for hydrogen-derivatives), into hydrogen storage or to a consumer. A well-connected ecosystem with transnational hydrogen infrastructure offers not only a reliable and secure supply, but also the same fair market prices to all connected participants, thus giving the best possible price signal for investment in supply, transport and consumption assets. Markets and regulation will lead to a co-ordinated approach. The co-operation of all actors is needed, entailing private companies, public institutions and centres of innovation[21]. The ecosystem will not only be defined by physical components; the regulatory framework, master agreements for trading, technical design standards for the physical assets and so on will also define the hydrogen ecosystem. Ideally, solutions that are globally valid can be found so that technical standards, for example, are then the same in all countries, hence allowing a faster rollout.

Given the complexity of this target picture, it is highly likely that development nuclei (or "clean energy hubs") in proximity to maritime import infrastructure will become highly attractive to industrial hydrogen consumers, provided that the industrial sites in these areas allow for additional factories.

21 The World Bank, together with partners, launched in 2022 the Hydrogen for Development Partnership (H4D) to assist developing countries in accelerating low-carbon hydrogen deployment.

To address these infrastructural challenges, the Clean Energy Marine Hubs (CEM-Hubs) initiative was launched in July 2023 at the Clean Energy Ministerial (CEM). It is a cross-sectoral public–private platform intended to de-risk the investments needed to produce low- and zero-emission fuels that are to be transported or used by the maritime sector. The aim of the initiative is to become the high-level platform that can catalyse and support the alignment of effort across the energy–maritime value chain. Participants are the International Chamber of Shipping (ICS), the International Association of Ports and Harbors (IAPH) and the Clean Energy Ministerial (CEM), led by the governments of Brazil, Canada, Greece, Norway, Panama, Uruguay and the United Arab Emirates. The International Renewable Energy Agency (IRENA) and the Global Centre for Maritime Decarbonisation (GCMD) support the initiative. All these bodies are collaborating to unlock the production, transport and use of low-carbon fuels for the world at scale.

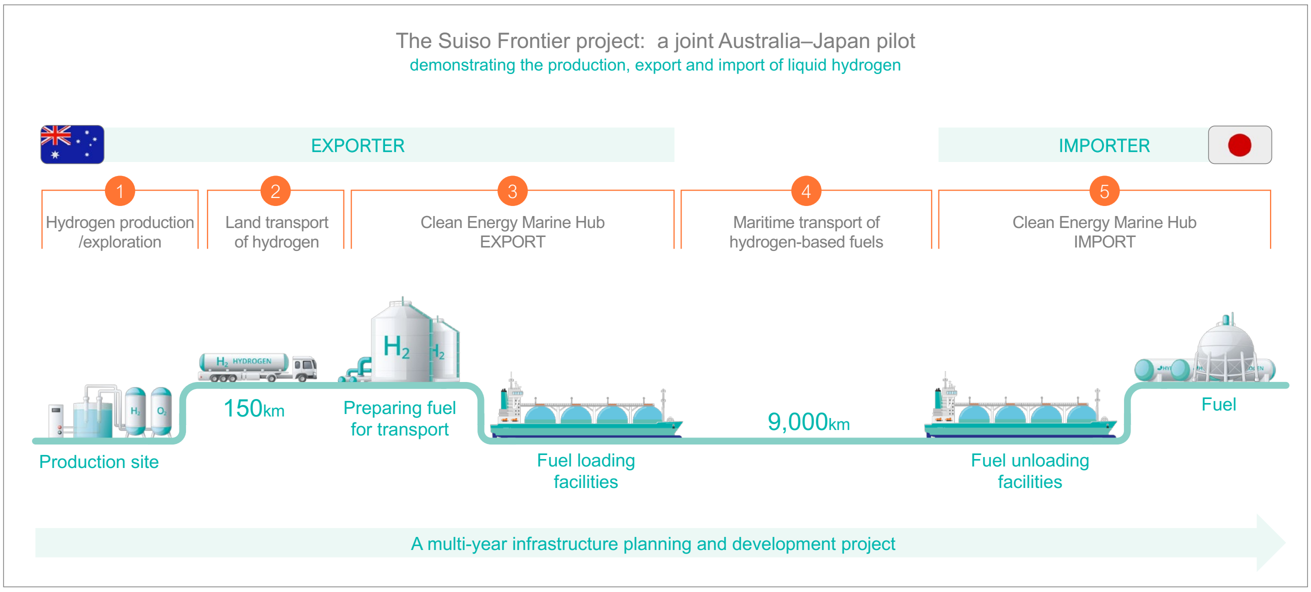


Figure 3.3: Example of maritime transport infrastructure

As an example of the potential to develop adequate maritime infrastructure for hydrogen (liquid) transport, a joint Australia–Japan pilot has been developed – the Suiso Frontier project – to demonstrate the production, export and import of liquid hydrogen from Australia to Japan. Infrastructure to transport hydrogen needs to be established and to be tested thoroughly to meet security. If sufficient land for industrial sites is available in proximity to the clean energy hubs, these hubs might develop into central cores of a hydrogen economy – extending to industrial use cases in all parts of the value chain. In consequence, this transformation may also affect the clean energy hubs, since there might be a shift from hydrogen trade to the trade of hydrogen products. Clean energy hubs will also play a crucial role with regard to the potential modification of the value chain.

3.3 Hydrogen demand pull and requirements to reach the target

The timeline to implement the target picture is determined mainly by the onshore infrastructure (power generation, electrolysers and pipelines), and to a lesser extent by the maritime import infrastructure. This is a consequence of the number of actors and range of equipment, and a complex interplay of regulated and liberal markets. In a study, the IEA (2021) expects substantial growth in hydrogen consumption in response to climate change ambitions. Whereas hydrogen produced on-site grows from 72.6Mt (2020) to 114.3Mt (2050), merchant hydrogen increases far more, from 14.5Mt (2020) to reach 413.9Mt (2050)[22]. The compound annual growth rate of hydrogen consumption between 2020 and 2050 is hence 6.2% (on-site 1.5% and merchant 11.8%). Hydrogen production is driven by multi-sector demand, since there are several use cases where hydrogen is by far the most promising way to achieve deep decarbonisation, e.g. steel and fertiliser production and some chemical processes. Hence, sufficient security of demand can be expected for exporters of hydrogen.

Despite the reasonable 6% annual growth rate for hydrogen consumption, the challenges for hydrogen supply are significant. Assuming that all hydrogen is supplied by electrolysis in 2050 leads to the need for annual growth in climate-neutral electricity production of 630TWh. Consequently, a higher pace of growth in renewable power production is needed – the highest increase in recent decades was between 2020 and 2021 with 511TWh. The requirement is hence not unrealistic, but one should keep in mind that renewable additions are needed not only for hydrogen production, but also to replace existing fossil generation.

Simultaneously, transport infrastructure needs to be built. Ports are in an interesting position, since industrial sites are often already in proximity and hence the development of hydrogen infrastructure is obvious. Initial steps in this direction are already being taken by Amsterdam and Rotterdam, Singapore and Houston, for example[23].

Pipelines have already been built as initial pilot projects, for example in Europe. These are a combination of new build and conversion of existing systems. This hydrogen backbone is essential to deliver hydrogen to existing industrial sites. These measures in hydrogen importing countries give a clear signal to hydrogen exporters that hydrogen demand is there, and consumers are preparing for a hydrogen economy.

The growth in hydrogen demand is expected to be triggered by replacing fossil-based hydrogen consumption in existing industrial sites, since this necessitates merely a change of the hydrogen feedstock – but not a change of operations. Additional use cases depend on the development of hydrogen-based technologies. The scaling of innovative hydrogen use cases would need additional amounts of hydrogen that are most likely to be imported in the case of existing sites where current production cannot easily be scaled up.

Policy support is key to unlock the path dependency in multiple sectors that could switch to hydrogen (even in hard-to-abate sectors). Currently, hydrogen supportive policies appear to focus predominantly on the supply side (e.g. tax breaks and other production incentives), and development of MOU agreements between countries and companies interested in hydrogen development. However, we are seeing that projects are stressed and do not reach a financial investment decision (FID) due to a lack of clarity in respect of the market and usage for the new hydrogen-based fuels. Augmenting demand-side support should be considered to boost demand creation and increase off-take agreements. Although hydrogen has the potential to be driven by multi-sectoral demand, each sector has its own regulatory and business ecosystem.

Targeting demand-side support could accelerate offtake agreements and uptake of hydrogen and its derivatives, particularly when costs are higher and learning curves and technological improvements have not yet developed, as it is typically the case in early-stage transformations. Priority will also need to be given to permitting and standards to facilitate rapid but safe adoption of these new technologies. There is much to be done still in establishing an enabling environment for hydrogen development and international coordination would be key in sharing best practices among governments interested in facilitating the transition.

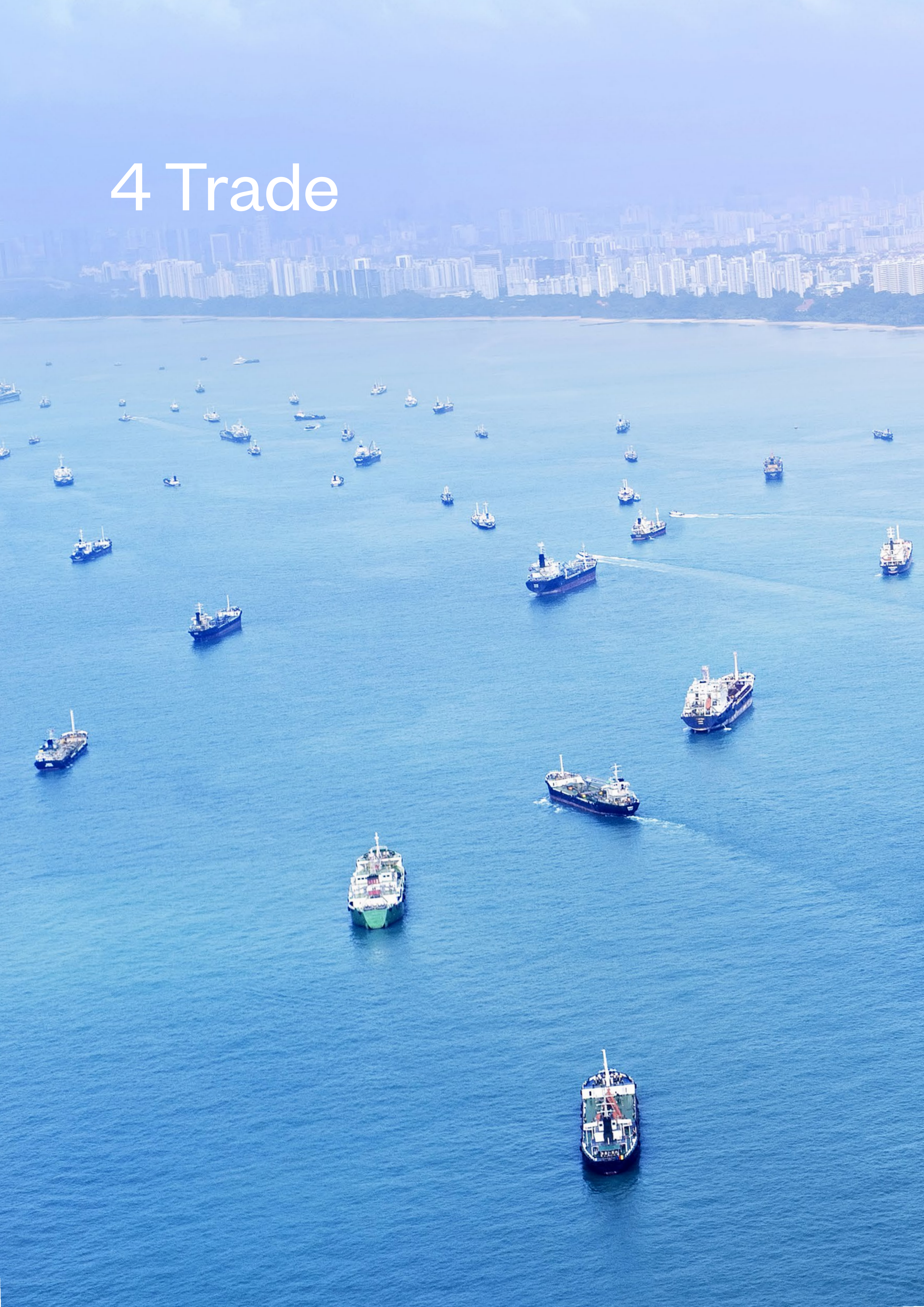
22 IEA, *Net Zero by 2050*, Paris, 2021

23 McKinsey, *Houston as the epicenter of a global clean-hydrogen hub*, June 2022

KPMG, *Taking Singapore forward as a regional green hydrogen hub*, July 2022

HyNetherlands project: https://hynetherlands.nl

4 Trade



4.1 Trade as a driver of hydrogen demand growth

Transporting energy commodities has been in the DNA of maritime shipping for centuries. It currently accounts for 36% of the world's transportation of primary energy, as regions with ample supply of primary energy (e.g. coal, oil and gas) are connected with demand centres. Maritime trade in hydrogen and hydrogen-based fuels is foreseen as an enabler of a global hydrogen economy for two reasons: firstly, because it will give access to lower-cost production, and secondly, because imports will increase energy access and enhance security of supply. Consequently, global trade in hydrogen will allow a faster transition to a net zero economy.

Ambitious climate policy could drive hydrogen demand in some industrialised countries, where various sectors are considering hydrogen and its derivatives as a solution to achieving climate neutrality. In densely populated areas, the expected demand for hydrogen could lead to severe bottlenecks. Supply via imports would overcome them and, given a variety of potential exporters, would also increase the security of hydrogen supply. Consequently, maritime import infrastructure will become key for the trading of hydrogen and hydrogen-based fuels, by connecting demand centres (such as Japan and South Korea) with suppliers (such as Australia).

Furthermore, global trade leads to economic benefits. Estimates by the Hydrogen Council show that the global benefits of trade could reach $460 billion per year by 2050. These savings mainly come from reducing total capital expenditure and operational expenses by 25%. Thus, trading helps to achieve climate neutrality at substantially lower costs.

It should be noted, however, that restrictions on hydrogen trade, such as high freight costs and legal or technical challenges, might lead to shifts in the value chain of certain sectors should it become easier to trade hydrogen-based products (e.g. green steel) than hydrogen-based fuels alone. For sectors considering hydrogen as an energy source and a potential solution to their greenhouse gas abatement efforts, parts of the value chain might relocate to sites with more attractive conditions for hydrogen production. An example of this might be fertiliser production, with ammonia as a key ingredient.

4.2 Markets with potential for high hydrogen demand

The three regions globally that are densely populated and highly industrialised (with a relatively high share of energy-intensive industries) and have a strong interest in using hydrogen are: Northwest Europe, Japan and South Korea (Figure 4.1). Expanding climate-neutral electricity production in these areas already has two tasks to fulfil: replacing the existing fossil fuels in power production with renewables; and meeting increased demand for electrification in the transport and heating sectors. Adding hydrogen's demand for electricity becomes an additional third challenge. Hence imports are the most likely solution to address the hydrogen balance in these areas. Maritime imports of hydrogen are feasible for Japan and South Korea to intensify hydrogen use at scale. Northwest Europe could potentially rely on a reasonable share of pipeline imports (albeit with geopolitical complexities), but would still consider imports to address the region's hydrogen demand. In any scenario, maritime hydrogen trade offers greater flexibility for importers and exporters not only with regard to trading partners, but also with regard to the traded good (e.g. liquefied hydrogen, ammonia, methanol or liquid organic hydrogen carriers (LOHC)). Furthermore, with two of the three hydrogen importing regions focused on relying on maritime trade, potential exporters might be more interested in establishing a maritime trading infrastructure.

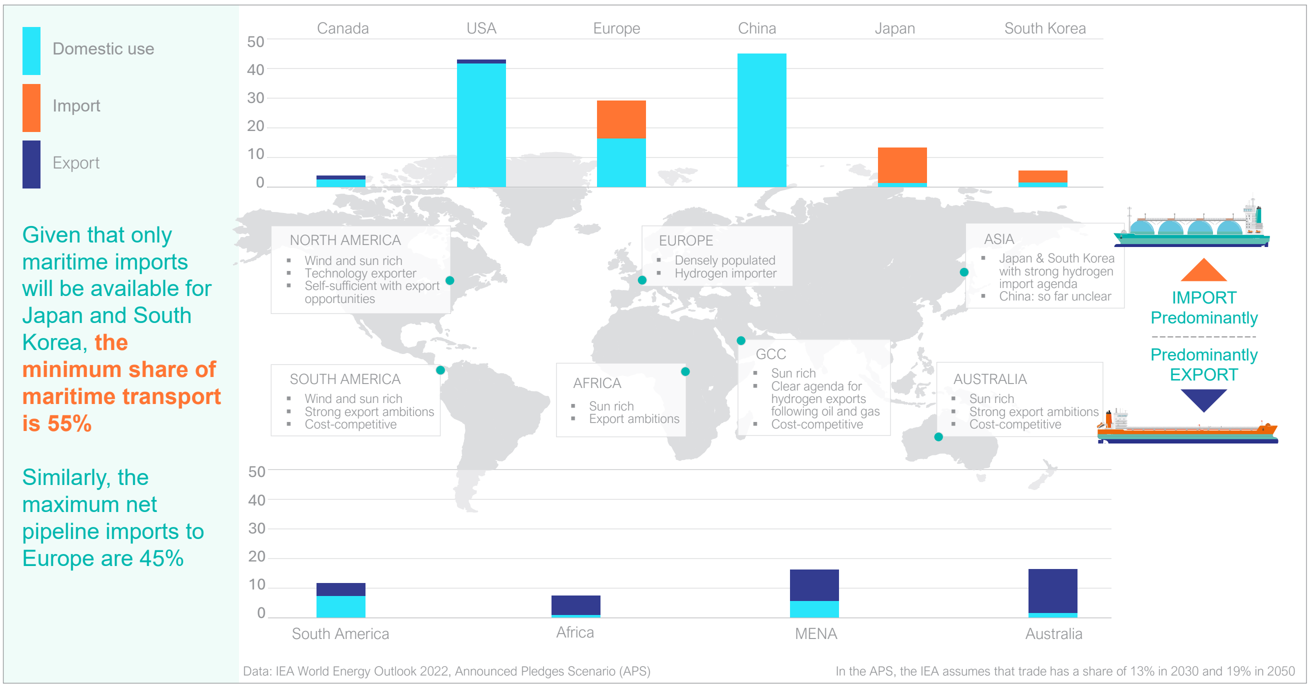


Figure 4.1: Global hydrogen balance
Source: Data from IEA, World Energy Outlook, 2022

> Europe, Japan and South Korea are considered as the main potential importers of hydrogen.

Northwest Europe

Hydrogen is particularly relevant for the Northwest Europe region, notably Benelux and Germany, primarily for material use. The chemical industry has great economic importance in this region: around 7.3% of the chemical and pharmaceutical industries' global turnover is generated in Benelux and Germany. There are also close economic ties in this sector with neighbouring countries such as France (2.5% of global sales) and Switzerland (2.0% of global sales). Furthermore, the region comprises important steel and cement producers. The ports of Amsterdam, Rotterdam, Antwerp and Zeebrugge are globally important trans-shipment points for crude oil, coal and liquefied natural gas (LNG) – and are also striving for a strong position as central European hydrogen hubs. Heavy goods logistics play an important role in Northwest Europe, as movements to and from sea ports are carried out by ship (e.g. the so-called Rhine route), rail and heavy goods traffic – in this respect, synthetic fuels are also of central importance[24]. In order to make sufficient quantities of hydrogen available to consumers, infrastructure is required for the production of hydrogen (and its compounds), its transport from producer to consumer, its storage and its importation.

The Northwest Europe region, including Denmark, France, Norway and the United Kingdom, consumed an average of 6.3Mt of hydrogen annually in the last decade. This corresponds to around 5% of global and 60% of European hydrogen demand. Current demand is mainly concentrated in refineries and the chemical industry. Around 40% of the hydrogen produced in Germany is used in refineries for the desulphurisation of fuels. Current demand is met almost exclusively by so-called grey hydrogen, which is produced by steam reforming of natural gas instead of renewables. In particular, around 40% of chemical production in the European Union is concentrated in the Antwerp-Rotterdam-Rhine-Ruhr cluster, which is why the region is also one of the world's largest hubs for the production and use of hydrogen.

A detailed look at current consumption in the Northwest Europe region (comprising Benelux, Germany, Denmark, France, Norway and the United Kingdom) gives the following picture: ammonia production (1.8Mt

H_2/year) and refineries (1.6Mt H_2/year) are the main sources of demand for pure hydrogen, while other industries (e.g. electronics and glass production) and new applications (e.g. transport and grid feed-in) are relatively minor sources of hydrogen demand. Electromobility is expected to reduce demand for oil-based fuels, and at least part of ammonia production is expected to be relocated to other regions. However, new applications in the areas of transport, industry, electricity generation and heat production will more than compensate for the decline.

Demand for hydrogen mixed with other gases (e.g. natural gas or process gases) fluctuates between 2.4Mt and 3.0Mt H_2/year. A small proportion of this demand comes from special applications such as methanol production (350,000t H_2/year) and steel production with direct reduced iron (DRI) (25,000t H_2/year). The remainder comes from the use of hydrogen-containing gas mixtures as a by-product, mainly from petrochemical processes (between 1.4Mt and 2.0Mt H_2/year) and the steel industry (between 550,000t and 700,000t H_2/year).

With current technology, total hydrogen consumption in the above-mentioned countries would require 258TWh of electricity at best (i.e. its lowest). For comparison, electricity generation from wind in the eight countries mentioned amounted to 277TWh in 2021, hence hydrogen's future electricity needs are nearly equivalent to current wind generation in the region.

It can be assumed that demand for hydrogen in Northwest Europe could rise sharply in the future. This is because the region has high energy requirements and ambitious climate targets: Belgium, like Luxembourg, is planning to become climate-neutral by 2050, Germany by 2045 and the Netherlands pledged to reduce its emissions by 95% by 2050. Hydrogen is seen as part of a climate protection strategy that allows large parts of industrial activity to be maintained whilst reducing their emissions. The strong economic interdependence of the region suggests close co operation between national policies in order to achieve a regional hydrogen market. However, these climate targets can only be achieved through the use of climate-friendly hydrogen. A study recently showed that 60% of the Dutch target for industrial emissions can be achieved simply by replacing the existing production of grey hydrogen with low-carbon or green hydrogen.

According to Aurora Energy Research, the Northwest Europe region currently consumes 95TWh (2.85Mt) of hydrogen based on fossil fuels, mainly produced from natural gas and used in heavy industry, which could be replaced by green hydrogen as part of the European strategies. According to Aurora, hydrogen demand increases to 214TWh by 2050 (6.42Mt), if hydrogen use focuses primarily on industrial applications and only selected solutions in the transport and building heating sectors are considered as consumers. In a scenario with a broader use of hydrogen, demand rises to a significantly higher 727TWh (21.81Mt).

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24 Synthetic fuels here means fuels built with hydrogen, e.g. ammonia, methanol, methane and Fischer-Tropsch fuels. See also International Chamber of Shipping, *Fuelling the Fourth Propulsion Revolution,* May 2022.

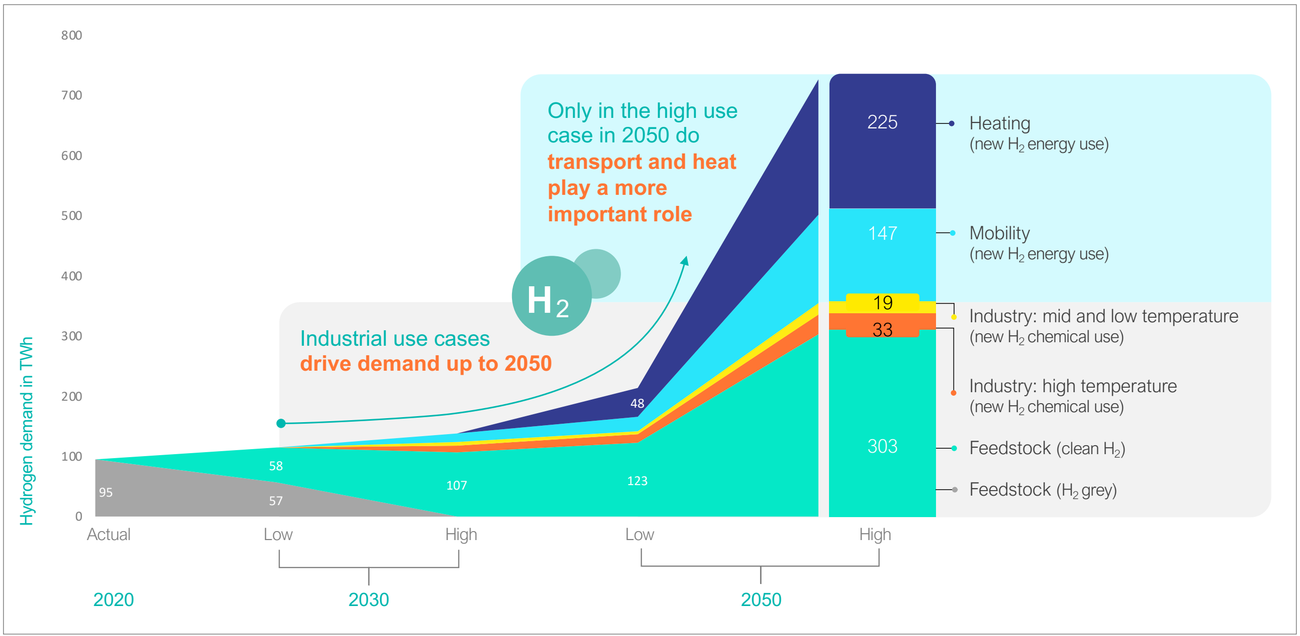

Figure 4.2: Hydrogen demand development in Northwest Europe

Source: World Energy Council Germany

> Industrial use cases drive demand up to 2050. Only in the high use case in 2050 do transport and heat play a more important role.

If this total hydrogen demand in 2050 is to be met exclusively as green hydrogen in the region, the demand for green electricity could range between 238TWh and 1,083TWh. By comparison, total electricity generation in the Benelux countries and Germany amounted to 809TWh in 2021 (including wind at 165TWh and solar PV at 65TWh). The demand for electricity for hydrogen electrolysis is therefore considerable. It is therefore less surprising that Aurora also considers blue hydrogen to be indispensable in 2050: in one scenario, the proportion of blue hydrogen in 2050 is 65%. Scenarios with a high demand for hydrogen also suggest the need for imports. For its scenarios, Aurora quoted hydrogen prices of between €1.6/kg and €2.8/kg, converted to €48/MWh and €84/MWh.

If the hydrogen market is organised as a market economy, price elasticity plays the decisive role when it comes to which consumers will use hydrogen and when. Especially at the beginning of the market ramp-up, relatively high market prices must be expected until learning curve effects and competition can ensure lower prices. This suggests the eventual phasing-in of the consumer sectors. It is likely that industrial applications will consume significant quantities of hydrogen first, followed by electricity generation and then the transport sector. Other sectors, such as the heating market, depend heavily on national regulations, so it is difficult to make general statements about their switch to hydrogen. This is also consistent with the results of a meta-study[25], which also suggest that the major growth on the consumption side will take place between 2030 and 2050. Figure 4.3 also indicates reasonably high baseload demand that is somewhat independent of market prices.

To illustrate the huge demand in industrial use cases, three industrial sites Duisburg (Germany), Ghent (Belgium) and IJmond (Netherlands) are considered[26], where mainly steel mills set the demand for hydrogen. The demand for renewable electricity can be assessed based on two scenarios for their hydrogen demand, low and high, and then compared with the national wind and solar PV production of electricity. This clearly illustrates the crucial role the availability of renewable electricity plays in a hydrogen economy.

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25 M. Riemer et al., *Future hydrogen demand: A cross-sectoral multiregional meta-analysis*, HYPAT Working Paper 04/2022, Karlsruhe: Fraunhofer ISI (ed.), 2022

26 Max Schönfisch et al., *Hydrogen cluster Belgium, the Netherlands, and North-Western Germany*, Institute of Energy Economics at the University of Cologne, 2021

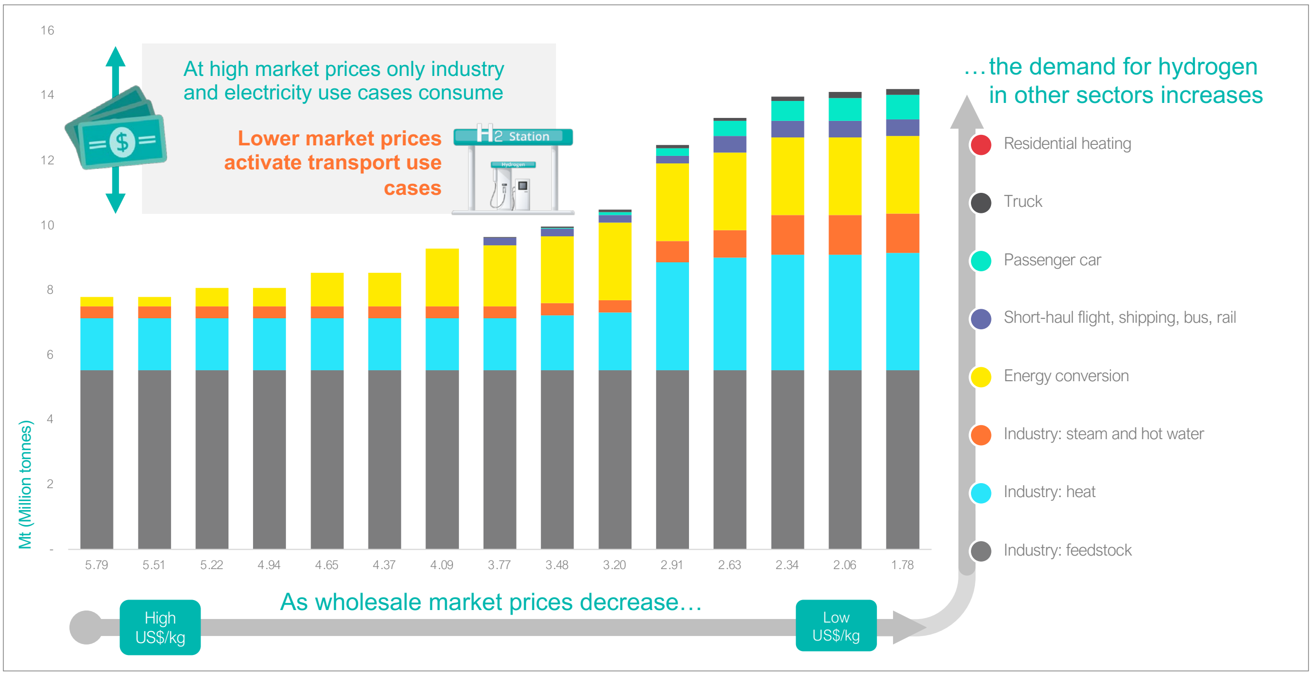

Figure 4.3: Hydrogen demand in Germany in 2045

Source: World Energy Council Germany

With lower hydrogen market prices, demand increases, mainly by supplying further industrial use cases, power production and finally transport.

	Scenario	Demand for hydrogen		Electricity required for production	2021 National power production		% of national power supply needed for one steel plant	
	Low, High, Average	TWh	Mt	TWh	Wind (TWh)	Solar (TWh)	Wind (TWh)	Solar (TWh)
Germany Duisburg	Low	6	0.18	7.14	117.70	49	6%	15%
	High	12	0.36	14.28	117.70	49	12%	29%
ONE STEEL PLANT	Average	9			117.70		9%	
Netherlands IJmond	Low	4	0.12	4.76	17.89	11.44	27%	42%
	High	8	0.24	9.52	17.89	11.44	53%	83%
ONE STEEL PLANT	Average	6			17.89		40%	
Belgium Ghent	Low	3	0.09	3.57	11.88	5.61	30%	64%
	High	6	0.18	7.14	11.88	5.61	60%	127%
ONE STEEL PLANT	Average	4.5			11.88		45%	

The percentage of the country's national wind-generated power supply needed for one steel plant

Vast amounts of additional renewable energy will be needed to produce Europe's required hydrogen, **potentially requiring imports to accommodate their demand**

Figure 4.4: Hydrogen demand and its electricity requirements for three steel plants in Northwest Europe

Source: Weltenergierat Deutschland

South Korea

Another country expected to have high demand for hydrogen is South Korea. Hydrogen has been considered part of a future South Korean energy system for several years. In January 2020 the National Assembly passed the Hydrogen Economy Promotion and Hydrogen Safety Management Law (Hydrogen Law). This sets the rules for the support of the hydrogen industry (e.g. R&D subsidies, loans and tax exemptions) as well as safety standards.

South Korea plans a mix of grey, blue and green hydrogen towards 2030, with total consumption of 3.9Mt annually (with slightly more than half of it imported, i.e. 2Mt/year). By 2030 this would lead to electricity demand of 79TWh and between 19GW and 25GW of electrolysing capacity (for comparison, Chile produced 87.8TWh of electricity in 2021).

For 2050 the aim is to produce 5Mt per year (3Mt renewable, 2Mt low-carbon) and import 23Mt. South Korea is hence looking to rely heavily on imports. By 2050 domestic hydrogen production would increase electricity demand to 851TWh and electrolysing capacity to 203–266GW (for comparison, South Korea generated 600.4TWh of electricity in 2021).

South Korea is targeting a strong increase in hydrogen usage by 2040. It aims to expand its annual market from 130,000t at present to 5.26Mt per year. For the transport sector, South Korea's New Deal (announced in 2020) sets the 2040 fuel cell electric vehicle (FCEV) target at nearly 3 million, including 2.9 million domestically manufactured fuel cell cars, 30,000 fuel cell trucks and 40,000 fuel cell buses. In 2020 South Korea led the world in FCEV installation, with over 10,000 FCEVs on the road, thereby doubling the national stock from 2019. Figure 4.5 lists the main targets[27].

In the medium term (2030) the government plans to support the development and introduction of new hydrogen logistic technologies, namely "liquid hydrogen" (hydrogen carriers), "liquefied hydrogen" (cryogenic hydrogen) and "solid hydrogen" (hydrides) for energy storage and road transport. Tank lorries for liquid and liquefied hydrogen for actual distribution are planned to start in 2030. In addition, the development of hydrogen pipelines for pressures at 50 bar and above are planned. Initially, major hydrogen sources will be connected to the pipeline, and later a nationwide network is planned.

27 Yoon, Y.G. (H_2KOREA), *Current Status of the Korean Hydrogen Economy*, 26 February 2020

Sector		Target volume and time horizon
Mobility	FC cars	81,000 (2022) 100,000+ (2025) 2040: 2.9 million (domestic) and 3.3 million (export)
	FC taxis	2040: 80,000 (domestic) and 40,000 (export)
	FC buses	2040: 40,000 (domestic) and 20,000 (export)
	FC trucks	2040: 30,000 (domestic) and 90,000 (export)
	Hydrogen-powered ships, trains, drones and construction machinery will also be supported and are mentioned in the government paper, but no further details are disclosed.	
Power and heat	Central power generation (NG FC)	1.5GW (2022) 8GW domestic (2040) 7GW export (2040)
	Distributed power generation (NG FC) ("For Homes and Buildings")	50MW (2022) 2.1GW+ (2040)
	Increase distributed power generation	
Overall	FCEVs and stationary FC: Hydrogen consumption: 470,000t (2022); 1.94Mt (2030) Hydrogen energy will account for 5% of gross energy consumption (5.26Mt) in 2040	

Notes: FC = fuel cell; NG = natural gas

Figure 4.5: South Korea's main hydrogen targets

Notes:

1. Typical values for FCEV consumption are 1kg hydrogen per 100km. With an annual distance of 20,000km, this would lead to demand of 0.2t hydrogen per year. A 1 million FCEV fleet would consequently consume 0.2Mt hydrogen. (retrieved from: https://www.bmw.com/en/innovation/how-hydrogen-fuel-cell-cars-work.html)

2. A recent value for FC bus consumption is 10.25kg hydrogen per 100km. Pederzoli, D.W., Carnevali, C., Genova, R. et al, 'Life cycle assessment of hydrogen-powered city buses in the High V.LO-City project: integrating vehicle operation and refuelling infrastructure', *SN Appl. Sci., Vol. 4, Issue 57*, 2022 https://doi.org/10.1007/s42452-021-04933-6

3. Typical assumption for consumption is 8kg hydrogen per 100km; e.g. McKinsey, *Unlocking hydrogen's power for long-haul freight transport,* 2 August 2022

Japan

Japan is expected to be the second-largest demand market for hydrogen imports, second only to South Korea. Hydrogen is used in Japan for many industrial purposes, roughly 2Mt per year. The lion's share is consumed by oil refining at 70%, the rest mainly for ammonia and methanol production.

In 2017 the Japanese government issued the Basic Hydrogen Strategy and became the first country to adopt a national hydrogen framework. Through a series of legislative measures and plans, it aims to expand its hydrogen economy from the current 2Mt to 3Mt by 2030 and over 20Mt of demand by 2050[28]. The main consumers of hydrogen in the Japanese plan are the power sector (5–10Mt), steel plants (7Mt) and transport (6Mt)[29].

The Japanese government's Green Growth Strategy sees renewables meeting between 50% and 60% of electricity demand in 2050, with the remainder supplied by nuclear and thermal plants with carbon capture utilisation and storage (CCUS) (30–40%) and 10% hydrogen- and ammonia-fuelled generation[30]. As an intermediate step, hydrogen and ammonia will make up 1% of both the primary energy mix and the electricity supply mix in 2030[31]. METI also announced plans to co-fire fossil fuels with ammonia (20% by 2030 and 50% by 2050)[32] and to commercialise the technology for ammonia-fuelled power generation by 2050. Hence, Japan has a substantial interest in importing hydrogen, since the local production of hydrogen with renewable electricity is only possible to a very limited extent.

Japan considers three conditions as necessary to realise affordable hydrogen: on the supply side inexpensive sources are needed, as well as large-scale hydrogen supply chains, and on the demand side large-scale uptake of hydrogen usage is needed in transport and power generation, and for industrial processes where electrification is difficult[33].

The Japanese hydrogen strategy targets large-scale use of hydrogen near ports: the major supplies of hydrogen in port areas allow sufficient volumes for large industrial complexes, including power generation and industrial sectors.

Japan is aware of the fact that hydrogen is currently a costly path – hence it has put a strong focus in the strategy on reducing costs by innovation, also giving Japanese industry a strong competitive position with regard to hydrogen technologies, especially end-use technologies. For example, Japan is a technology leader on fuel cells and hence has strong interest in promoting this technology class in other countries[34]. Its cost goal is a reduction in hydrogen costs from the current ¥100/Nm3 (normal cubic metre[35]; $7.57/kg) down to ¥30/Nm3 in 2030 ($2.27/kg), and not more than ¥20n/Nm3 in 2050 ($1.51/kg)[36 37].

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28 METI, *Update to the Green Growth Strategy*, June 2021; METI, *Outline of Strategic Energy Plan*, October 2021

29 METI – Hydrogen and Fuel Cell Strategy Office, *Japan's vision and actions toward hydrogen-based economy*, 25 March 2022

30 IEA, *Japan 2021 – Energy Policy Review*, Paris, May 2021

31 METI, *Strategic Energy Plan*, October 2021

32 Ammonia can be co-fired in coal-fired power stations (project led by Kansai Power, started in 2020) and in gas-fired power stations (IHI, started in 2017). One main challenge is in both cases the reduction of NOx emissions.

33 METI, *Hydrogen and Fuel Cells Strategy Office, Japan's Vision and Actions toward Hydrogen Economy*, 25 May 2022

34 Jane Nakano, CSIS – Center for Strategic and International Studies, *Japan's Hydrogen Industrial Strategy*, 21 October 2021

35 1Nm3 of hydrogen gas is equal to 0.08988 kilograms or 1.2699 litres. Exchange rate ¥100 = $0.68.

36 A general source for importing costs incl. transport of hydrogen, methanol, synthetic natural gas and ammonia is the PtX Atlas: https://maps.iee.fraunhofer.de/ptx-atlas/

37 The goal is rather ambitious: during the Egyptian Economic Conference 2022 (October 2022), the Minister of Electricity and Renewable Energy Mohamed Shaker declared that Egypt has the potential to produce green hydrogen at the lowest cost in the world, seen to be reduced from $2.68 (€2.72) per kilogram in 2025 to $1.70/kg by 2050

4.3 Potential benefits of hydrogen trade: driver of scale and future affordability

Global trade in hydrogen-based fuels could enhance security of supply of this fuel and is hence decisive for scaling up hydrogen-based processes in industrialised countries. Furthermore, trade establishes access to lower hydrogen production costs.

The European Union has set a target for hydrogen consumption of 20Mt by 2030, half of this to be imported. No figures for 2050 have been communicated so far.

The South Korean government has made it clear that the import of hydrogen will be key for meeting its hydrogen targets. In its first strategy statement on hydrogen in November 2021, a consumption goal of 27.9Mt hydrogen per year by 2050 was announced, leading to an economic effect of 1,319 trillion won, the creation of 567,000 jobs and a greenhouse gas reduction of 200Mt. The hydrogen is to be clean (i.e. green or blue). Self-sufficiency of 60% is targeted by expansion of domestic production and by importing clean hydrogen produced by South Korean technology and with South Korean investment.

In the case of Japan, the benefits of trade can be clearly shown. Without importing hydrogen, Japan is only capable of supplying roughly 4Mt hydrogen to its consumers (see Figure 4.6). Importing hydrogen will increase the available amount of hydrogen to Japanese consumers by up to 21Mt, depending on the global market price. This is important for two reasons: firstly, it reduces the specific cost of hydrogen in Japan since the hydrogen production and transport costs for imported hydrogen are lower than local production; secondly and even more important, it will also increase the amount of hydrogen available to use cases massively. Consequently, decarbonisation will happen faster in Japan under a scenario with imports compared with a self-sufficient hydrogen approach. Thus, hydrogen imports are beneficial for economic and ecological reasons.

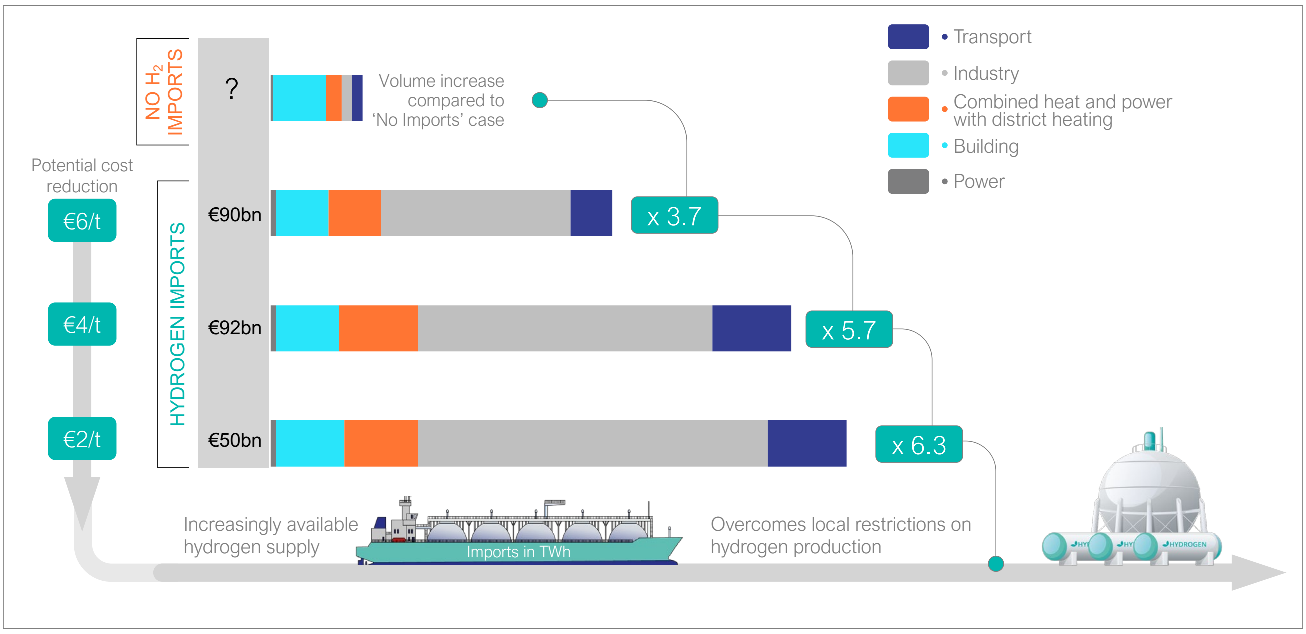

Figure 4.6: The benefits of hydrogen maritime transportation for Japan in 2050

Enabling imports into Japan reduces the specific hydrogen costs and more importantly increases the amount of available hydrogen.

For Japan and South Korea, maritime shipping is the only reasonable import route. There is already substantial long-term experience of transporting ammonia and methanol by ship. Maritime shipping therefore has the advantage of existing import facilities at ports. This might lead to development where interregional transport is mainly done by maritime shipping and to a lesser extent by pipeline. Concerns about security of supply are higher for pipeline imports given the recent experiences with natural gas imports in Europe.

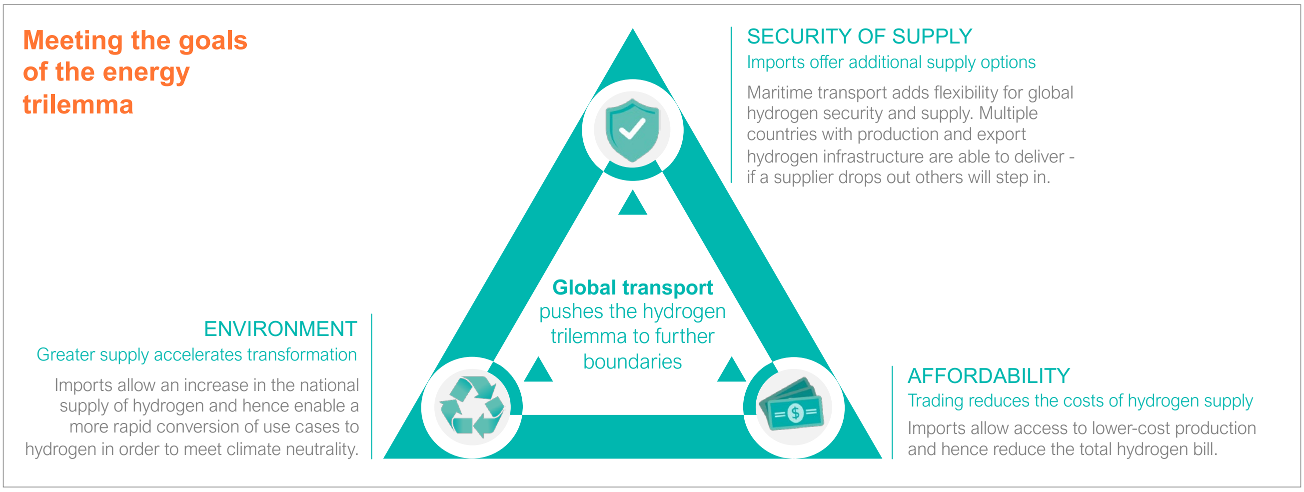

Figure 4.7: The benefits of hydrogen trilemma

> The future hydrogen world benefits from global trade in three dimensions: affordability, security of supply and climate protection.

4.4 Shipping as an enabler of hydrogen demand growth and international hydrogen market development

Looking at the demand centres in Asia (Japan and South Korea) and the potential exporters in Africa, Australia, Latin America and the Middle East, only maritime shipping is able to establish hydrogen trade. For Europe, pipeline imports (e.g. from Northern Africa) might become an additional option. However, even for Europe access to supply from southern parts of Africa, Australia, Latin America and the Middle East will rely on maritime shipping.

As shown in figure 4.8, the two Asian economies would have a combined hydrogen demand of 33 million tonnes, leading to a combined electricity increase of approximately six times their current renewable electricity production. In addition, the combined total of vessels required to transport hydrogen to these two countries could represent an additional 457 hydrogen vessels[38].

Maritime trade needs specific port infrastructure, which is described in the concept of a “clean energy marine hub”, a global initiative led by energy and transport ministers[39]. The initiative focuses on public–private efforts to accelerate the transport and use of low-carbon fuels by the maritime sector, enabling the energy–maritime value chain to support the global energy transition This infrastructure is key to enable maritime imports into the demand centres – and it is hence key to making faster and more affordable deep decarbonisation possible in densely populated and highly industrialised countries. The clean energy marine hubs will then serve as nuclei for the establishment of a hydrogen economy, firstly by becoming an obvious site for industries associated with this hydrogen economy, and secondly by connecting more distant existing industrial sites to these hubs by pipeline.

38 Please see appendix for the methodology for number of vessels for hydrogen and ammonia.

39 https://www.cleanenergyministerial.org/initiatives-campaigns/hubs/

Consequently, maritime shipping will act as an enabler of the hydrogen economy. The demand for hydrogen to allow deep decarbonisation of key industries, such as steel and fertiliser production, is enormous and needs external supply on a massive scale. This transition will only be made possible by maritime trade. As soon as the trading infrastructure is present and the key industries are deeply decarbonised, the use of hydrogen-based fuels will trickle down to fuel the maritime shipping sector itself, since most of the infrastructure (including bunkers) is present, requiring the vessels to adjust their engines and on-board fuel storage system to the new fuels.

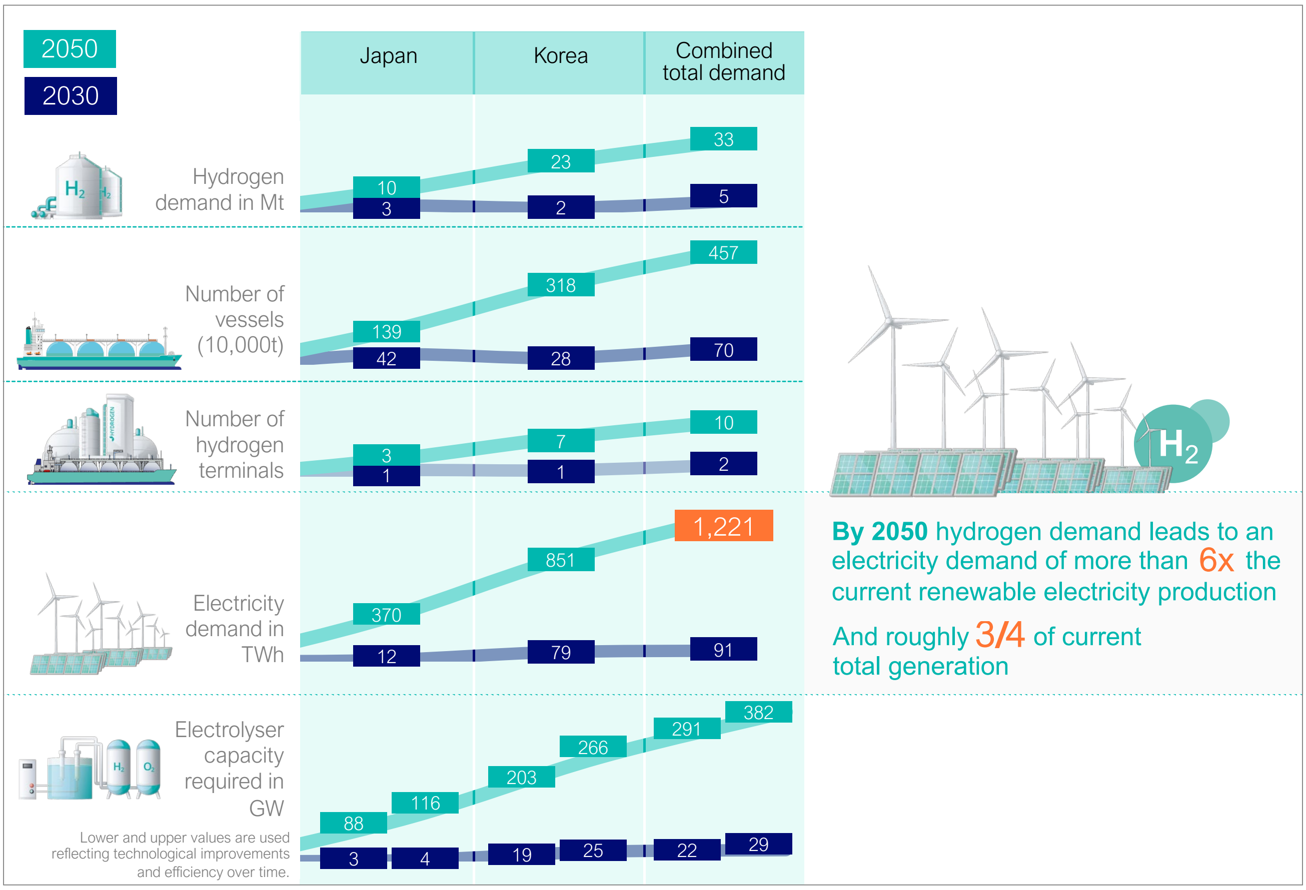

Figure 4.8: Asia market demand (Japan and South Korea)

Japan and South Korea have an explicit import strategy for hydrogen. Both countries use only maritime shipping to access the global market. For potential exporters the announced import volumes in the hydrogen import strategies serve as an important benchmark.

5 Conclusions

Hydrogen has an important but not dominant role in the transformation towards climate neutrality. Hydrogen will predominantly be used as feedstock in industry, for example for ammonia, steel and cement production. Its use as a fuel is restricted to specific hard-to-abate sectors, for example in aviation and maritime shipping, or to establish seasonal storage for power and heat. Compared with the current demand for fossil fuels or the future demand for renewables, hydrogen demand measured in energy content is much smaller.

Hydrogen demand depends strongly on climate ambitions and could benefit from offtake agreements with multiple sectors. The growth in hydrogen demand, as well as the replacement of existing fossil-based hydrogen consumption, is driven by climate ambitions. Deep decarbonisation leads to substantial demand for hydrogen from multiple sectors. Consequently, security of demand for producers and exporters relies on adherence to the Paris Agreement.

Scenarios for future hydrogen demand show huge variability and uncertainty from now towards 2050. Given the enormous degree of uncertainty with regard to technological development, scenarios for hydrogen demand currently show significant variability as to the total demand for hydrogen and the consuming sectors. From an economic perspective, the key driver will be the global price for hydrogen: at very low market prices, hydrogen will be applied in a broad range of applications, being typically in competition with direct electrification.

The rate and timeline of hydrogen uptake varies between sectors due to infrastructure, regulatory and sectoral ecosystem challenges and is likely to take place in stages. Not all sectors will require the same degree of transformation to incorporate hydrogen as a replacement for fossil fuels.

To unlock investment, governments should also focus their attention on supporting demand side derisking over supply side subsidy. Without this, the transition to a hydrogen economy will be stifled and will not deliver on the decarbonisation objectives set by governments and industry.

Industrial demand, and not transport, will vastly dominate hydrogen demand in the coming decades, acting as a baseload for hydrogen demand. Overwhelmingly, the considered scenarios underline the dominance of hydrogen consumption by industry in the coming decades. Industries that already use hydrogen currently as a feedstock are technically in an advanced position since they merely have to change their hydrogen source – if the economics allow it. Additionally, those sectors that can relatively easily pass through additional hydrogen costs to their customers are economically in an advanced position – if they develop technologies based on hydrogen. Nonetheless, the pressure on industry to decarbonise globally will lead to a certain baseload demand for hydrogen.

The scale of electricity demand for green hydrogen production is unprecedented and leads to once-in-a-generation opportunities and challenges. Renewable electricity is considered a cornerstone for achieving a climate-neutral energy system and hence an essential solution for transport and heating/cooling. However, this also leads to competition for green electricity that is also needed to produce green hydrogen. Since the power demand for hydrogen electrolysis is enormous, the global power system would need to grow substantially more than the tripling renewable energy target by 2030 announced at COP28 to make a hydrogen economy a reality.

The need for hydrogen transport by ship requires the energy–maritime value chain to shift towards a low-carbon infrastructure that is fit for purpose. Import centres acting as clean energy hubs create opportunities for hydrogen-based industrial development; however, hydrogen and hydrogen-based fuels need to find their way to industrial customers. Consequently, a land-based transport and distribution system is also needed. Typically, this will be realised with pipelines – in rare cases, road or rail might also be used. Industries in proximity to importing ports will benefit earliest from the available hydrogen. With additional transport infrastructure, sites at a distance from the sea will also be reached. Building this infrastructure rapidly in each economy will be critical for countries to maintain their competitive position versus other countries or regions.

Maritime trade infrastructure is essential for scaling up hydrogen demand and reducing costs. The enormous demand for hydrogen due to steel and fertiliser production will only in rare cases be met by local production. The latter would require sufficient space for enormous renewable energy production, which is not realisable in densely populated and highly industrialised areas. Consequently, the further operation of these industrial plants depends on access to sufficient import volumes of hydrogen. Alternatively, the relocation of some industrial processes closer to the sites of hydrogen production might be considered, with higher-value parts of the value chain staying in the industrialised areas.

Demand-pull for hydrogen is further enabled by trade. Given the industrial baseload demand for hydrogen and the challenges of meeting this demand in highly industrialised, densely populated and highly electrified regions, trade will enable the transition towards a hydrogen economy. Firstly, trade establishes access to additional and independent supply sources, leading to security of supply. Secondly, global trade also allows access to cheaper sources compared to local production, hence improving affordability. In summary, these two drivers will allow for more rapid deep decarbonisation in industrialised regions and is hence decisive in meeting the goals of the Paris Agreement.

The role of maritime shipping is primarily as an enabler of a hydrogen economy and is key for global energy security. Maritime shipping may ultimately become a key source hydrogen demand itself, as this transport mode requires storable fuels with sufficient energy density. However, given that hydrogen will in the initial decades primarily be used for deep decarbonisation in industry, the first task for maritime shipping is to enable the transition to a hydrogen economy by establishing global trade.

Consequently, maritime shipping sees enormous opportunities in the emerging hydrogen economy. However, the infrastructural challenges of producing the necessary amount of hydrogen and establishing the required port facilities are key tasks on the path to making the hydrogen world a reality.

Appendix: Typical vessel data

To compare the vessels carrying liquefied hydrogen, liquid ammonia and methanol, the following data for the physical properties of the fuels are used[1] :

	Liquefied ammonia	Methanol	Liquefied hydrogen
Density [kg / m3]	680	792	70.8
Gravimetric energy density [MJ / kg]	120	15	21.18
Volumetric energy density [PMJ / l]	12.92	11.88	8.49

Typical ammonia and methanol vessels do exist. They might offer some scaling potential, but to make the comparison with the existing fleet of ammonia and methanol vessels easy, the current vessel sizes are used.

A typical ammonia vessel in our considerations is assumed to load 84,000 m3 liquid ammonia[2]. This would correspond to 57,120 tonnes ammonia with an energy content of 1,085,280,000 MJ or 0.30 TWh. There are globally 130 ports, where ammonia bunkers are present[3] .

A typical methanol vessel in our considerations is assumed to have a deadweight tonnage of 50,000 tonnes[4]. A load of 50,000 tonnes methanol has an energy content of 750,000,000 MJ (0.21 TWh), i.e., roughly two thirds of the energy content of the load of the typical ammonia vessel. There are globally 120 ports, where methanol bunkers are present[5].

A typical hydrogen vessel is not yet available but planned. Based on the experiences with the Suiso Frontier, there are plans for ships carrying liquefied hydrogen with 40,000 m3 and even 160,000 m3 load[6]. The latter would be able to carry 10,000 tonnes of hydrogen[7]. This corresponds to an energy load of 0.33 TWh, i.e., slightly larger than the typical ammonia vessel.

One should note that the notion of a standard vessel is not fixed, but only reflects typical sizes (respectively planned sizes). However, it shows that the vessel sizes are of the same magnitude of order – consequently, no big differences can be expected with regards to the number of needed vessels for a given amount of energy to be transported.

As a typical voyage time, 50 days are used (including the time for loading and unloading), which is also used for VLCCs between the Middle East and Japan[8].

1 Chatterjee et al, 'Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector', *ACS Energy Lett.* 2021, 6, 12, 4390–4394 Publication Date: November 15, 2021, https://doi.org/10.1021/acsenergylett.1c02189, Copyright © 2021 American Chemical Society

2 Seo, Y.; Han, S., 'Economic Evaluation of an Ammonia-Fueled Ammonia Carrier Depending on Methods of Ammonia Fuel Storage', *Energies 2021, 14, 8326.* https://doi.org/10.3390/en14248326

3 International Shipping News, 27 April 2022, *Emerging ammonia bunkering network set to fuel carbon-neutral ambitions,* https://www.hellenicshippingnews.com/emerging-ammonia-bunkering-network-set-to-fuel-carbon-neutral-ambitions/

4 Methanex, https://www.methanex.com/our-business/marketing-logistics-and-supply-chain

5 Maritime News, 5 Jul 2022, *Proman Stena Bulk Takes Delivery Of Second Methanol-Fuelled Tanker* - Stena Pro Marine

6 Press release ClassNK, 28 April 2022, https://www.classnk.or.jp/hp/en/hp_news.aspx?id=7923&type=press_release&layout=1

7 Argus, 22nd April 2022, *Japan's KHI develops liquefied hydrogen carrier*

8 Mitsui O.S.K. Lines, *Let's see the Routes and Speed of Cargo Ship*, 5th July 2022, https://www.mol-service.com/blog/vessel-speed-and-sailing-days

Ammonia

Using the figures just introduced, the following table can be calculated with regard to the weight (standard vessel 57,120 t):

Amount	1 Mt	5 Mt	10 Mt
# of voyages	18	88	175
# of voyage days per year	875	4,377	8,754
# of ships needed	2.40	11.99	23.98
# of ships (rounded)	3	12	24

And with regards to the energy (standard vessel 0.30147 TWh):

Amount	5 TWh	10 TWh	50 TWh
# of voyages	17	33	166
# of voyage days per year	829	1,659	8,292
# of ships needed	2.27	4.54	22.72
# of ships (rounded)	3	5	23

Methanol

Using the figures, the following table can be calculated (standard vessel 50,000 t):

Amount	1 Mt	5 Mt	10 Mt
# of voyages	20	100	200
# of voyage days per year	1,000	5,000	10,000
# of ships needed	2.74	13.70	27.40
# of ships (rounded)	3	14	28

And with regards to the energy (standard vessel 0.20833 TWh):

Amount	5 TWh	10 TWh	50 TWh
# of voyages	24	48	240
# of voyage days per year	1,200	2,400	12,000
# of ships needed	3.29	6.58	32.88
# of ships (rounded)	4	7	33

Hydrogen

Using the figures just introduced, leads to (standard vessel 10,000 t):

Amount	1 Mt	5 Mt	10 Mt
# of voyages	100	500	1,000
# of voyage days per year	5,000	25,000	50,000
# of ships needed	13.70	68.49	136.99
# of ships (rounded)	14	69	137

And with regards to the energy (standard vessel 0.3333 TWh):

Amount	5 TWh	10 TWh	50 TWh
# of voyages	15	30	150
# of voyage days per year	750	1,500	7,500
# of ships needed	2.06	4.11	20.55
# of ships (rounded)	3	5	21

Consequently, one typical vessel (ammonia or hydrogen) would transport roughly 0.3 TWh energy content.

Comparing with a hydrogen pipeline

Assuming a hydrogen flow rate of 100,000 Nm^3/h , a pipeline under full load would transport 78,735 t hydrogen per year. The planned commercial tanker mentioned in section 2.3 about Japan would deliver 10,000 t hydrogen. With roughly 13 trips per year, 130,000 t hydrogen could be transported by ship. This indicates that maritime shipping is able to transport the same magnitude of order as pipelines, however, with more flexibility regarding both importing and exporting countries.

Currently, hydrogen pipelines are also tested whether they can transport 100% hydrogen . A blend up to 10% should always be possible, sometimes even higher values of 30% are mentioned, since natural gas typically also contains some hydrogen. However, dedicated hydrogen-only pipelines are needed in a climate-neutral world. They will also be important to transport hydrogen from the international ports to the supply centres.

9 Laurent Bedel and Michel Junker, *Natural gas pipelines for hydrogen transportation*, WHEC 16, 13–16 June 2016, Lyon/France

10 H2HoWi project by Westnetz, various media releases


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