International Chamber of Shipping

Shaping the Future of Shipping

Fuelling the Fourth Propulsion Revolution

An Opportunity for All

In collaboration with Professor Dr Stefan Ulreich, University of Applied Sciences, Biberach, Germany

May 2022

Fuelling the Fourth Propulsion Revolution

An Opportunity for All

International Chamber of Shipping
7th Floor, Walsingham House, 35 Seething Lane, London EC3N 4AH

Telephone + 44 20 7090 1460
info@ics-shipping.org
www.ics-shipping.org

Cover image: 3d rendering of a liquid hydrogen renewable energy ship, Shutterstock

In collaboration with Professor Dr Stefan Ulreich, University of Applied Sciences, Biberach, Germany

International
Chamber of Shipping

Shaping the Future of Shipping

Foreword

Decarbonisation and the creation of (net) zero carbon fuels presents a massive economic opportunity for shipowners, companies and countries, as fuel producers, importers and exporters.

This summary report outlines how shipping will play a fundamental role in delivering these fuels globally and act as an enabler for governments and industries to achieve their climate targets.

It showcases why the maritime industry must be accounted for in international decarbonisation plans and have access to the same (net) zero carbon fuels they will be transporting to decarbonise; the world's renewable energy generation would need to increase up to 100% just to supply enough (net) zero carbon fuel to power the shipping industry.

The enormous scale of the opportunity and transformation of the fourth propulsion revolution for governments, ports, developing economies, and key maritime stakeholders is laid out in this summary report.

What is a (net) zero carbon fuel?

Various fuels meet the criteria to be considered climate neutral. Biofuels could be considered to be climate-neutral as the plants used for biofuel production absorb carbon dioxide as they grow. This process is known as a closed carbon cycle.

Similar considerations hold true for synthetic fuels that are produced using captured carbon dioxide and hydrogen. Fuels with a closed carbon cycle are often called 'net zero carbon fuels'. Other fuels such as hydrogen or ammonia do not contain carbon and consequently will not emit carbon dioxide, leading to the notion of 'zero carbon fuels'.

In this report, the term '(net) zero carbon fuels' includes biofuels, and synthetic fuels built from climate-neutral hydrogen, such as ammonia, hydrogen, methanol. All of these fuels, however, will lead to climate-neutral shipping.

This research was created in collaboration with author Professor Dr Stefan Ulreich, University of Applied Sciences, Biberach, Germany and Chair of the Task-force Renewables of the European Federation of Energy Traders. ICS is also grateful to the following people and organisations for their input and peer review of this report:

Roland Roesch, Deputy Director at the Innovation and Technology Center and Gabriel Castellanos, International Renewable Energy Agency (IRENA)

Araceli Fernandes and Elizabeth Connelly, International Energy Agency (IEA)

The full report is available on the International Chamber of Shipping website ics-shipping.org.

Contents

Executive Summary

The UNFCCC Paris agreement of 2015 aims for global climate-neutrality by the middle of this century. The global shipping industry has pledged to achieve net-zero CO_2 emissions by 2050, meaning that the fourth propulsion revolution will be green. The transition to new fuels presents enormous opportunities as well as critical transformational challenges for all segments of the global economy.

Current geopolitical tensions are creating fuel supply uncertainty and heightening energy security concerns. This increases the pressure to accelerate the transition to green fuels, as well as establish alternative fuel hubs and routes to increase resilience. Governments, ports, developing economies, and key stakeholders that create renewable energy supply centres and production hubs will benefit greatly from early mover advantage.

The International Energy Agency's (IEA) Net Zero Emissions by 2050 scenario says to decarbonise the world, global electricity demand will increase to 60,000 TWh, up from 23,230 TWh in 2020. Shipping will not only be a consumer of (net) zero emission carbon fuels to meet decarbonisation targets, but is critical for transportation of green fuels as it is the most economical option over long distances (above 10,000km). At least half of (net) zero fuels are expected to be moved by ships, according to the International Renewable Energy Agency (IRENA), making maritime a key enabler of the decarbonisation of land-based industrial sectors.

However, maritime decarbonisation is highly dependent on the transition speed of energy producers, in terms of building renewable energy production facilities ashore at scale, catalysts such as global levies needed to accelerate production of fuels at scale, as well as with updated infrastructure at ports.

Governments and industry must act now to ensure that their energy transition plans account for and support the vital role that shipping will play in delivering renewable energy and hydrogen plans. Policy, funding and actions must combine to create an easy path towards the green propulsion transition. This is where development finance can play a significant role in de-risking the much needed investment required to move to a (net) zero carbon fuel future.

This research has looked to identify the amount of electricity needed to produce (net) zero carbon fuels for maritime use as part of the wider global energy transition. For shipping's (net) zero carbon fuel needs, electricity from renewable sources used to supply shipping would need to increase by up to 3,000 TWh. This would require the equivalent of all of the world's current renewable energy production just to provide shipping's fuel needs.

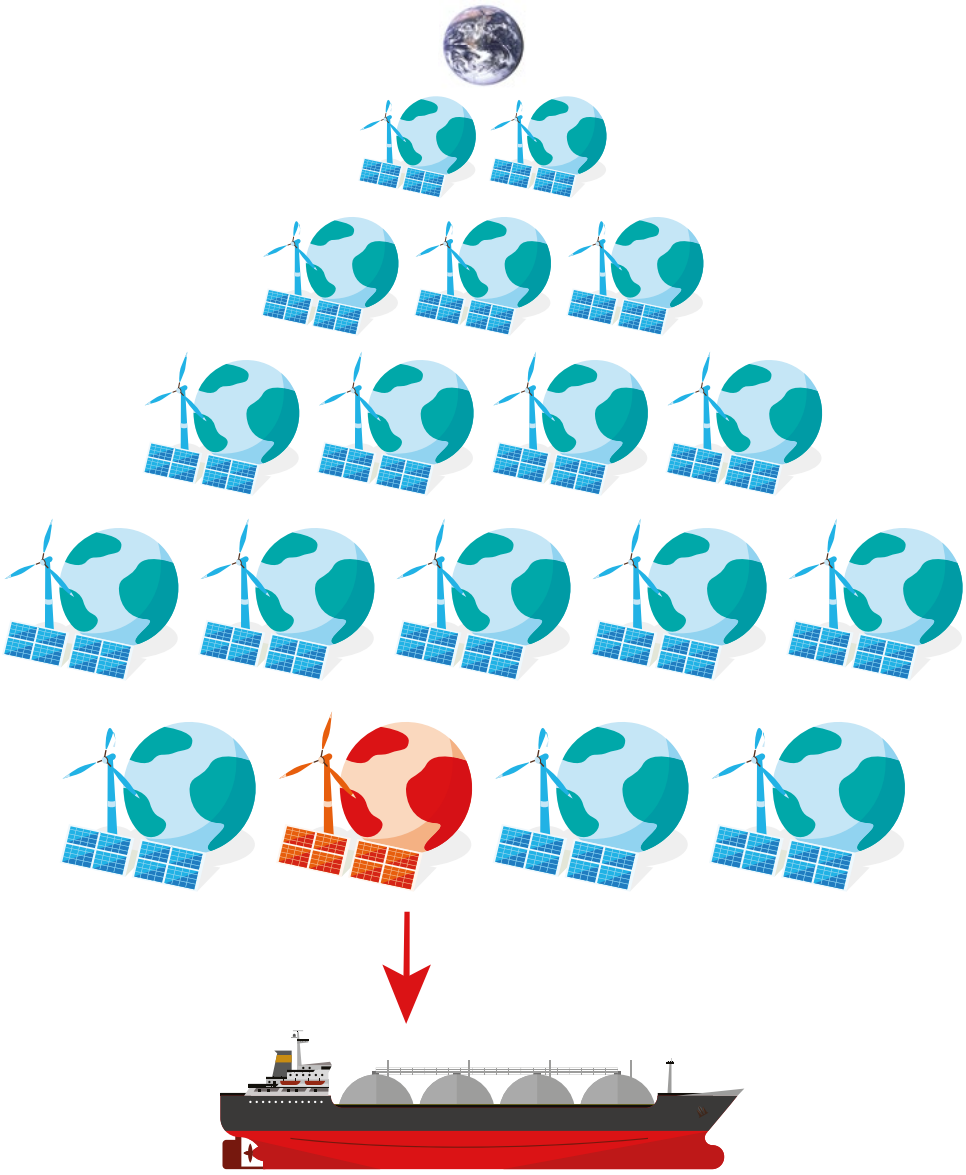
Key takeaways

1	**Producing (net) zero carbon marine fuels, especially close to ports, will create a significant opportunity for renewable energy producers** It could require the equivalent of all the world's current renewable energy production just to supply shipping's (net) zero carbon fuel needs.
2	**Shipping will have a multi-fuel future** No one fuel can replace current fossil fuels for maritime and decarbonising will require a mix of bio-fuels, e-fuels, natural gas and hydrogen derivatives such as ammonia and methanol.
3	**High demand for (net) zero carbon fuels presents opportunities for the global south** Developing economies are well-placed to become fuel suppliers and exporters of (net) zero carbon fuels but must move quickly to gain early mover advantage and will need support from the international community for capacity building and access to finance.
4	**Renewable energy production of (net) zero carbon fuels provides economic opportunities for all** Investors should be confident in opportunities for (net) zero carbon fuel production as the demand for hydrogen-based solutions is expected to increase strongly in many industrialised countries with strong green policies, that do not have the potential to produce enough renewable hydrogen for their own needs.
5	**Invest in infrastructure and research, development and demonstration now or economic gains will be minimised** Early mover advantage is vital and all stakeholders, including governments, ports, fuel suppliers and industry must invest now to ensure a stable supply of (net) zero carbon fuels.

1 Replacing conventional marine fuels with (net) zero carbon fuels, especially close to ports, will create a significant opportunity for renewable energy producers and stakeholders

(Net) zero carbon fuels such as hydrogen-based fuels are expected to become an essential part of the climate-neutral maritime fuel mix in coming decades. Renewable electricity production must be rapidly increased to capitalise upon this opportunity and ensure fuel security for maritime, which will underpin the decarbonisation of other land-based industries. It is crucial for shipping that production facilities for new fuels are within easy access of ports and new bunkering hubs are established to ensure shipping can access and deliver (net) zero fuels globally.

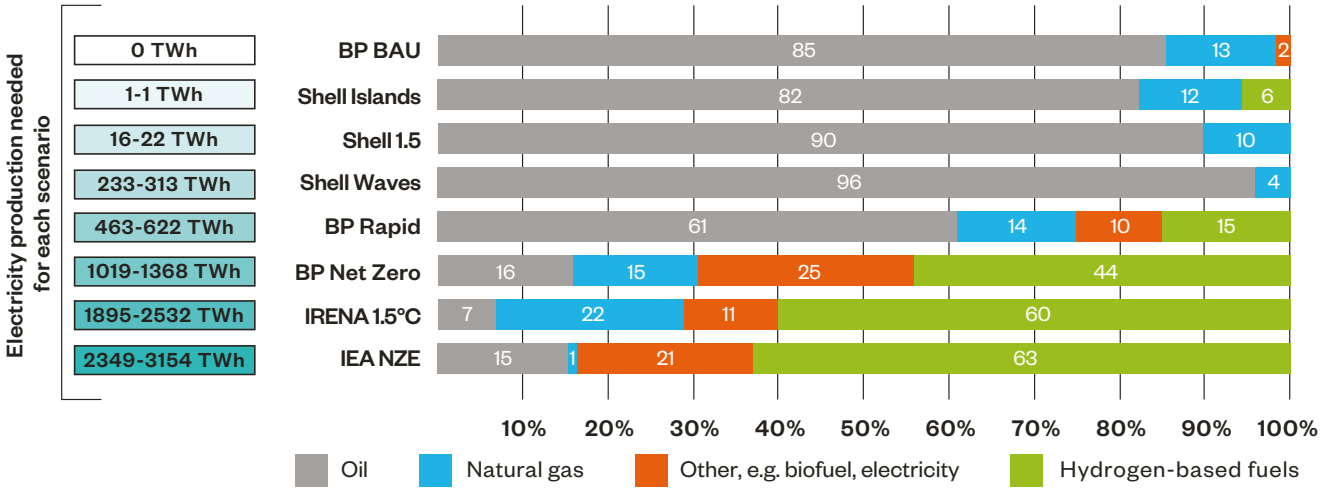
The scale and challenge to supply alternative fuels to decarbonise the shipping sector is often underestimated. To supply shipping's (net) zero carbon fuel needs (as outlined in International Energy Agency and IRENA scenarios), electricity from renewable sources used to supply shipping would need to increase by up to 3,000 TWh considering expected technology efficiencies by 2050. This could require the equivalent of all of the world's current renewable energy production just to provide shipping's fuel needs.



To achieve the IEA's Net Zero Emissions by 2050 scenario we would need an 18-fold increase in the world's existing renewable production capacity. Shipping would require the equivalent of one of these worlds to meet its own renewable energy needs.

2 The decarbonisation of shipping will have a multi-fuel future

The maritime industry's green transition will take time and consist of a multi-fuel future as there is no single replacement for affordable and readily available current fossil fuels. Biofuels, e-fuels, natural gas and hydrogen derivatives are all likely to play a role in the future fuel mix for shipping. New production ecosystems must be built rapidly across the globe to meet decarbonisation goals. A global carbon levy would be an effective tool to reduce the enormous costs of a large-scale transition away from fossil fuels.



Various scenarios of fuel mixes for maritime shipping in 2050

Note: Each scenario is explored in detail in the full version of this report

Sources: International Energy Agency (IEA), Shell, BP and International Renewable Energy Agency (IRENA).

Using and transporting these new fuels comes with significant operational and safety challenges which will need to be addressed. Defined and agreed global safety and sustainability standards for hydrogen-based fuels and strong safety standards for the transport and use of (net) zero fuels must be developed quickly, to keep pace with the transformation. Seafarers and those in the supply chain will need to be trained and new standards developed to maintain safety and minimise risk.

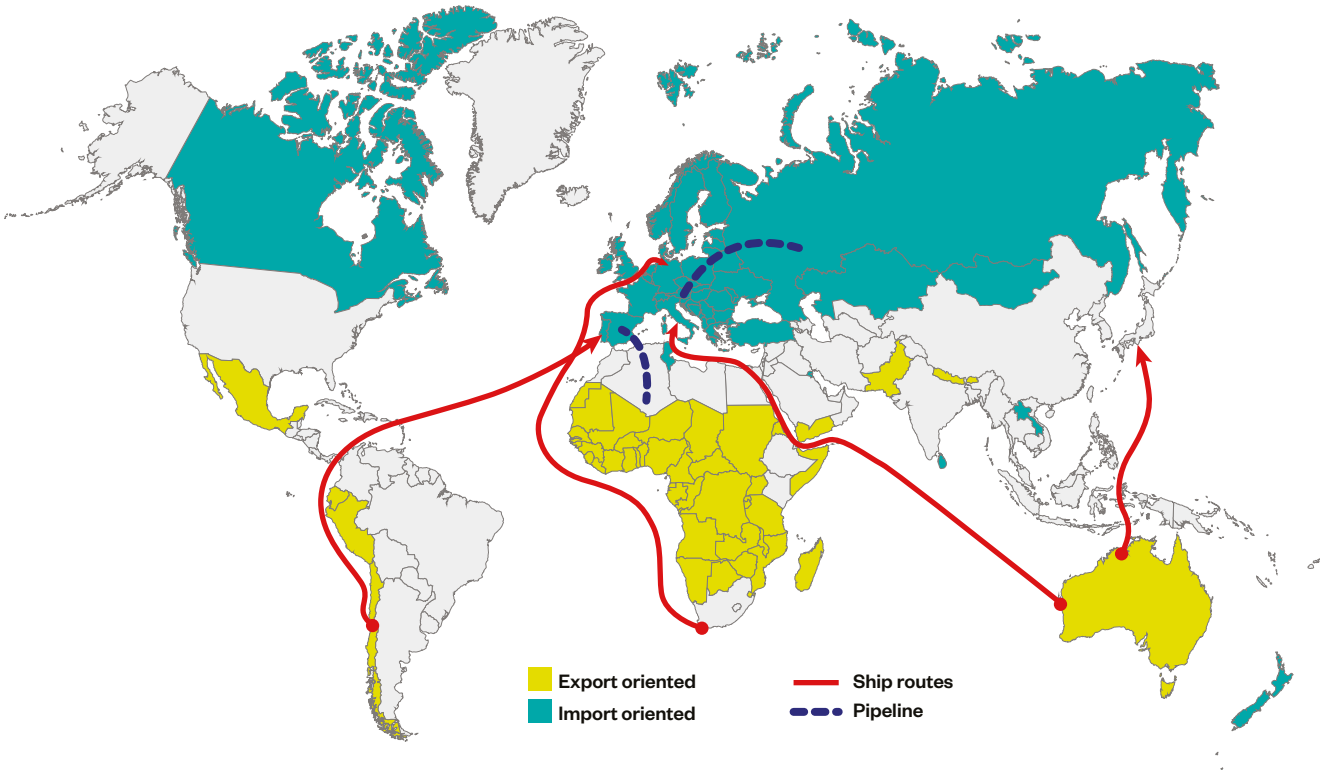
3 Supply side dynamics: High demand for (net) zero carbon fuels presents enormous economic opportunities for the global south

Developing economies are well placed to benefit economically by becoming fuel supply producers and exporters of (net) zero carbon fuels to meet high demand from Europe, North America and Asia. Shipping presents the most cost effective means to trade (net) zero carbon fuels from these supply hubs to different parts of the world over long distances.

Regions such as Latin America and Africa are expected to benefit from a 20%+ lower cost of production and transport of fuels due to the abundance of solar and wind in these regions. Existing energy hubs in the MENA region are primed to transform themselves from fossil fuel sellers to (net) zero carbon fuel supply hubs due to their excellent wind conditions and high solar radiation.

However, hydrogen and (net) zero carbon fuel facilities must be urgently developed to ensure access to a highly competitive market. In setting up these facilities location is important. Export strategies and policies, along with enhanced international cooperation agreements, must also be created rapidly. Countries such as Algeria, Argentina, Australia, Chile and Morocco have already begun this journey.

Developing economies must be supported by the international community to increase capacity building, construct necessary infrastructure and access finance to gain early-mover advantage and establish themselves as the world Energy supply Energy Hub in the global (net) zero fuel markets.



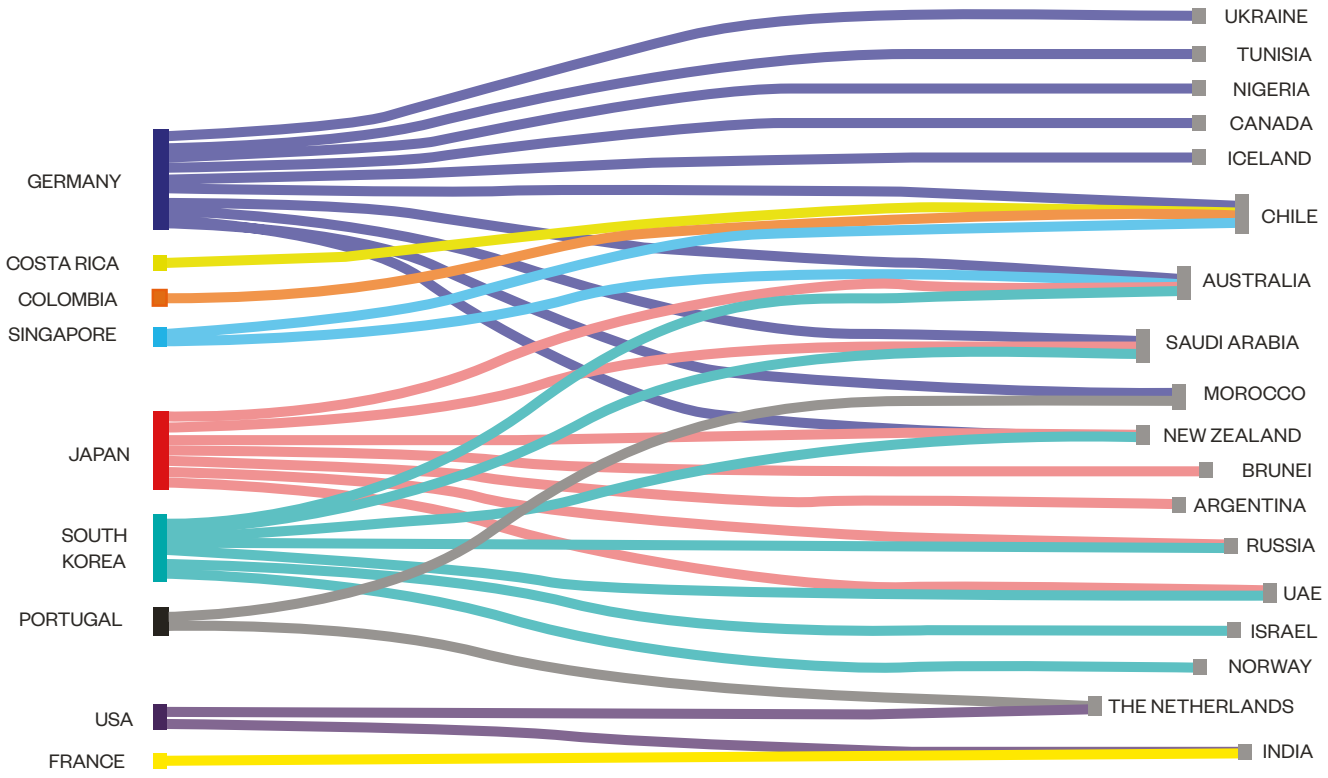
This shows countries that have currently identified their import/export preference. We see significant growth opportunities as countries around the world clarify their positions as they seek to enhance their energy security needs.

4 Demand side dynamics: renewable energy production poses massive economic opportunities for all stakeholders

As the (IEA) Net Zero Emissions by 2050 scenario outlines, in order to decarbonise the world, electricity demand will need to increase to 60,000 TWh, up from 23,230 TWh in 2020. Specifically, the demand for hydrogen-based solutions is expected to increase sharply from countries without the capacity to produce sufficient renewable hydrogen to meet their green targets. IEA's Net Zero Emissions by 2050 scenario states electricity demand for hydrogen production (including synthetic ammonia) is expected to be 14,500 TWh by 2050. All hard-to-abate sectors, including shipping, cement and steel, will require these fuels to reach decarbonisation targets. This should give investors confidence to back the most promising hydrogen production sites and logistics, including those in developing economies. Shipping offers the security of cost effective supply of (net) zero carbon fuels from a multitude of exporting countries to receiving countries across the globe. High fossil fuel prices – driven both by market scarcity and carbon pricing – will help to develop the hydrogen market further.

Given the expected production cost differentials across the world (expected range of €72.60/MWh to €156.40/MWh in 2050), the global trading of hydrogen could create substantial benefits for exporting and importing countries. The first international cooperation projects between countries have already been established. Over time, these bilateral initiatives should merge into a truly global, harmonised and level playing field. The global value chain can benefit from accepted global standards for contracts and quality. Most of the bilateral agreements will spur maritime transport demand as they will likely need to be shipped over long distances, whilst offering flexibility to supply and demand hubs.

Shipping's decarbonisation is deeply intertwined with the wider energy transition and the industry will compete for (net) zero carbon fuels with other sectors. Production facilities for new bunkering fuels need to be within easy access of ports, unless future technologies and bunkering systems permit otherwise. Estimates show a production potential of more than 10,000 TWh for (net) zero carbon fuels in coastal regions worldwide making the case for immediate investment.



Bilateral agreements on hydrogen.

Source: Based on the World Energy Council, National Hydrogen Strategies, 2021.

5 Invest in infrastructure and RD&D now or economic opportunities will be delayed

Substantial investment is needed to achieve the enormous potential for (net) zero carbon fuels, including hydrogen, hydrogen-based fuels and sustainable biofuels. Funding for Research, Development and Demonstration (RD&D) from both industry and the public sector, as well as for production facilities and transport infrastructure around emerging fuel hubs is imperative. Despite some promising announcements and plans, there continues to be a lack of investment in zero-emission technologies, with the IEA highlighting that the total amount of corporate R&D investment for maritime has decreased, from $2.7 billion in 2017 to $1.6 billion in 2019.

Fuel exporters seeking financing will want proof of a stable demand outlook for (net) zero carbon fuels, including hydrogen, in order to present bankable projects. To achieve this physical infrastructure will need to be established at pace, as well as generic trading infrastructure. The latter might already be available within existing global trading houses for commodities. To meet all these challenges coordinated global efforts are needed.

There is a significant opportunity for the development finance community to catalyse the global energy transformation and de-risk future investments. Investment in renewable projects in developing economies does not always present the scale needed to meet the requirements of development finance institutions, leading to what is sometimes referred to as a lack of bankable projects. Investing in larger scale generation, production and transportation infrastructure enables existing development finance to be unlocked creating a strong pipeline of bankable projects that meet development finance criteria. Such early investment would send a significant market signal, which can then be easily scaled when additional revenue sources are available. Without re-risking investment economic opportunity for all could be delayed.

Additional investment is key. This will accelerate technology-readiness levels, increase demonstration and deployment to reach the required scale of production, and drive down production costs of (net) zero carbon fuels within this decade.

Abbreviations

AME	Andes Mining and Energy
BIMCO	Baltic and International Maritime Council
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture utilisation and storage
CDR	Carbon dioxide removal
CII	Carbon Intensity Indicator
CIS	Commonwealth of Independent States
CO_2	Carbon dioxide
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EFET	European Federation of Energy Traders
EJ	Exajoule
ESMAP	Energy Sector Management Assistance Program
EU ETS	European Union Emissions Trading Scheme
FAME	Fatty acid methyl esters
GDP	Gross domestic product
GHG	Greenhouse gas
GW	Gigawatt
HFO	Heavy fuel oil
ICAP	International Carbon Action Partnership
ICS	International Chamber of Shipping
IEA	International Energy Agency
IMO	International Maritime Organization
IMRF	IMO Maritime Research Fund
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISDA	International Swaps and Derivatives Association
Kw	Kilowatt
LCA	Life cycle assessment
LCOE	Levelised cost of electricity

LNG	Liquefied natural gas
LOHC	Liquid organic hydrogen carriers
MDO	Marine diesel oil
MENA	Middle East and North Africa
MEPC	Marine Environment Protection Committee
MGO	Marine gasoil
MOU	Memorandum of understanding
MSD	Medium speed diesel
Mt	Megatonne (one million tonnes)
NPV	Net present value (NPV)
NZE	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
PtL	Power-to-Liquid
PtX	Power-to-X
PV	Photovoltaic
RD&D	Research, Development and Demonstration
SABIC	Saudi Basic Industries Corporation
SEEMP	Ship Energy Efficiency Management Plan
SOx	Sulphur oxides
SSD	Slow speed diesel
TWh	Terawatt-hour
VLGC	Very large gas carrier
VLSFO	Very low sulphur fuel oil
WEC	World Energy Council

Definitions

Abatement In this report, abatement means reducing or eliminating greenhouse gas emissions.

Biofuel A fuel produced from organic material (biomass) including plant materials and animal waste.

Blue hydrogen Produced from natural gas, with CO_2 emissions captured by Carbon Capture Utilisation and Storage (CCUS).

Carbon intensity indicator (CII) An IMO measure, the CII measures how efficiently a ship transports goods or passengers and is given in grams of CO_2 emitted per cargo-carrying capacity and nautical mile. The ship is then given an annual rating ranging from A to E, whereby the rating thresholds will become increasingly stringent towards 2030. (courtesy DNV)

Energy Efficiency Design Index (EEDI) An IMO measure, the EEDI is a carbon design/technical efficiency indicator that provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO_2) per ship's capacity-mile (the smaller the EEDI the more energy efficient ship design) and is calculated by a formula based on the technical design parameters for a given ship. The EEDI applies to new ships.

Energy Efficiency Existing Ship Index (EEXI) An IMO measure, the EEXI is a carbon design/technical efficiency indicator which is applicable to most in-service vessels over 400 Gross Tonnes (GT) and operating internationally. It is similar to its predecessor, the Energy Efficient Design Index (EEDI), but applies to existing ships outside EEDI regulations. Emissions are described per cargo tonne and mile. The EEXI is scheduled to come into force on 1 January, 2023.

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

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

Market foreclosure The production limitation put on a producing organisation if either it is denied access to a supplier, or it is denied access to a downstream buyer.

Net zero carbon fuels Fuels with a closed carbon cycle.

Ship Energy Efficiency Management Plan (SEEMP) An IMO measure, the SEEMP provides guidance on procedures and practices aimed at improving the energy efficiency and conservation on board ships.

Synthetic fuel A liquid or gaseous fuel from a source such as coal, shale oil, tar sands, or biomass, used as a substitute for oil or natural gas. In this report the term synthetic fuels, or synfuels, refers both to hydrogen produced from renewable electricity, and to fuels derived from hydrogen, such as ammonia and methanol.

Zero carbon fuel Fuels that do not contain carbon.

1 Introduction

The internationally agreed goal to limit global warming to well below 2°C compared to pre-industrial levels requires a climate-neutral world by the middle of this century. The IMO adopted in 2018 an initial strategy on the reduction of GHG emissions from ships, underlining its commitment to abating international shipping emissions.

One key element of decarbonisation is to increase electrification based on climate-neutral power generation. This solution can be applied in some instances to the mobility sector, e.g., for private transport via electromobility and electric trains. However, this type of solution will not work for all sources of GHG emissions. Many transport modes rely on the high energy density of fuels, and storing liquid or gaseous fuels is much easier than storing electricity. Hence, synthetic hydrogen-based fuels and biofuels[1] are expected to be part of the future global energy supply for those sectors with hard-to-abate GHG emissions.

Synthetic hydrogen-based fuels and biofuels are expected to be traded globally; this approach substantially enhances the security of supply and helps to keep the market price of these fuels at a competitive level. Consequently, maritime transport will be an important enabler of affordable climate-neutral solutions. The reliable supply of synthetic fuels and biofuels will give consumers enough confidence to switch to these fuels, meaning that producers can expect reliable demand. This will be key to ramping up both the production sites for these fuels and the adoption of relevant technologies in the consumption sectors.

> Maritime transport enables the realisation of climate-neutral solutions by facilitating global trade in synthetic fuels and biofuels.

Strong global demand for synthetic fuels and biofuels opens completely new opportunities for many developing countries that have excellent conditions to produce climate-neutral electricity in a very cost-efficient way, and consequently to produce biofuels at a competitive cost. Increasing demand for (net) zero carbon fuels in developed economies and from international consumers, such as aviation and maritime transport, offers interesting growth opportunities for developing countries. Backed by stable demand for these fuels, projects can be financed by multilateral development banks such as the World Bank, the Interamerican Development Bank or private investors. Perhaps more important for the exporting countries, these realised projects may also work as a nucleus for stronger electrification and sustainable development. Thus, global trade in (net) zero carbon fuels stands to facilitate equitable global development with widespread benefits.

> Global trade in (net) zero carbon fuels can lead to equitable development of non-OECD countries.

Appropriate infrastructure is needed at ports to establish global trade, including facilities for bunkering and distributing fuels. This infrastructure will also facilitate global trade in synthetic fuels and biofuels. In many locations this infrastructure is already established for crude oil, oil derivatives, liquefied natural gas (LNG), ammonia, methanol and biofuels. Hence, expertise in dealing with synthetic fuels and biofuels is present in all elements of global trading. The physical infrastructure for distribution, transport and storage might develop either by enhancing existing infrastructure or by building dedicated new infrastructure using existing competence and knowledge. This would ensure a rapid ramp-up in the supporting infrastructure. Similarly, expertise on the rules of trade is needed, including standardised contracts, product definitions and dealing with international customs, tariffs, duties and taxes. This expertise has existed in the maritime shipping industry for decades for fuels such as crude oil, coal and LNG and hence can easily be extended to the new fuels.

1 In this report the term synthetic fuels, or synfuels, refers both to hydrogen produced from renewable electricity, and to energy carriers derived from such hydrogen, such as ammonia and methanol.

> Global maritime trade in synthetic fuels and biofuels can build on vast existing expertise and knowledge, both for physical trading and the rules of trade.

Additionally, synthetic fuels and biofuels will help the maritime sector to decarbonise alongside other transport modes such as heavy-duty vehicles and international aviation. Climate-neutral maritime transport can be achieved together with further measures, especially energy efficiency. Consequently, the increasing availability of (net) zero carbon fuels will help the maritime sector to achieve climate neutrality in an environmentally and economically sustainable manner. Vessels that are capable of using more than one fuel will be better placed to make the decarbonisation transition than vessels that can only use one type of fuel. Additionally, being capable of using more than one fuel is also a better hedge against adverse market movements in a specific (net) zero carbon fuel.

> Global availability of synthetic fuels and biofuels at dedicated ports can pave the way to climate-neutral maritime transport.

Since synthetic fuels (including hydrogen) and biofuels will be used in various sectors to abate carbon dioxide (CO_2), it is imperative from an economic point of view to use these fuels in applications where the marginal cost of GHG abatement is lowest. This is the case for many industrial use cases as well as for road transport. Consequently, especially during the ramping-up of production facilities for hydrogen-based fuels and biofuels, the comparatively low supply of (net) zero carbon fuels might be used primarily in these sectors with their low GHG abatement costs. Non-economic factors such as public perception and national regulations might also influence investment decisions, leading to an economically less favourable outcome.

> The faster the global scaling up of hydrogen production will be, the faster maritime shipping can leverage that scale-up for demand making it easier for the shipping industry to access synthetic fuels.

The maritime sector can prepare itself for the large-scale use of (net) zero carbon fuels. First, it can increase its efforts with regard to energy efficiency. This will help to reduce the future demand for fuels and reduce the fuel bill for each ship. Consequently, the economics of applying (net) zero carbon fuels will improve. Second, RD&D on engines and fuel storage is needed to enable shipowners to make the right investment decision and make an investment as robust as possible, although engine manufacturers are already well advanced in the development of ammonia engines, for example. Of particular interest will be solutions offering a multi-fuel approach – both for engines and fuel storage – which will allow the gradual phase-in of climate-friendly fuels while simultaneously reducing the share of conventional fuels.

> The maritime sector can prepare for a future with (net) zero carbon fuels by increasing energy efficiency ambitions and RD&D projects with (net) zero carbon fuels.

By enabling the international transport of synthetic fuels, and by creating the infrastructure for global trade in (net) zero carbon fuels, the maritime sector will enable many sectors with hard-to-abate GHG emissions to meet their climate targets.

The electricity sector was also viewed as a hard-to-abate sector at the start of this century, when climate change concerns led to the first attempts to reduce GHG emissions. Technological solutions existed in the form of renewable energy and nuclear technologies, and initial ideas on carbon capture were discussed and implemented. RD&D helped to reduce the cost of implementing the various climate-neutral technologies, allowing an industry to ramp up in parallel to produce the equipment needed for this dramatic and ongoing transformation of the electricity sector. While there is still much work to be done to decarbonise the electricity sector, it is interesting to note that electrification is now seen as an inevitable part of a climate-neutral future. The maritime sector will follow a similar path and also become part of the solution as a key enabler of a truly global climate-neutral economy.

2 Climate-Neutral Scenarios

2.1 Overview

Various scenarios describe the path towards a climate-neutral world. Despite major differences, they do have relevant things in common:

- (Net) zero carbon fuels are needed in all available forms: synthetic hydrogen-based fuels, biofuels, and fossil fuels in combination with carbon capture, utilisation and storage (CCUS)[2] and carbon dioxide removal (CDR)[3];
- All sectors, including industry, transport and buildings, will consume (net) zero carbon fuels;
- These (net) zero carbon fuels will be traded globally; and
- Hydrogen-based fuels will play a decisive role as fuel for maritime transport.

The main focus of this chapter is the development of the fuel mix in these scenarios. Various scenario results from IEA, IRENA, BP and others are presented and analysed. These scenarios offer important insights for the potential development of the shipping sector towards 2050. It is important to understand that scenarios describe possible future worlds depending on certain assumptions. Hence, they should not be understood as forecasts or predictions, but instead as potential outcomes depending on the scenario assumptions, e.g., future policies and regulatory framework favouring the use of (net) zero carbon fuels, as well as the ability to enforce such decarbonisation enabling framework.

2.2 IEA Net Zero by 2050

In May 2021 the IEA published their roadmap for the global energy sector: Net Zero by 2050.[4] Its basis is that a net zero energy system is the prerequisite to limit the global temperature rise to 1.5°C as stated in the Paris Agreement of 2015. With the Net Zero Emissions by 2050 Scenario (NZE), the IEA sets out a pathway for the global switch from fossil fuels to (net) zero carbon fuels.

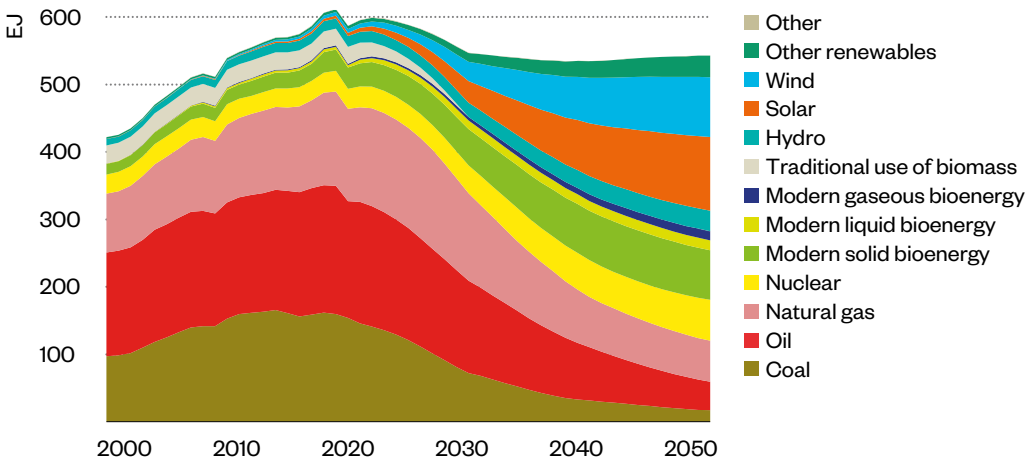


Figure 2.1: The changing energy mix of the total energy supply in the IEA NZE scenario – the currently dominating fossil share (oil, coal, gas) will be mainly replaced by renewable sources
Source: IEA, Net Zero by 2050, 2021

2 CCUS as a technology class reduces GHG emissions by capturing CO_2 and either uses it as raw material for further processes or stores it permanently. With this technology class, the captured GHGs are not emitted to the atmosphere.

3 CDR (also called negative emissions technology) describes a way to remove GHGs from the atmosphere, for example by creating carbon sinks with afforestation or with technological solutions such as direct air capture (DAC), where CO_2 is directly captured from the ambient air.

4 IEA, *Net Zero by 2050 - A Roadmap for the Global Energy Sector*, Paris, 2021

Under the NZE, the size of the total world energy supply is almost stable by 2050: increasing prosperity triggers higher demand, which is partially compensated by energy efficiency gains. Conventional fossil fuels (coal, gas and oil) decrease strongly from 464EJ (2020) to 105EJ (2050). While energy from fossil fuels has a strong decline, it does not vanish completely and is made climate friendly by using CCUS and CDR technologies. Renewable energy consumption increases strongly from 69EJ (2020) to 362EJ (2050), while nuclear rises from 29EJ to 61EJ.

Currently, fossil fuels are transported from production centres to supply centres, for example crude oil from the Middle East is shipped to Asia and Europe. Nevertheless, the replacement of fossil fuels by renewable sources will not reduce the need for global energy trade. As some regions have better conditions to produce renewable energy compared with others (e.g., higher and more constant wind speeds, higher solar irradiation, more available space due to lower population density), the production of renewable energy is likely to focus on these areas. Consequently, it will need to be transported from these supply areas to demand centres as necessary. The transport of this energy is then possible via biofuels (solid, liquid, gaseous) and via hydrogen-based synthetic fuels such as methanol and ammonia, produced from climate-neutral energy sources.

Similarly, the current non-energetic use of fossil fuels as feedstock for processes (e.g. oil or natural gas in the chemical sector or coal in steel manufacturing) will be replaced by hydrogen-based synthetic fuels. Consequently, the demand for synthetic (net) zero carbon fuels will not only be driven by the energy demand, but also by industrial demand.

Thus, synthetic fuels and biofuels are an important cornerstone for achieving climate-neutrality in hard-to-abate sectors (e.g., transport and industry), where a fuel switch away from fossil fuels towards (net) zero carbon fuels is then enabled.

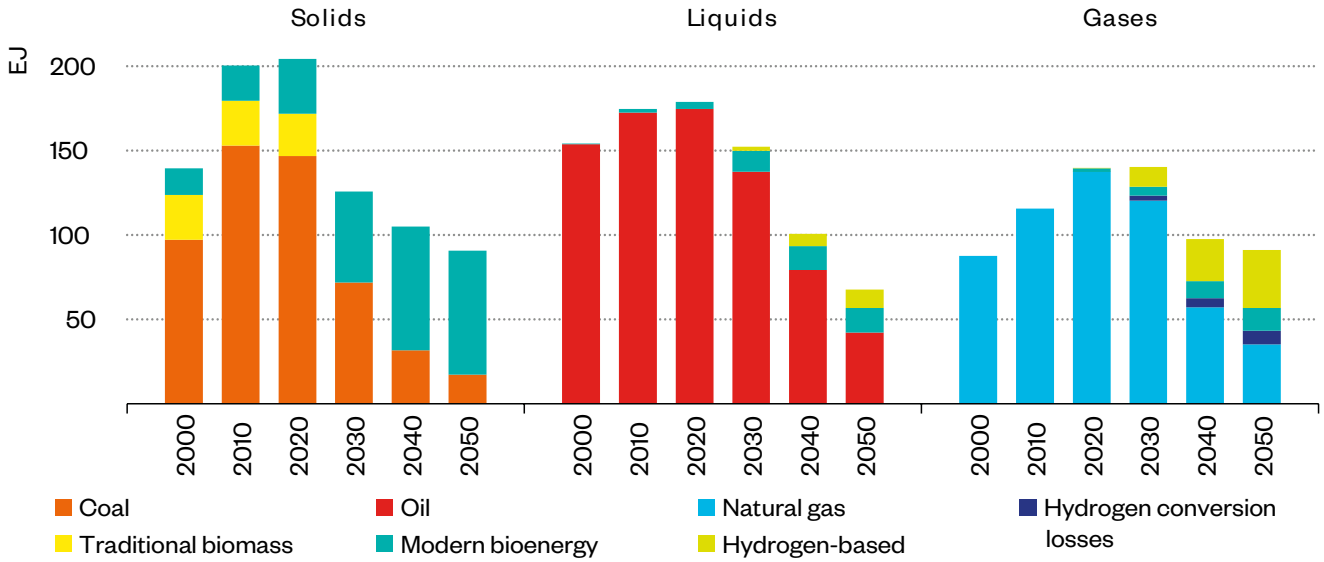


Figure 2.2: The transition in fuels under the IEA NZE scenario renewable sources will replace fossil fuels over time

Source: IEA, Net Zero by 2050, 2021

KEY POINT:

The decline of fossil fuels will be partially compensated by biofuels and hydrogen-based fuels.

In the NZE, biofuels and hydrogen-based fuels increase their share of the global fuel mix from 6% (2020) to 27% (2050). The IEA also points out that this is a sharp increase:

> *"The increase in gaseous hydrogen production between 2020 and 2030 in the NZE is twice as fast as the fastest ten-year increase in shale gas production in the United States."*

However, the increase would happen globally and not only in a single region. In the IEA scenario the installed electrolyser capacity increases from 850GW (2030) to 3,000GW (2045), i.e. an annual increase of slightly more than 140GW. However, this necessitates a rapid innovation phase up to 2030, with RD&D, demonstration projects and initial deployment to prove the technologies work sufficiently reliably and to drive down costs. Fossil fuels decrease their share in the global fuel mix from 79% (2020) to 17% (2050). Consequently, CCUS and CDR technologies are needed to achieve climate neutrality.

The CO_2 price in the NZE is $250 per tonne (t) CO_2 in advanced economies and $200/t CO_2 in emerging economies by 2050. For comparison, market prices in the EU emissions trading system (ETS) during 2021 have ranged between roughly €50/t and €90/t. The Swedish carbon tax – which is perceived as the most expensive carbon tax worldwide – was €114/t in autumn 2021.

The use of hydrogen-based synthetic fuels and biofuels covers applications in industry, transport and buildings to meet the goals of the Paris Agreement. Hydrogen and hydrogen-based synthetic fuels might in part be generated on-site using electricity. However, the strong demand and the use of the most economic production sites for hydrogen leads to the development of global trade in hydrogen over time. The IEA projects major exports from gas- and renewables-rich areas in the Middle East, Central and South America and Australia to the demand centres in Asia and Europe. It estimates that around half of global ammonia and a third of synthetic liquid fuels are traded in 2050. This would lead to a global trade of hydrogen-based fuels of 2.2 TWh.

Additional infrastructure at ports and in the maritime sector is needed to enable this trade. In the IEA scenario the number of export terminals at ports for hydrogen and ammonia trade increases to 150 by 2050 (from 60 by 2030), i.e. between 2030 and 2050 roughly five export terminals per year need to be established.

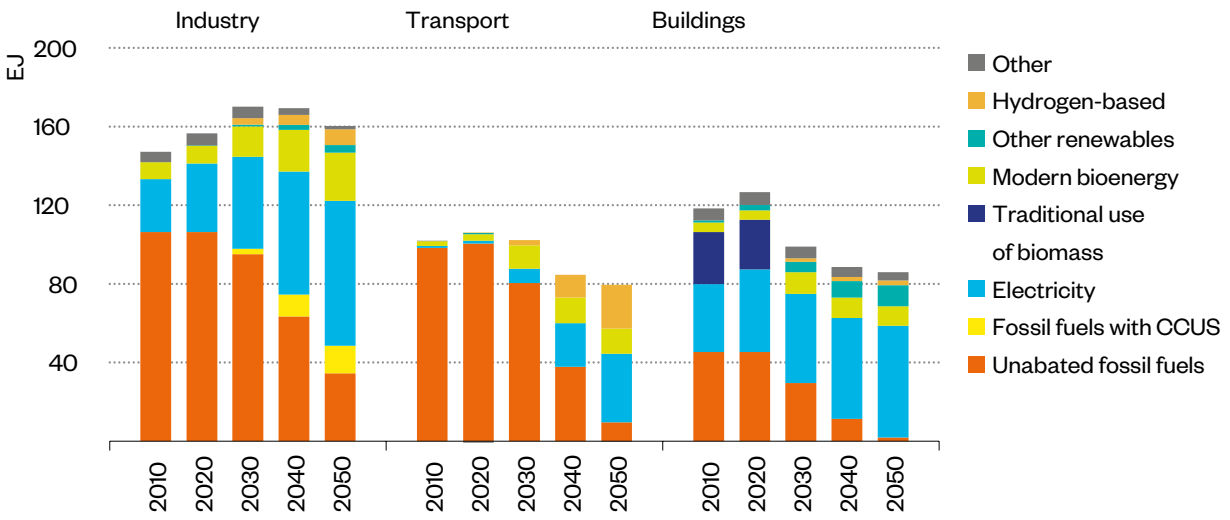


Figure 2.3: End-use energy consumption by source in the IEA NZE scenario

Source: IEA, Net Zero by 2050, 2021

KEY POINT:

End-use sectors switch from unabated fossil fuels to electricity, renewables, hydrogen-based fuels and CCUS.

> The IEA points out the essential role of hydrogen-based fuels and biofuels for all sectors to achieve climate neutrality and the need for global trade in these fuels.

With regard to maritime transport, the IEA highlights the long lifetime of vessels, which is up to 35 years. Consequently, shipping might be one of the few transport modes that will not become climate neutral by 2050. Nevertheless, in the IEA NZE scenario shipping emissions are reduced by 6% per year and decrease to 120 million tonnes (Mt) CO_2 in 2050. The IEA notes a lack of easily available low-carbon options. Whereas energy efficiency and other operational measures (e.g., wind assistance) lead to short-term gains, switching to (net) zero carbon fuels (biofuels, hydrogen, ammonia) delivers major abatement in the long term. One should note that drop-in fuel solutions will enhance decarbonisation, since the use of these fuels can be done with existing ships and existing engines without modifications or only small modifications.

In the IEA's NZE scenario, ammonia and hydrogen consumption combined reaches a share in the maritime fuel mix of around 60% in 2050 (see Figure 2.4) to become the largest propulsion energy source in maritime, while the share of sustainable biofuels reaches almost 20%. Electricity is not considered a major solution for the maritime sector, since the energy density of batteries is substantially lower than the density of liquid fuels. Hence electricity might play a role only for short travel distances.

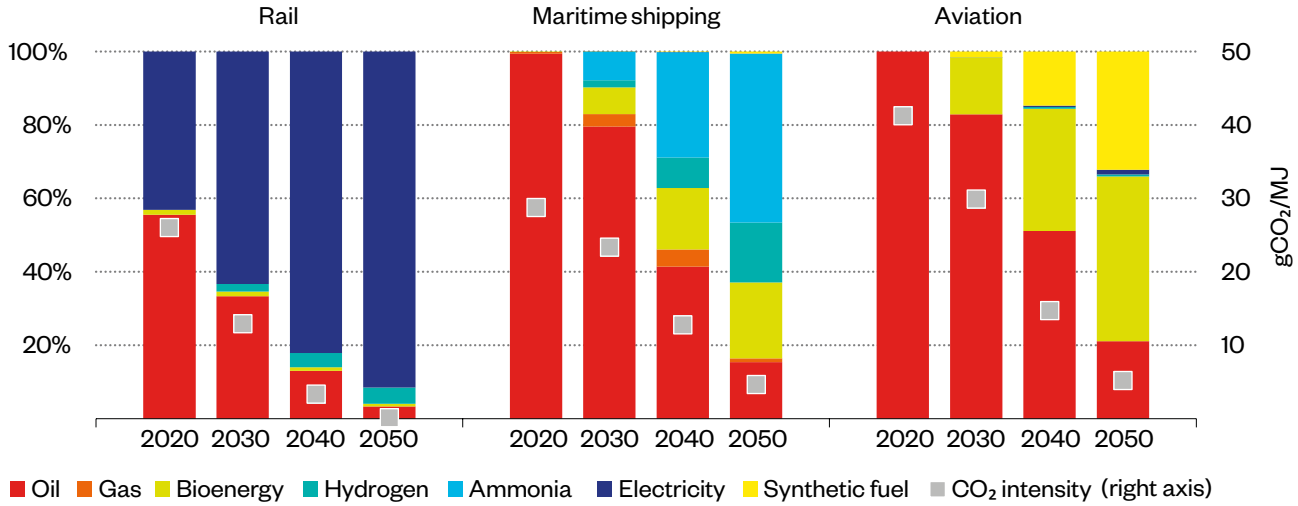


Figure 2.4: Global energy consumption by fuel and CO_2 intensity in non-road sectors in the IEA NZE scenario. Hydrogen-based fuels to gradually become the largest energy source for maritime

Source: IEA, Net Zero by 2050, 2021

KEY POINT:

(Net) zero carbon fuels will play a decisive role in maritime shipping and aviation, whereas rail transport will be decarbonised overwhelmingly by electricity.

2.3 BP Net Zero in 2050

The BP Energy Outlook 2020[5] considers, inter alia, a Net Zero 2050 scenario, which can be compared immediately with the IEA NZE Scenario. In total, the BP Energy Outlook defines three scenarios, Rapid, Net Zero and Business-as-usual, for in-depth discussion.

In the Rapid Scenario, the global temperature rise is limited to well below 2°C by 2100 due to measures reducing GHG emissions from energy use by roughly 70% by 2050. The Net Zero Scenario assumes further

5 BP, *Energy Outlook 2020*, 2020

measures to the Rapid Scenario, leading to a 95% fall in GHG emissions by 2050, limiting the temperature rise to 1.5°C. Business-as-usual is a reference scenario, where current government policies and technologies evolve with the same speed seen in the past.

BP also qualifies some sectors as hard to abate, i.e. these sectors are difficult to electrify, leading to the need for other low-carbon fuels. Apart from the marine sector, this is also the case for aviation, heavy-duty trucks, iron and steel, cement and chemicals.

The results from BP are very similar to the IEA NZE: a strong increase in the renewables share of the fuel mix, which again necessitate global trade between production and consumption centres. Both the BP Net Zero and IEA NZE scenarios calculate a carbon price, for BP Net Zero scenario it reaches a level of $250/t CO_2 (2050).

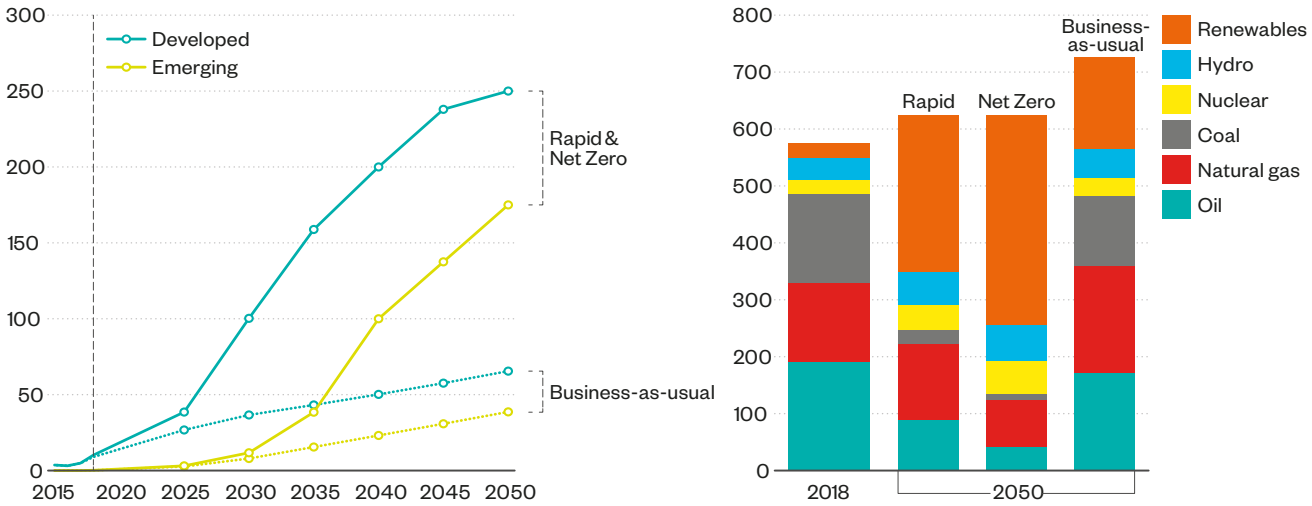


Figure 2.5: Average carbon prices in developed and emerging regions (left), and primary energy consumption by source (right), in the BP scenarios

Source: BP, Energy Outlook 2020, 2020

KEY POINT:

The fuel mix in the BP Net Zero Scenario is dominated by renewables; the carbon price in this scenario increases to up to $250/t CO_2.

Again, the high renewable share in the fuel mix – partially transformed into green hydrogen – leads to international trade. The BP scenario shows a similar magnitude of hydrogen consumption as the IEA NZE Scenario (BP Net Zero 44% and IEA NZE 63%), although for biomass BP is more conservative. Both the IEA and BP are also more conservative on biomass than the Intergovernmental Panel on Climate Change (IPCC) scenario.[6] However, apart from the size of the contribution, biofuels and synthetic fuels based on hydrogen are viewed as essential contributors in all scenarios. And again, the strongly reduced but still present use of fossil fuels in the global energy mix leads to CCUS and CDR as key technologies to reach climate neutrality.

6 Another recent study by Enerdata even assumes that by 2029 global biofuel production may reduce sharply: Enerdata, *Biofuel evolution perspectives: Analyst Brief*, August 2021

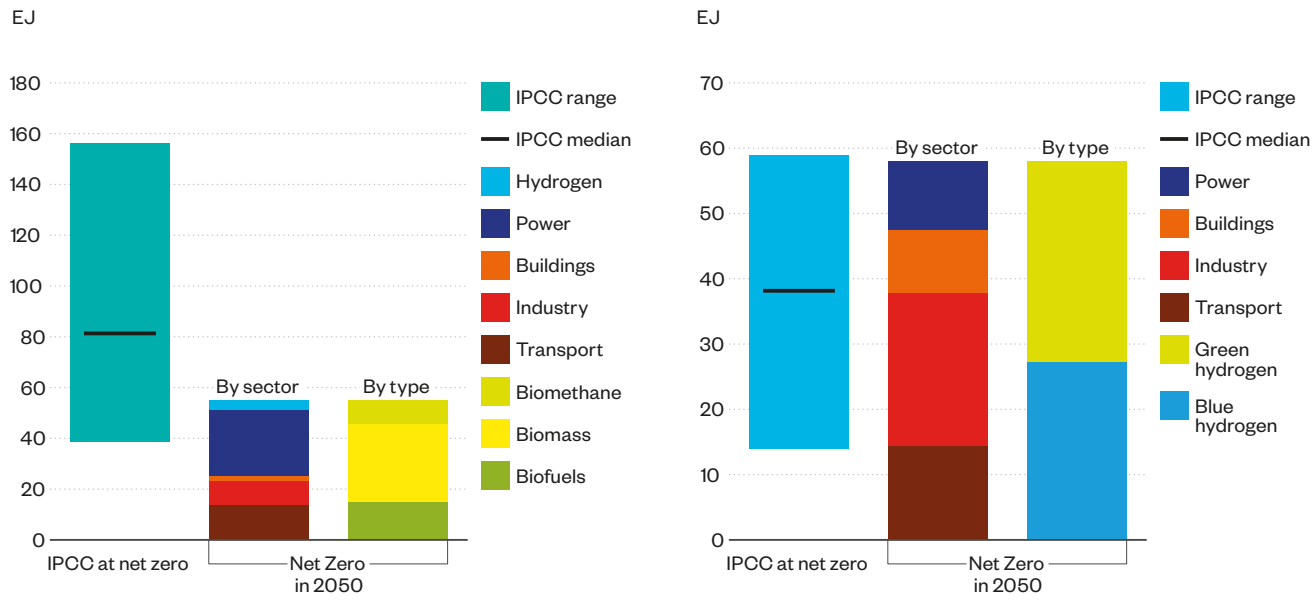


Figure 2.6: The role of bioenergy (left) and hydrogen (right) in the BP Net Zero Scenario, compared with the IPCC scenario

Source: BP, Energy Outlook 2020, 2020

BP's Energy Outlook also considers the regional development of energy demand. Global growth in energy demand can be seen in all three scenarios. There is however a difference between developed and developing economies energy demand in BP scenarios. Developed economies show a slight decrease in total energy consumption, and emerging countries an increase. This essentially leads to the conclusion that in developed economies the energy transformation is only a change of the type of fuel in the energy mix, whereas emerging economies have to address both a change of type of fuel and a higher demand growth of fuels.

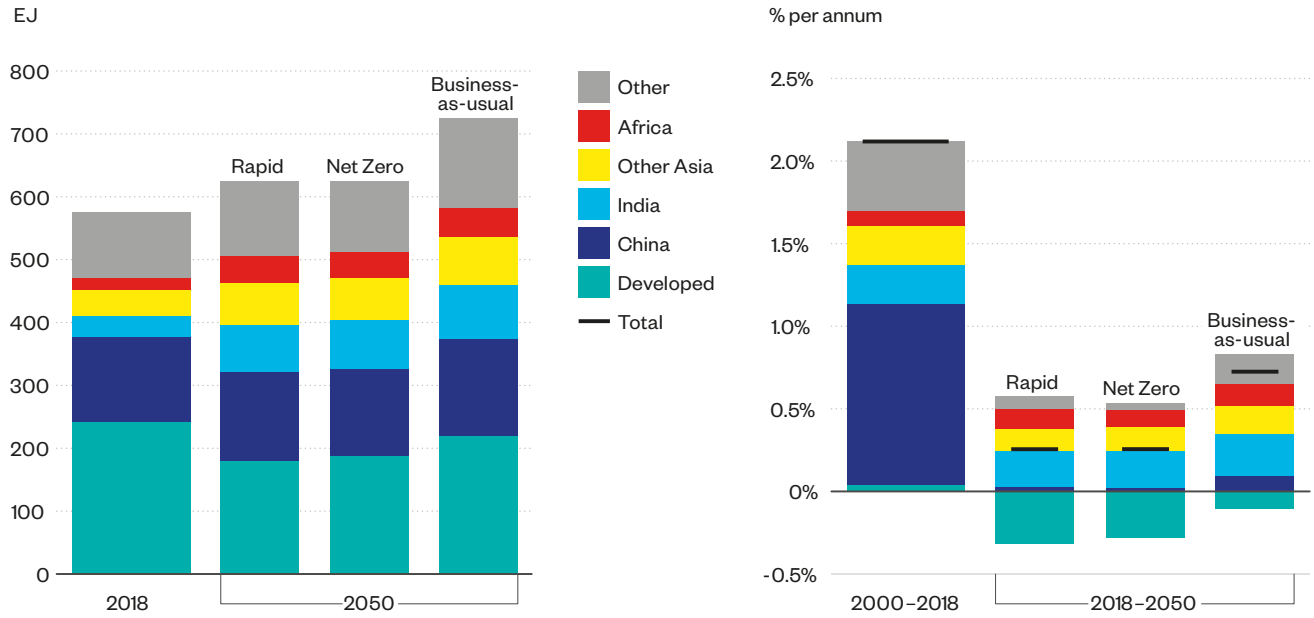


Figure 2.7: The regional development of energy consumption, total consumption (left) and growth rates (right), in the BP scenarios

Source: BP, Energy Outlook 2020, 2020

BP also provides some insights with regard to scenarios for transport sectors.

Primary energy demand in the marine sector only increases in the Business-as-usual Scenario, from 11EJ in 2018 to 13EJ in 2050. In the Rapid Scenario it sees a small decrease to 10EJ in 2050, and in the Net Zero Scenario even further to 7.6EJ in 2050. In the Rapid Scenario the increased levels of trade keep the demand somewhat stable, while in Net Zero an increasing preference for the consumption of locally produced goods and reduction in oil trade contribute to reduced shipping demand by around a third by 2050 relative to Business-as-usual.

In contrast to aviation, the shipping sector can diversify its fuel mix more broadly and use hydrogen (either as liquid hydrogen or as ammonia), LNG[7] and biofuels. In Rapid and Net Zero, non-fossil fuels account for 40% and 85% of marine transport fuel by 2050 respectively, with more than half of that from hydrogen. Conversely, under Business-as-usual, marine demand for oil increases slightly by 2050, with natural gas increasing its share of the sector fuel mix to just under 15% and non-fossil fuels accounting for just 1%.

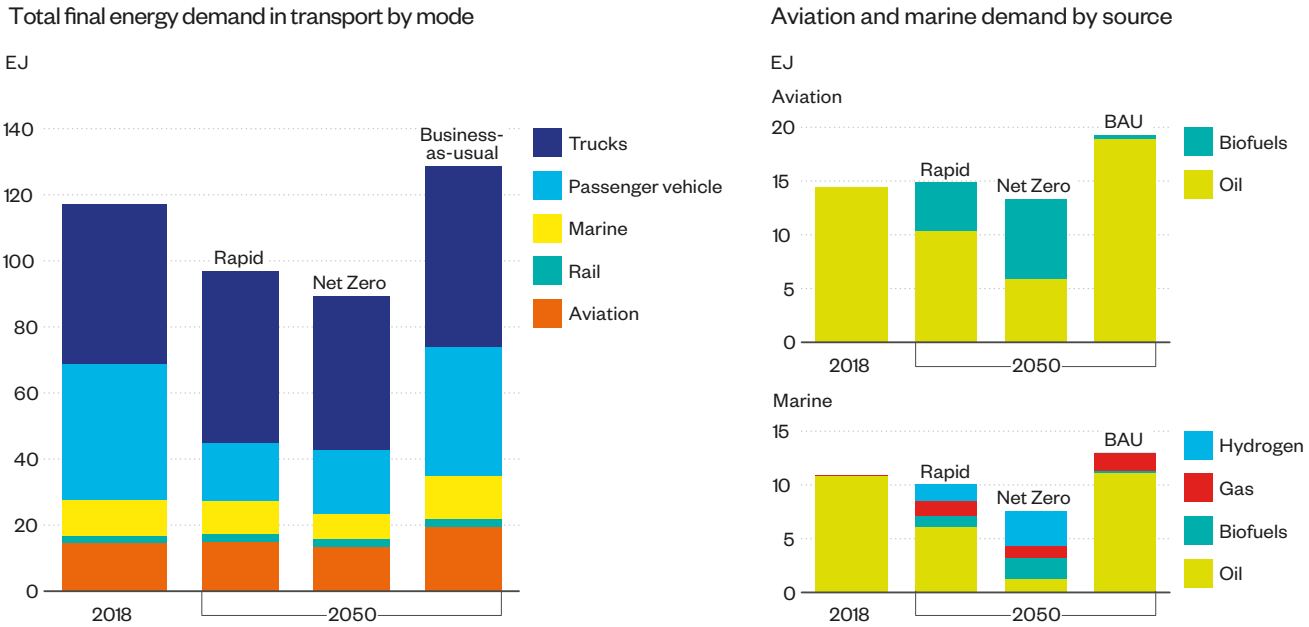


Figure 2.8: Final energy demand by transport mode by 2050 and energy source in the BP scenarios
Source: BP, Energy Outlook 2020, 2020

KEY POINT:
The development of the fuel mix in the BP scenarios: biofuels and hydrogen play a crucial role, especially in the Net Zero Scenario where hydrogen fuels become the largest energy source in the maritime sector by 2050.

Whereas the power sector is maritime transport's main competitor for biomass, industrial use cases such as cement and steel manufacturing are expected to be its main competitor for hydrogen. This leads to the conclusion that shipping will be competing with other industry sectors for hydrogen.

> BP emphasises the role of (net) zero carbon fuels both as hydrogen-based fuels and biofuels. Growing energy demand is mainly expected in emerging economies.

7 Although in recent years shipping has been adopting LNG as a fuel, there is currently concern over methane slip and fugitive emissions. Consequently, the rate of take-up may slow in the coming years. Nonetheless, synthetic methane (or e-methane) as a (net) zero carbon fuel might emerge as a solution in the future, hence a decision for LNG as ship fuel might be based on this expectation and consequently be very reasonable as a means to reach carbon-neutral transport.

2.4 Shell Sky 1.5

In the Shell report about Energy Transformation scenarios, three long horizon scenarios (up to the year 2100) were considered: Waves, Islands and Sky 1.5 scenarios. All three scenarios describe different reactions to the COVID-19 pandemic situation.

Only in Sky 1.5. the pace of change and timing are fast enough to limit global warning as agreed in the Paris agreement of 2015. The Sky 1.5 scenario is built on lessons from previous energy transitions and still ongoing transformations of the economy. Hence, the deployment of new technologies and their mass roll-out is heavily addressed as well as behavioural changes. This scenario is driven by a "health first" reaction to the COVID-19 crisis. Consequently, an accelerated decarbonisation takes place.

The ShellWaves scenario concentrates on the economic response to the COVID-19 crisis: "wealth first". Other goals are less important, however, after having fixed the economy, measures to meet the goal of the Paris Agreement are taken, leading to a late – but fast – decarbonisation.

In the Shell Islands scenario, the governmental and public reaction to COVID-19 is "security first". This leads to increasing nationalism and less global cooperation. Despite some progress of climate-friendly investments, the result here is also a late and slow decarbonisation.

The Shell Sky 1.5 Scenario[8] assumes an acceleration in global decarbonisation ambitions to come close to the goals of the Paris Agreement. To this end, a high level of international cooperation is needed, not only with regard to political alignment, but also with regard to economic and technological cooperation.

Whereas the IEA NZE mainly provides a global picture, the Shell Sky 1.5 Scenario also looks at regional development. One main outcome is that while energy consumption in OECD countries is stable, non-OECD countries see strong consumption growth in the coming decades.

This means that OECD countries will experience a qualitative change by replacing the existing energy system with a climate-neutral one. Meanwhile, non-OECD countries have the opportunity to leapfrog established technologies and implement climate-neutral solutions as their economies grow, albeit in the face of a huge challenge with regard to finance.

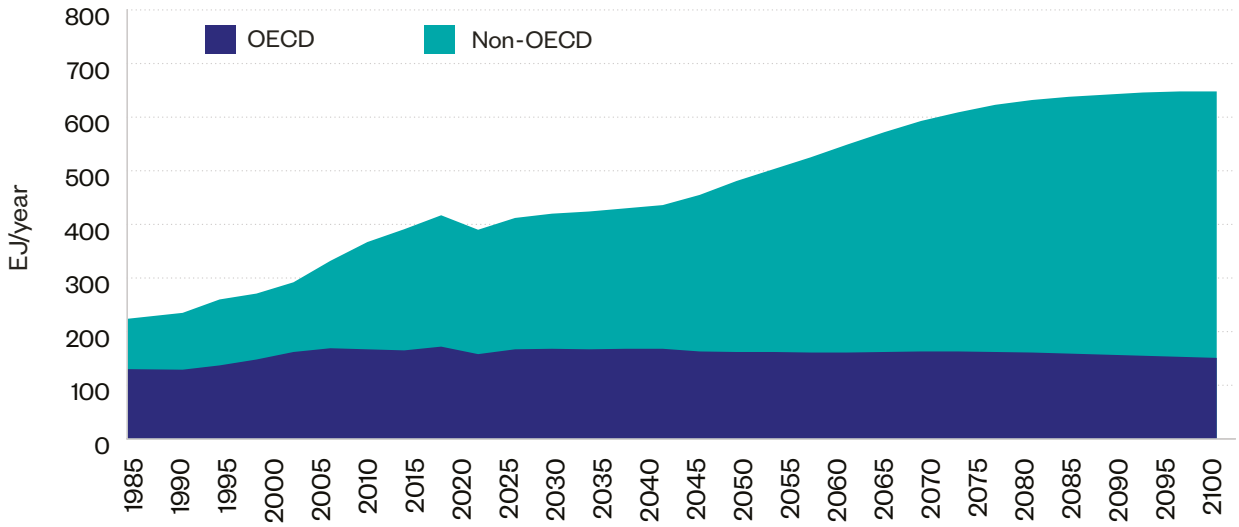


Figure 2.9: Final energy consumption in OECD and non-OECD countries in the Shell Sky 1.5 Scenario

Source: Shell, The Energy Transformation Scenarios, 2021

KEY POINT:

Growing energy demand originates almost completely from non-OECD countries.

8 Shell, *The Energy Transformation Scenarios*, 2021

As with the BP scenarios, Shell also mentions the hard-to-abate sectors and views maritime transport as one of them. Furthermore, Shell also refers to this sector as "hard-to-electrify". Consequently, liquid fossil fuels are replaced by biofuels and hydrogen in the Shell scenarios. Due to demand for fuels in other sectors (e.g. aviation and chemicals), for Shell, the maritime sector still consumes liquid hydrocarbon fuels (including biofuels) to a large extent by 2100.

In the Shell Waves Scenario, hydrogen demand is driven by the transport and buildings sectors; in the Islands Scenario, it is predominantly transport driving the demand; and in the Sky 1.5 Scenario, it is industry and transport. At the early stages, hydrogen supply is mainly from natural gas in combination with CCUS and from electrolysis with climate-neutral electricity.

The Shell scenarios assume the long-term use of liquid hydrocarbons (including biofuels) for maritime transport. Hence, the Shell scenarios do not lead to the disappearance of GHG emissions by 2100.

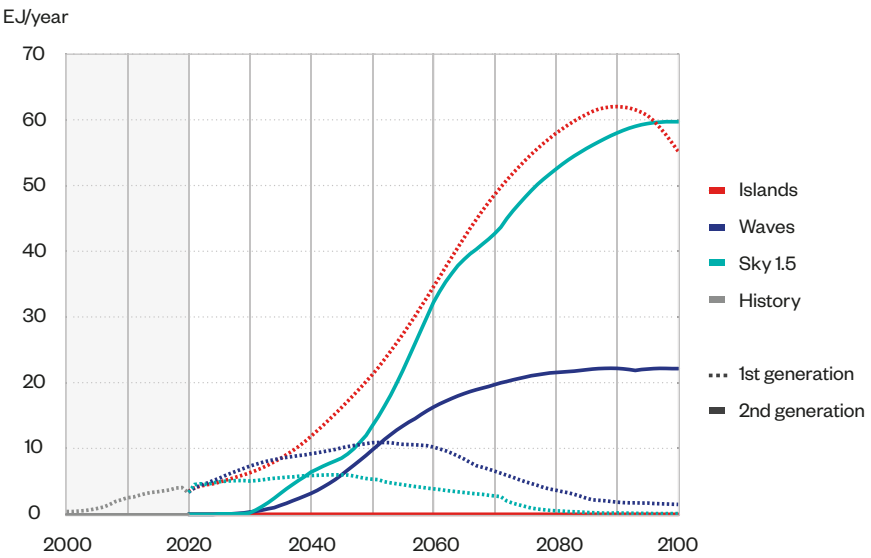


Figure 2.10: Demand for biofuels in the Shell scenarios – major increase comes beyond 2050

Source: Shell, The Energy Transformation Scenarios, 2021

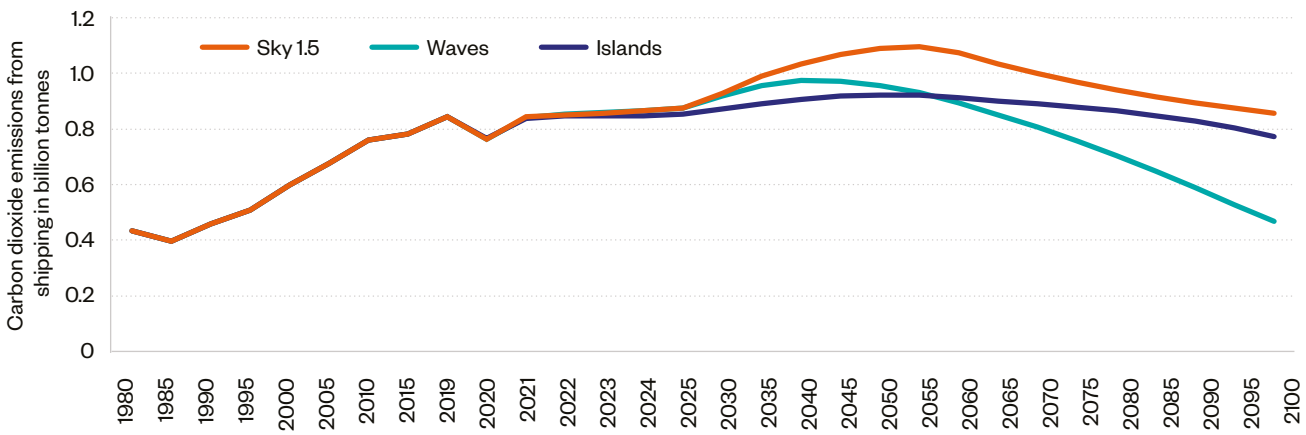


Figure 2.11: CO_2 emissions from the maritime sector (freight and passenger) in the Shell scenarios – major reductions occur after 2050

Source: Shell, The Energy Transformation Scenarios, 2021

Liquid hydrocarbon fuels dominate the fuel mix for freight transport by ship in the Sky 1.5 Scenario. Gaseous hydrocarbons and hydrogen only emerge very gradually.

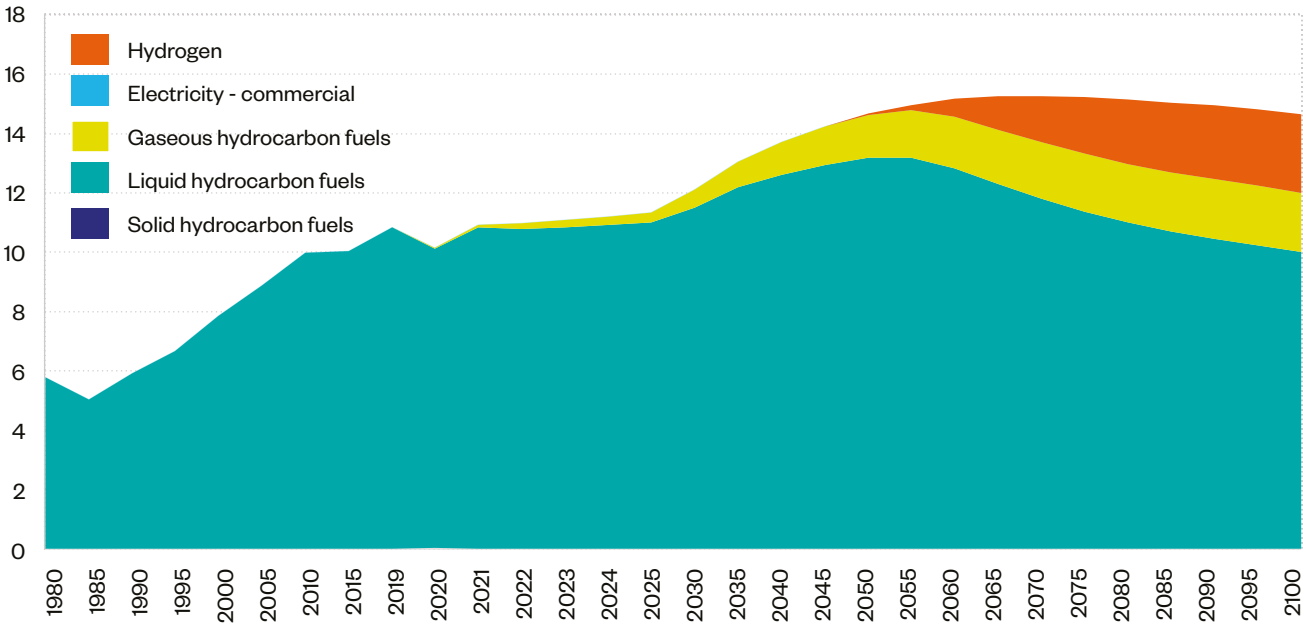


Figure 2.12: Fuel mix for maritime freight transport in the Sky 1.5 Scenario – hydrogen occurs late and to a very limited extent

Source: Shell, The Energy Transformation Scenarios, 2021

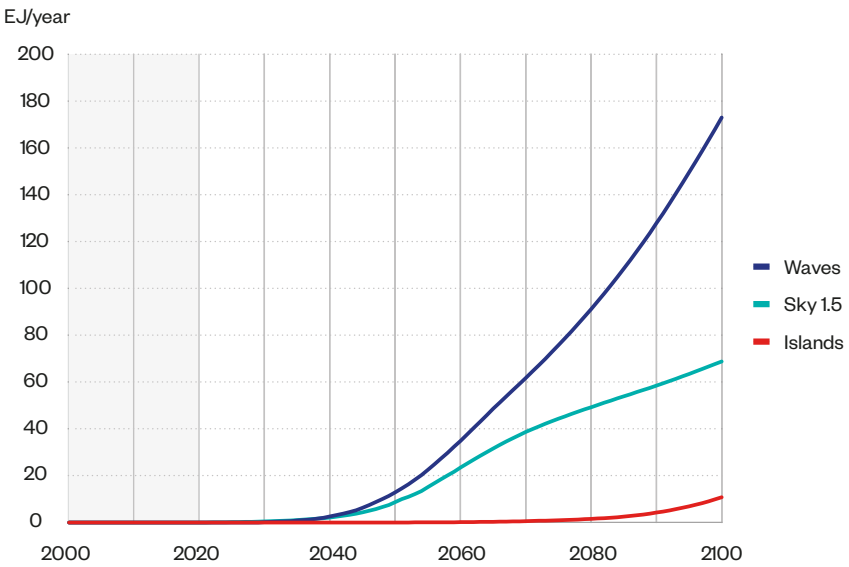


Figure 2.13: Hydrogen demand in the Shell scenarios

Source: Shell, The Energy Transformation Scenarios, 2021

KEY POINT:

In the Shell scenarios, the more that global cooperation is evident, the higher the use of hydrogen, indicating that global trade is highly beneficial to the usability of hydrogen.

In the long run Shell sees biofuel demand stagnating in all scenarios, whereas hydrogen continuously grows. This reflects the generic limitations of biofuels in contrast to the less limited options to produce hydrogen. Apart from its usefulness in various sectors both as a fuel and as a chemical feedstock, hydrogen's availability is also key to its ubiquitous use in many sectors.

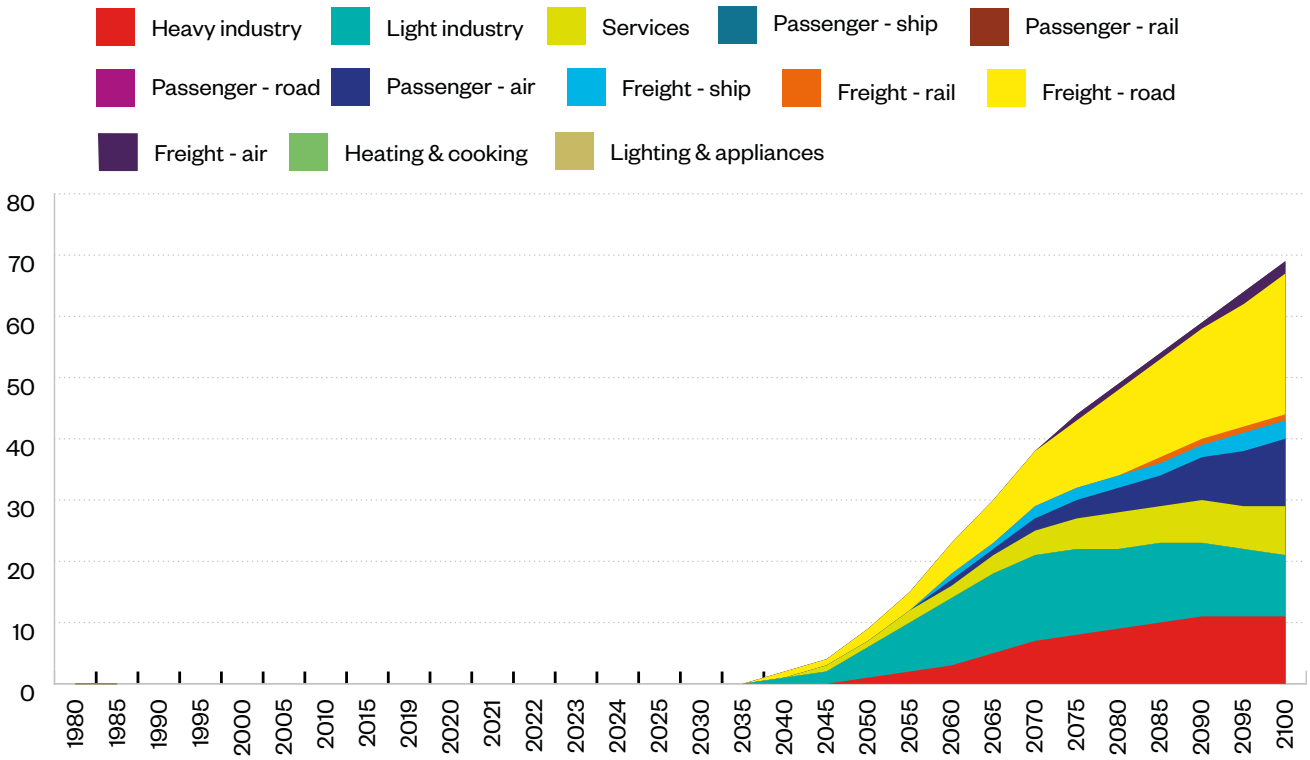


Figure 2.14: Hydrogen consumption in various sectors in the Sky 1.5 Scenario

Source: Shell, The Energy Transformation Scenarios, 2021

In the Sky 1.5 Scenario, shipping has a share of between 1% and 4% of annual global hydrogen consumption to 2100. In comparison, freight road transport has between 24% and 33%. Light industry has a share of over 50% in 2050, showing that this sector is the early mover in the hydrogen play, because there are limited alternatives for hydrogen as means to achieve climate neutrality. The maritime sector hence plays a somewhat limited role in hydrogen demand and consequently becomes a price taker.

Only in the Shell Sky 1.5 Scenario is the decarbonisation fast enough to limit the global temperature increase to 1.5°C. The Waves scenario assumes an "economy first" attitude as a reaction to the pandemic crisis and hence a late (but also fast) decarbonisation. The Islands scenario describes a world of increasing nationalism and less global cooperation, leading to late and slow decarbonisation.

Total final consumption by carrier (in %)	2050	2075	2100
Heavy industry	7	19	16
Light industry	53	31	15
Services	0	0	0
Passenger transport: ship	0	0	0
Passenger transport: rail	0	0	0
Passenger transport: road	14	11	12
Passenger transport: air	1	6	16
Freight transport: ship	1	4	4
Freight transport: rail	1	1	1
Freight transport: road	24	25	33
Freight transport: air	0	1	3
Residential: heating and cooking	0	0	0
Residential: lighting and appliances	0	0	0

Table 2.1: Share of hydrogen in the fuel mix of various transport modes in the Sky 1.5 Scenario

Source: Based on data in Shell, The Energy Transformation Scenarios, 2021

The Shell scenarios show a long-term growth story for hydrogen until the end of this century, driven by the long-term need for climate-neutral solutions. Shell considers hydrocarbons to continue to dominate the maritime sector by 2050.

2.5 Bloomberg New Energy Outlook 2021

In recent years BloombergNEF has regularly published its New Energy Outlook, describing long-term scenarios for the future energy world. The 2021 edition introduced three scenarios, each meeting the Paris Agreement goals (i.e., net zero emissions by 2050). All BloombergNEF scenarios (green, grey and red) use renewable energy to a large extent, complemented by various other technologies. The Green Scenario is characterised by the strong use of "green hydrogen"; the Grey Scenario complements renewables with CCUS technologies; and the Red Scenario assumes small modular nuclear reactors as an important energy source. The primary energy mix is consequently very different for the three scenarios.

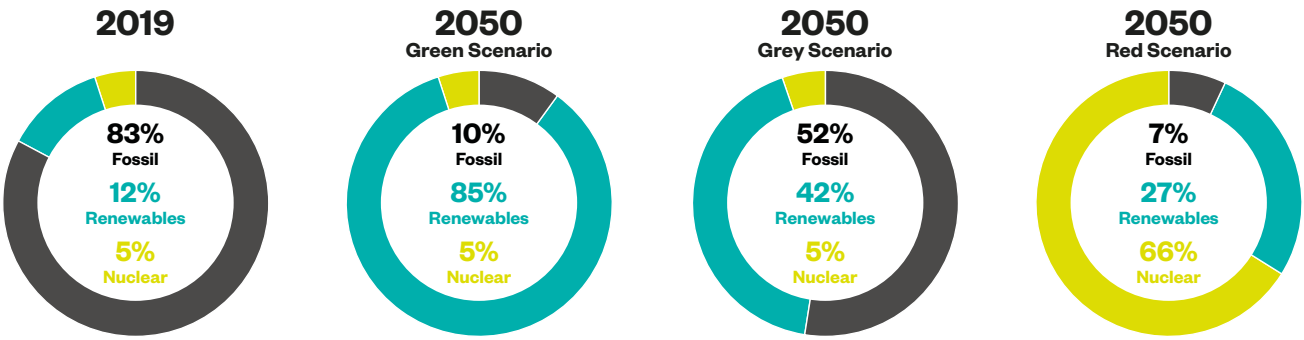


Figure 2.15: Global primary energy supply in Bloomberg NEF scenarios with a very different primary energy mix

Source: BloombergNEF, New Energy Outlook, 2021

Electricity plays a major role in all three scenarios: the share of electricity in total final energy is roughly 50% across all scenarios (the 2019 share is 19%). In the Grey Scenario, electricity generation is about 62,200TWh (more than double the global electricity production in 2019). In the Green Scenario almost half of the electricity generated is used to produce green hydrogen, hence total electricity production is 121,500TWh, which is double the amount in the Grey Scenario.

This leads to a demand for hydrogen of 190Mt in the Grey Scenario and 1.31 billion tonnes in the Green Scenario[9]. Hydrogen is used in almost all areas in the Green Scenario, making hydrogen the key replacement for fossil fuels. BloombergNEF points out that the massive scale-up needed for renewable generation is limited in regions with high energy consumption due to land constraints. Consequently, these countries might import hydrogen, shift domestic production to offshore renewables, or use other climate-friendly technologies such as CCUS or nuclear.

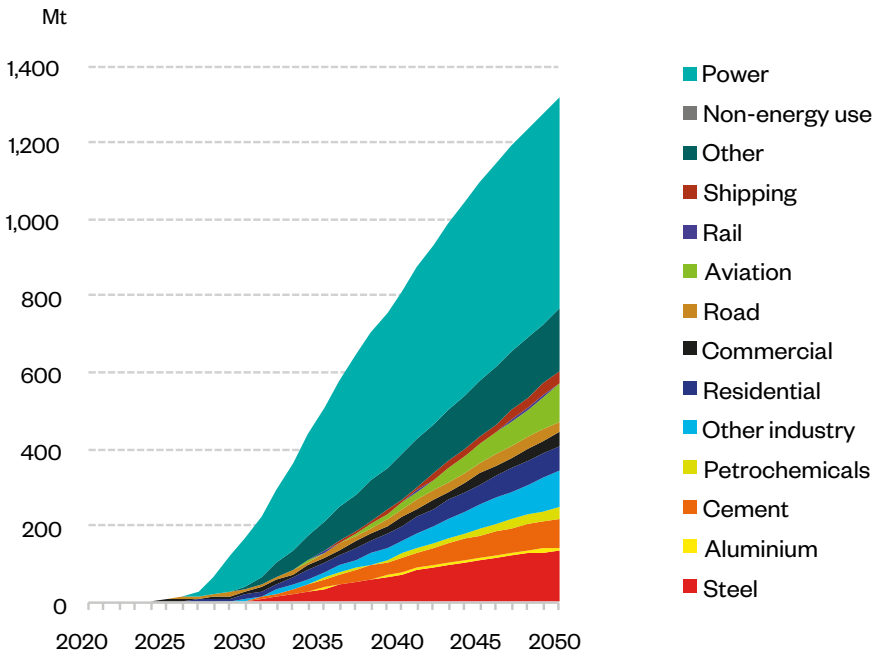


Figure 2.16: Hydrogen consumption in the Green Scenario – hydrogen is used in multiple sectors, and although power consumes more hydrogen, shipping also has a growing need for hydrogen

Source: BloombergNEF, New Energy Outlook, 2021

> BloombergNEF considers that hydrogen will play a major role in a renewable world and hydrogen trading will be needed.

For maritime transport, BloombergNEF anticipates that energy efficiency measures will achieve two thirds of the emission reductions in each of the three scenarios by 2030 and roughly 45% of the sector's abatement by 2050.

In both the Green Scenario and the Red Scenario, biofuels and ammonia (based on zero carbon hydrogen) contribute to further emission reductions; each of them contributes between 18% and 35%.

In the Grey Scenario biofuels grows to a share of 46% of final energy for maritime shipping in 2050 (from only 4% in 2030). Interestingly, in this scenario CCUS plays a substantial role, supplying a share of roughly 17% by the middle of this century – thus allowing the further use of oil-based fuels.

9 Using the 33.33 kWh/kg energy content of hydrogen, this translates into 6,333 TWh resp. 43,662 TWh.

2.6 IRENA shipping scenario

IRENA discusses the decarbonisation of maritime shipping by 2050 in a report published in autumn 2021, presenting (inter alia) a decarbonisation scenario for the sector. As in the previously mentioned scenarios, (net) zero carbon fuels play a decisive role. Renewable ammonia has a 43% share of the maritime fuel mix in 2050. Interestingly, this amount of ammonia is roughly 50% higher than current global ammonia production. Maritime shipping still emits GHGs in 2050 – but reaches an 80% reduction against the 2018 baseline.

IRENA views the development of (net) zero carbon fuels as a major uncertainty. In its 1.5°C Scenario, IRENA assumes the rapid diffusion of (net) zero carbon fuel technologies. (Net) zero carbon ammonia is the dominant fuel and the GHG emissions from maritime shipping are 144Mt CO_2 in 2050.

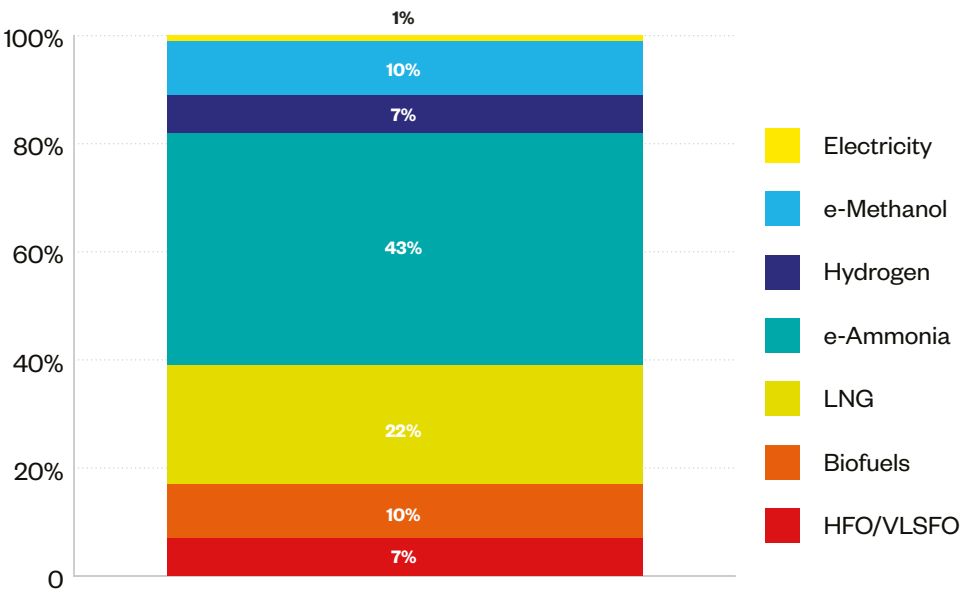


Figure 2.17: Fuel use for maritime shipping in the 1.5°C Scenario, 2050

Notes: e-Ammonia = zero carbon ammonia; e-Methanol = net zero carbon methanol; HFO = heavy fuel oil; VLSFO = very low sulphur fuel oil.

Source: IRENA, A pathway to decarbonise the shipping sector by 2050, 2021

IRENA acknowledges that the use of methanol requires fewer engine modifications in comparison to ammonia. Furthermore, ammonia requires tanks that are three to four times larger and is caustic and corrosive. New bunkers are also needed. However, ammonia contains no carbon atom in contrast to methanol. Consequently, methanol production needs very competitive carbon capture prices to succeed against ammonia.

2.7 World Energy Council

The World Energy Council has performed a comparative assessment of various hydrogen consumption scenarios. Hydrogen consumption increases in all its scenarios, ending in a range between 6% and 25% of total final energy consumption by 2050.[10]

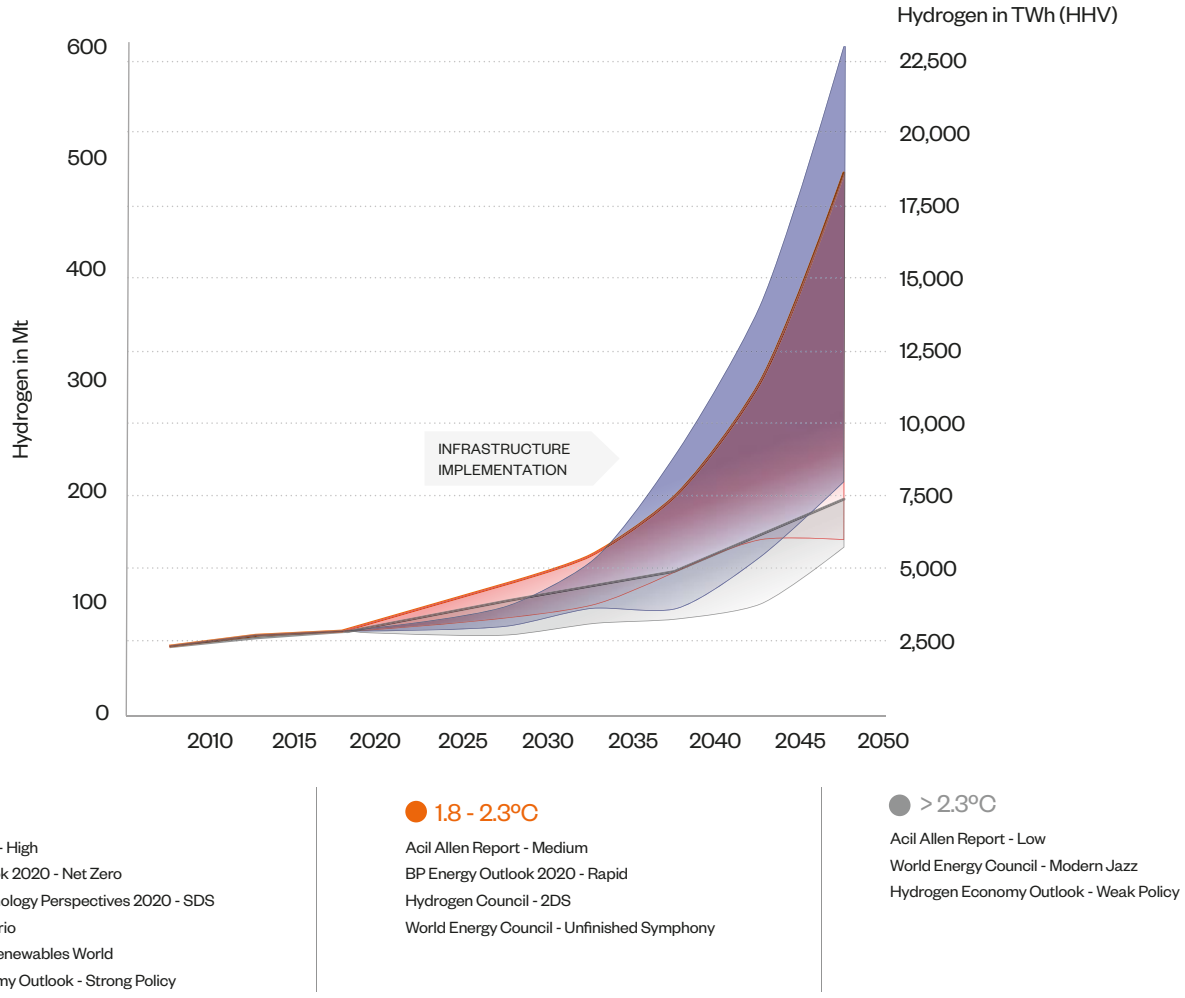


Figure 2.18: Hydrogen consumption in various scenarios

Source: World Energy Council, Hydrogen Demand and Cost Dynamics, 2021

KEY POINT:

The more hydrogen replaces fossil fuels, the stronger the curb on global temperature rise in the scenarios.

Considering the dramatic increases in hydrogen consumption under numerous scenarios, it is notable that there is currently no multilateral discussion on developing a global market for (net) zero carbon fuels. Countries with a hydrogen strategy appear to be focusing on different topics, for example Europe is focusing on demand, the Middle East on supply, and Asia on ammonia as a transport fuel. More specifically, Korea is concentrating on fuel cells for transport solutions, and Germany on industrial use cases.

Consequently, bilateral partnerships are the main political tool for negotiations between demand regions and supply regions at the moment. While this is certainly useful to start the development of (net) zero carbon fuels, it will be crucial to develop a general understanding that all these bilateral agreements will sooner or later need to merge into a global approach.

10 World Energy Council, *Hydrogen Demand and Cost Dynamics*, 2021

It is interesting to note that huge potential hydrogen importers such as Germany, Japan and South Korea are very active in concluding bilateral partnerships. This indicates that a reasonable level of demand for hydrogen on the global market can be expected. Consequently, investment in hydrogen infrastructure for its production, transport and storage may represent a solid business case for the long term.

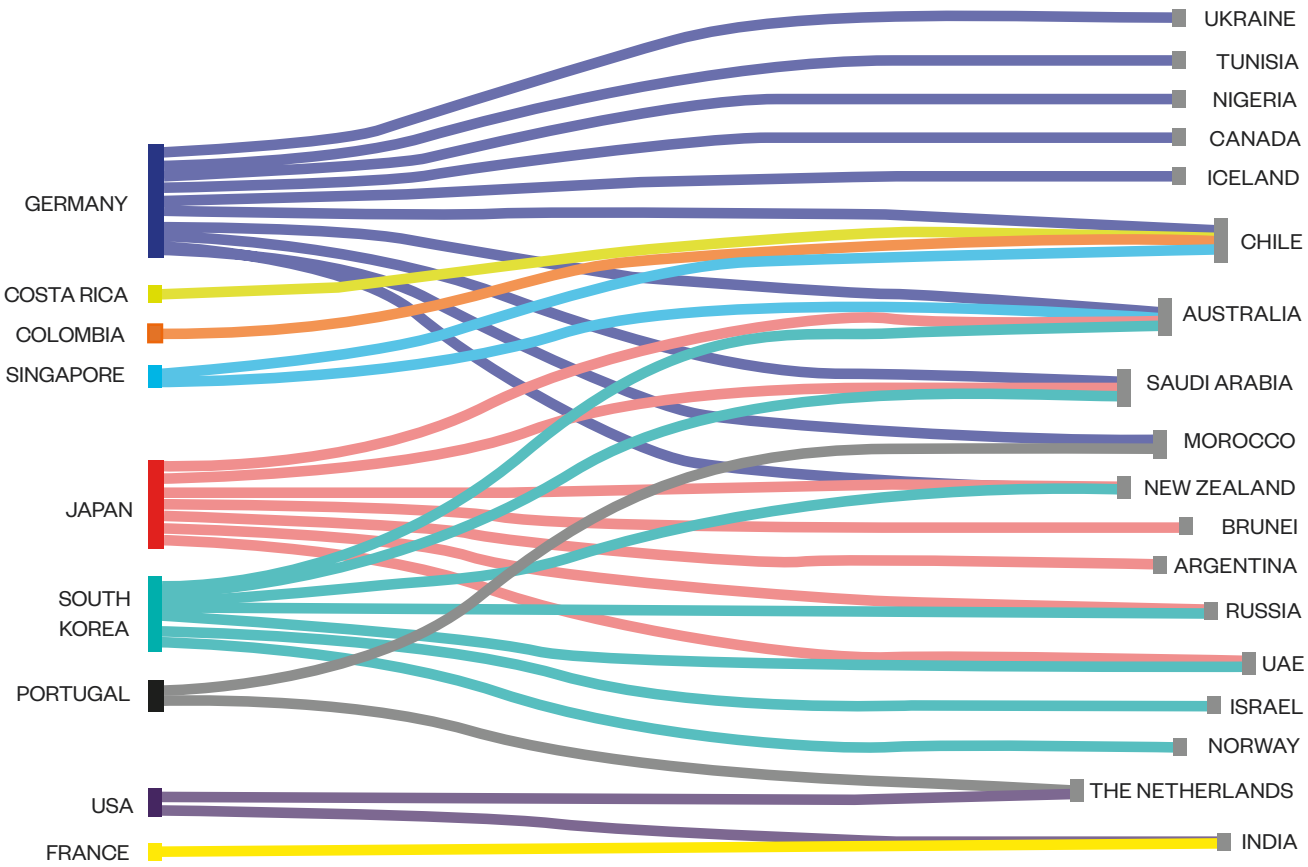


Figure 2.19: Bilateral agreements on hydrogen – there is a remarkable tendency to conclude bilateral agreements, that will need maritime shipping to deliver (net) zero carbon fuels due to the long distances for transport, only a few might lead to pipeline transport

Source: Based on the World Energy Council, National Hydrogen Strategies, 2021

In view of the increasing demand for hydrogen worldwide, importing countries are actively looking for hydrogen partnerships. These bilateral arrangements might serve as a starting point to develop a global market supported by shipping.

2.8 Electricity Needed for Hydrogen-Based Fuels

The production of (net) zero carbon fuels is connected with electricity generation, since it is based on the hydrogen generation by electrolysis. Consequently, an assessment of the needed climate-neutral electricity production is needed to understand the amount of electricity that is required to produce hydrogen-based fuels. To this end, one can use generic values, e.g. how much electricity (measured in energy units kWh) is needed, to produce an energy unit (again kWh) of (net) zero carbon fuel.

The minimum and maximum levels in the table are due to the used technologies and indicate the possible band width of used equipment for electrolysis.

Figure 2.20 shows the results of typical values[11].

	FfE Min	FfE Max	IEA 2021 Min	IEA 2021 Max	IEA 2030 Min	IEA 2030 Max	IEA 2050 Min	IEA 2050 Max
Hydrogen	1.23	1.72	1.23	1.79	1.19	1.54	1.11	1.49
Methane	1.54	2.00	1.60	2.32	1.55	2.00	1.44	1.94
Methanol	2.08	2.33	1.68	2.39	1.62	2.07	1.52	2.01
FT-fuels	1.55	2.78	1.69	2.45	1.63	2.11	1.52	2.04
E-OME	2.70	3.03	n.a.	n.a.	n.a	n.a.	n.a.	n.a.
E-DME	1.96	2.22	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ammonia	2.15	2.42	1.60	2.32	1.55	2.00		

Figure 2.20: Electricity generation (in kWh) needed to produce one kWh of hydrogen-based fuels for the maritime sector

Source: Author's calculations with data from IEA and FfE.

If we were to replace the 2018 (last available IMO data) total fuel consumption of maritime shipping (339.27 million t HFO) and assume an energy demand of 2.68 kWh to produce 1 kWh of (net) zero carbon fuel, following the methodology proposed by Shell (39th International Vienna Motor Symposium, 2018), we would require 10,555 kWh per year of electricity. Although the amount of electricity is significantly high, this amount considers current technology efficiencies to understand the magnitude of order of electricity requirements and could be reduced substantially.

However, research and development could help to drive down this enormous amount of electricity in several ways. The energy efficiency of the vessels can be improved as well as the energy efficiency of the production methods for (net) zero carbon fuels. In addition, not all fossil fuels need to be replaced, as biofuels might also play a role. Furthermore, a very high potential of energy savings might come from a switch from internal combustion engines (ICEs) to fuel cells (FCs).

Consequently, this will lead to lower electricity demand in the previously considered scenarios (see Figure 2.20) and will therefore make the switch towards (net) zero carbon fuels a realistic opportunity.

2.9 Conclusions and Recommendations

(Net) zero carbon fuels will be needed to fulfil the requirements of a climate-neutral world. Various scenarios show a strong increase in zero carbon hydrogen consumption in all relevant sectors. (Net) zero carbon fuels will therefore not only be needed as transport fuels, but also as feedstock for various industrial use cases.

11 Values based on private communication by the IEA; FfE, Welche strombasierten Kraftstoffe sind im zukünftigen Energiesystem relevant? (6th February 2019) and Jessica Allen et al., Electrochemical Ammonia, Frontiers in Chemical Engineering, 30 Nov 2021

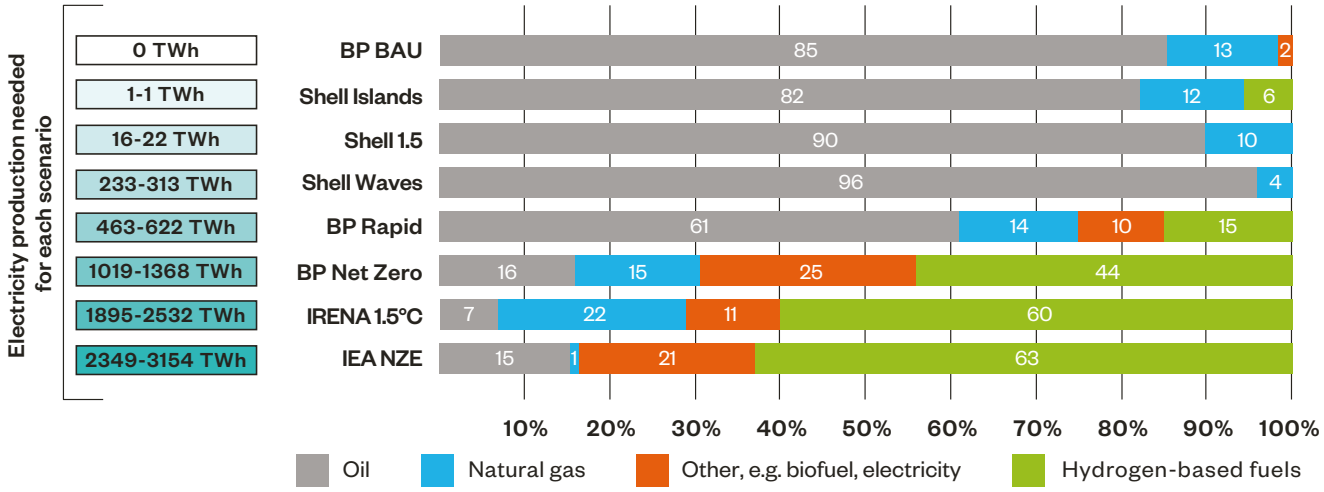


Figure 2.21: Various scenarios of fuel mixes for maritime shipping in 2050

Note: Each scenario is explored in detail in the full version of this report

Sources: International Energy Agency (IEA), Shell, BP and International Renewable Energy Agency (IRENA).

KEY POINT:

The electricity required for hydrogen-based fuels is higher in the Net Zero scenarios, where hydrogen reaches up to 60% of the total fuel mix, demanding between 1,000 and 3,000 TWh.

In 2050, (net) zero carbon fuels based on hydrogen play a decisive role in scenarios with zero or near zero emissions, with a share of 44% in the BP Net Zero Scenario and 63% in the IEA NZE Scenario. Simultaneously, the oil-based share is very low in these scenarios. Scenarios where the maritime sector experiences massive decarbonisation beyond 2050, because other sectors are preferably supplied with hydrogen, show a high share of fossil fuels in the 2050 mix.

The strong demand for (net) zero carbon fuels is high in particular regions such as Asia and Europe, but the production potential in these regions is limited. Consequently, global trade in (net) zero carbon fuels is needed to balance supply and demand. Currently global trade is being addressed with bilateral partnerships, where countries with a high anticipated demand for hydrogen are actively looking for supplying countries. This also indicates that investments connected with (net) zero carbon fuels offer a stable long-term business case.

The long-term demand outlook for (net) zero carbon fuels also offers attractive potential for various developing countries to attract investment in the production of biofuels or hydrogen-based synthetic fuels. Based on the scenarios presented, particularly on the Net Zero scenarios, the opportunities for the environmentally and economically sustainable development of these countries are enormous.

For global trade of (net) zero carbon fuels to occur, significant investment will be required in upgrading and building (net) zero carbon fuel infrastructure. This will include port infrastructure for loading/unloading, and storage and transport infrastructure to serve remote areas away from the coast. Furthermore, in terms of finance, standardised financial products will be required, standard agreements and trading expertise. To evolve from the fragmented situation of bilateral partnerships towards a global market for (net) zero carbon fuels, both policy and industry actors should actively promote the development of standards and certification that will help to facilitate global trade. These standards will eventually help projects to be financed and to facilitate trading in wholesale markets.

3 High Potential (Net) Zero Carbon Fuels

3.1 Overview

The goal of the 2015 Paris Agreement – to achieve climate neutrality by the middle of this century – creates the need for numerous decarbonisation technologies to be commercially available and affordable across economic sectors, including transport, industry and buildings. There is a strong case that energy efficiency and renewable generation of electricity will play a substantial role in reaching climate neutrality. However, there is concern that densely populated areas of Europe or Japan, for instance, may not manage to produce enough renewable energy within their borders to cover the local demand for heating and cooling, for transport and for electricity. This situation would lead to the need to balance energy demand and supply through international trade, where climate-neutral fuels are exchanged between producing regions and consuming regions. This is very similar to current trade in crude oil or LNG. The new (net) zero carbon fuels -for the maritime sector are expected to be partly biofuels and hydrogen-based fuels that will also be needed to a substantial extent to complement the fossil fuel trade.

In general, (net) zero carbon fuels have three different origins:

- Biofuels;
- Hydrogen-based fuels (mainly created with zero carbon hydrogen, e.g. ammonia); and
- Conventional fuels with complete GHG compensation via CDR technologies (see chapter 6).

Since demand centres for (net) zero carbon fuels are typically densely populated, it is likely that remote areas with low populations might serve as supply centres due to lower traded and production costs. Additionally, renewable energy production depends strongly on the site quality, which gives preference to specific high-performing regions. (Net) zero carbon fuels could therefore lead to new demand for freight transport and potentially new routes. The conventional fuel solution with CDR leaves existing fossil oil and gas routes unchanged, although the fossil freight volumes are subject to change on these existing routes.

Maritime transport is thus set to become a key enabler of the global energy transition needed to achieve global climate neutrality. The maritime sector will support the transport of goods across the whole energy transition supply chain. It will provide the global shipment of equipment to generate and store renewable electricity; the transport of critical minerals for the energy transition as lithium and cobalt as well as of (net) zero carbon fuels, helping to meet climate goals in a cost-efficient and timely manner. A future climate-neutral world will be well served by the global transport of liquid and gaseous synfuels, partly or potentially fully replacing current crude oil and LNG shipments. Some hydrogen might be produced in proximity to the consumption site, but given the restrictions in densely populated areas, this option is likely to be limited, for instance in Europe[12], where roughly half of the hydrogen demand in 2050 will be imported.

> The need for (net) zero carbon fuels globally leads to the demand for trade between production centres and demand centres

3.1.1 Drivers for (net) zero carbon fuels

The future development of (net) zero carbon fuels is driven by fundamental determinants to reduce emissions to meet the Paris agreement, particularly for the hard-to-abate sectors.

12 La Revue de l'Énergie, Decarbonised hydrogen imports into the European Union: challenges and opportunities, October 2021

The need for (net) zero carbon fuels is driven by the following factors:

- **Missing alternatives:** particularly in the transport sector, there is a strong need for fuels that can be easily stored and have a high energy density, e.g. in heavy road transport, aviation and shipping. For these end-use sector cases the chemical energy storage is preferred in comparison with batteries;
- **Storability:** despite many improvements in electricity storage, seasonal energy demand patterns for heating and cooling lead to the need to store large amounts of energy. This seasonal balancing is much more easily done with gaseous or liquid fuels in comparison with electricity[13];
- **Realising climate neutrality in numerous household applications:** the fuels for heating, cooking and transport in many households are based on crude oil and natural gas. Using synthetic fuels for these appliances allows immediate GHG reductions in areas that are difficult to reach, since they are often connected with substantial household investment. With synfuels, not only can appliances continue to be used as nowadays, but also the existing infrastructure for transport and distribution of these fuels can be used with no or only minor modification;
- **Public acceptance:** whereas there is a strong belief amongst a large proportion of the population that renewable electricity is important for a climate-neutral energy system, public acceptance of renewable projects is sometimes harder to obtain. Importing (net) zero carbon fuels might be the easiest answer to this dilemma, since existing energy transport infrastructure can be used to a large extent. The option of a gradual shift from today's energy system to a climate-neutral energy system by increasing the share of (net) zero carbon fuels over time might lead to a widely accepted transition, one that does not lead to immediate divestment and the consequent need for substantial new investment; and
- **Reducing costs to achieve a climate-neutral energy system:** the continuing use of transmission and distribution infrastructure (e.g. pipelines, filling stations, storage facilities, terminals) and household appliances for heating and transport will reduce the cost of a transition (including the transaction costs connected with behavioural changes).

> Hydrogen-based fuels have several drivers – with climate-neutrality as the most relevant one.

3.1.2 Need for global trade of (net) zero carbon fuels

Local production of (net) zero carbon fuels is certainly part of the solution, however for many countries imports may also play a major role in order to meet their demand for these fuels.

The need for global trade of (net) zero carbon fuels is driven by the following:

- **Cost advantages of imports:** Many of the most favourable sites for renewable generation are located at a distance from the current consumption centres. Consequently, local production close to the centres of consumption would be less economically beneficial. Even accounting for transport costs, it will still in many cases be much more economic to import for certain countries.[14] For example, studies suggest that hydrogen production costs in Germany are up to 50% more expensive in comparison with the lowest available production costs globally.[15]

13 In Germany, pumped hydro was able to store 40 GWh and battery storage to store 4.5 GWh in 2021. This corresponds to 0.01% of the annual electricity consumption. This indicates that the mentioned storage systems have benefits in providing short-term energy, but for seasonal energy demand e.g. due to heating and cooling, chemical storage systems e.g. for natural gas must be used. See also H.-W. Schiffer, S. Ulreich and T. Zimmermann, Klimaneutralität und Versorgungssicherheit – ein Widerspruch?, Energiewirtschaftliche Tagesfragen 5/22, pages 24-35

14 Global Alliance Powerfuels (2020) states "Global trade will reduce the levelized cost of power-fuels by up to 30% in some regions compared to a self-supply scenario".

15 Ben McWilliams and Georg Zachmann, *Navigating through hydrogen*, Bruegel, Brussels, April 2021; Dr Simon Schulte, Max Schönfisch and Gregor Brändle, *Wasserstoff: Bezugsoptionen für Deutschland*, ewi Policy Brief, Cologne, November 2020

- **Availability of sites for renewable electricity generation:** Suitable sites for renewable energy generation are limited in densely populated areas. Even if sites are present, social acceptance is not always a given. This is true not only for renewable production, but also for transmission grid infrastructure. The import of synfuels – especially into Europe[16] – and their subsequent transport and distribution via existing infrastructure (e.g. pipelines) can help to solve this situation.
- **Transportability of fuels:** Chemical fuels such as ammonia or methanol are attractive from a transport perspective because there is extensive experience in transporting them globally. This also means that transport costs are well-known and relatively low.
- **Global fuel trade supports economic and political stability:** The global trade in liquid and gaseous fuels can be gradually replaced by global trade in (net) zero carbon fuels. This offers export opportunities for countries with excellent conditions for climate-neutral energy production and cost-effective procurement for countries with low potential for climate-neutral energy production. This cooperation offers the prospect of strong political ties between the countries and increased global political and economic stability.
- **Global fuel trade strengthens security of supply (for importing countries) and security of demand (for exporting countries):** Importing countries have further flexibility to access sufficient supplies of (net) zero carbon fuels by ship, even if there is a short-term failure in the supply chain. A well-known example of the benefits of global trading supporting the security of supply/demand of fuels is the LNG market. The global market for LNG comprises 43 importing countries and 20 exporting countries[17]. Maritime transport (roughly 650 vessels) adds flexibility to the access of fuels for importing countries and provides an easy route for demand of these fuels in combination with the existing land-based liquefaction and regasification capacities.

> Global trade of hydrogen-based fuels helps to match the demand in various countries with the better production potential in other countries.

3.1.3 Actors for global trade of (net) zero carbon fuels

A recent study produced by Ram et al (2020)[18] considered the export and import potential of various (net) zero carbon fuels. The study finds that global trade of (net) zero carbon fuels offers opportunities in the long run for:

- **Developing countries:** those countries with the right conditions can establish energy exports as a long-term reliable business model, these countries can use the revenues from exports to increase electrification among the population and use the sites as a nucleus for further economic activity (the "renewables pull");
- **Current energy exporters:** many currently energy-exporting countries could transform their business model from fossil fuel exporters to climate-friendly exporters by harnessing climate-neutral electricity production; and
- **Energy importers**: The generation and export of synthetic fuels at reasonable cost is possible in many countries, thus leading to a lower level of dependency with regards to exporting countries and hence increasing the security of supply for importers, particularly for (net) zero carbon fuels.

The study concludes that by 2030 most of the world is import-oriented for Fischer-Tropsch[19] (FT) fuels, since the production costs in most regions are still comparatively high. The main export-oriented regions in 2030 are North America, Australia and the southern parts of South America.

16 Cédric Philibert, *After the Hydrogen Bubble Bursts: The Factors Shaping and Possibly Unfolding International Hydrogen Value Chains*, ifri, Paris, 17 September 2021

17 GIIGNL GROUPE INTERNATIONAL DES IMPORTATEURS DE GAZ NATUREL LIQUÉFIÉ, Annual Report 2021

18 Ram M., Galimova T., Bogdanov D., Fasihi M., Gulagi A., Breyer C., Micheli M. and Crone K., *Powerfuels in a Renewable Energy World – Global volumes, costs, and trading 2030 to 2050*, LUT University and Deutsche Energie-Agentur GmbH (dena), Lappeenranta and Berlin, 2020

19 Fischer-Tropsch fuels are synthetic fuels. Historically, they were derived mainly from coal.

Between 2030 and 2050 the export/import orientation of India, China, and countries of South America and Africa is expected to evolve. In the case of India and China, their position changes over time and eventually settles on no preference for imports over exports. Notably, sub-Saharan Africa continuously gains market share as an exporting region, driven by the declining cost of PV together with an excellent resource situation. Importers are mainly in the northern hemisphere, including Canada, Europe and Eurasia.

Ram et al (2020) find that many regions have a neutral export/import orientation. Nevertheless, this does not mean that they will not participate in global trading. For the reasons mentioned above – balancing seasonal fluctuations, benefiting from low market prices as an importer or high market prices as an exporter – these countries will also be part of a global market for (net) zero carbon fuels.

This analysis allows some conclusions with regards to the transport of (net) zero carbon fuels.

Firstly, intercontinental transport - especially from the Southern to the Northern hemisphere - is needed, which leads to maritime shipping as the preferred solution in comparison to pipeline transport between exporters and importers. Pipeline transport will certainly be the work horse for the national large-scale transport and distribution of (net) zero carbon fuels, but could only play a limited role with regards to exports and imports of (net) zero carbon fuels, if demand centres are far away from low-cost production centres as expected.

Secondly, the changes in export/import orientation of certain countries will make it difficult to justify a long-term investment in pipelines: pipelines are mainly triggered by uni-directional transport from a supplying country to an off-taking country. If either of these countries changes its preference, the original aim of the pipeline is no longer valid.

Thirdly, long-term investments as pipelines need a very safe multinational investment environment of all involved countries. In contrast, the local infrastructure for loading and unloading cargoes in a port needs a stable national environment and cargoes can easily be rerouted to stable jurisdictions if one party fails to perform.

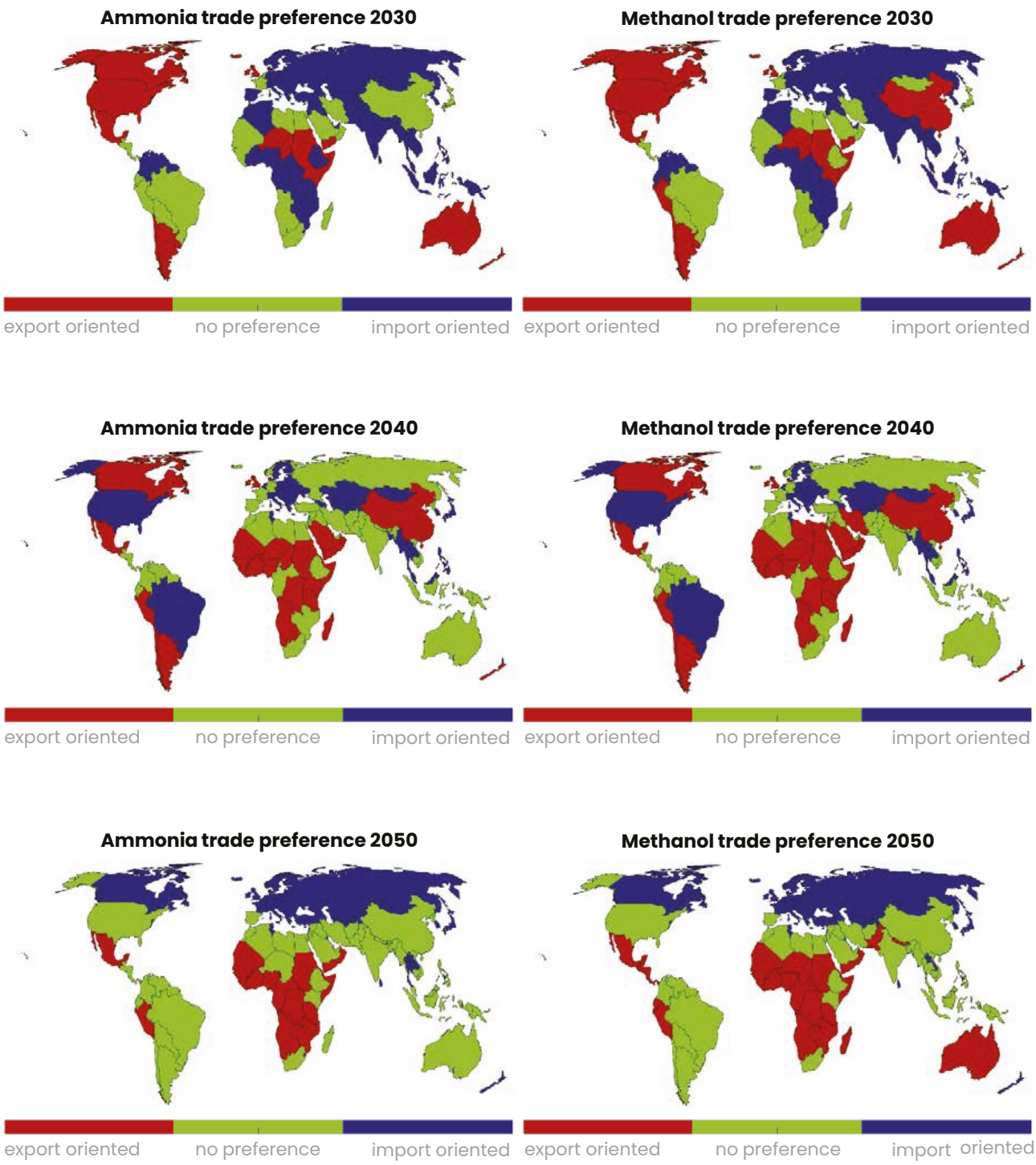


Figure 3.1: Development of trade preferences for the synthetic fuels ammonia and methanol, 2030–2050

Source: Ram M. et al., Powerfuels in a Renewable Energy World – Global volumes, costs, and trading 2030 to 2050, 2020

Global trade offers opportunities for all countries, helping importers to achieve climate neutrality at lower cost and exporters to finance (net) zero carbon fuel production.

3.1.4 National hydrogen strategies

Since 2020, the number of countries that have announced national hydrogen strategies has increased tremendously. More and more countries are viewing hydrogen and hydrogen-based fuels as an inevitable contribution to their climate-neutrality goals. Countries are therefore developing strategies to trigger local production of hydrogen and also to assess whether they might find opportunities in importing or exporting hydrogen-based fuels. These countries also look at research and development to find the best use cases for these fuels in industrial application, both for households and in the mobility sector.

The results of energy-economic considerations in the previous section of this chapter are underlined by the hydrogen strategies of various countries, as analysed in a recent World Energy Council (WEC) report.[20] The study emphasises the decisive role that governments see for hydrogen-based solutions: 20 countries (representing 44% of global GDP) have already passed a national hydrogen strategy, and another 31 countries (again representing 44% of global GDP) are supporting national projects (as of autumn 2020), although more countries have been analysing or making pledges in recent months. One reason to develop these strategies is to identify the position of the country and its industrial players in respect of the import and export of hydrogen and hydrogen derivatives.

20 World Energy Council Germany and Ludwig Bölkow Systemtechnik, *International Hydrogen Strategies*, September 2020

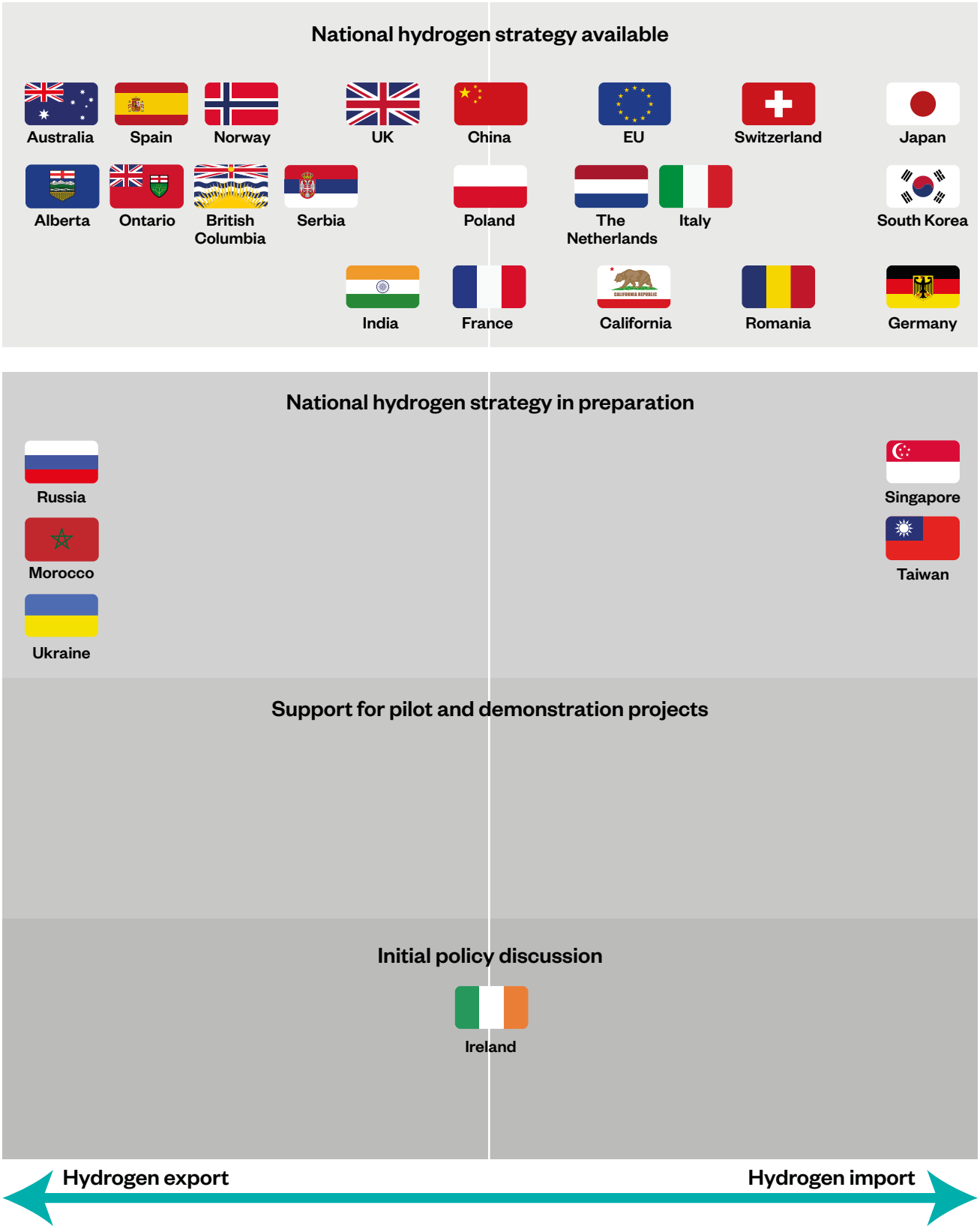


Figure 3.2: Selected countries' classification in respect of development of a dedicated hydrogen strategy and hydrogen import/export in 2022

Source: Based on World Energy Council and Ludwig Bölkow Systemtechnik, International Hydrogen Strategies, 2020 with author's updates

Three advanced strategies (those of Japan, Germany and Korea) explicitly consider hydrogen imports due to limited domestic production capacity. These countries are developing a clear import agenda. Other countries (e.g., Australia and Chile) have developed a clear export agenda due to their advantageous electricity production costs and other benefits e.g. water availability, stable framework and port capacities. Most countries have not made a clear stance yet on whether to become an exporter or importer. However, it is likely that countries with high industrial output and high population density will follow Japan, Korea and Germany.

> The numerous hydrogen strategies show the huge growth potential for hydrogen-based fuels worldwide.

The various strategies are mostly impartial with regard to the type of fuel, considering all possible ways to transport hydrogen, e.g. liquid hydrogen, liquid organic hydrogen carriers (LOHC), ammonia, methanol.

The national strategies of these countries (see Figure 3.3) show that these synfuels also offer a solution for sectors that are hard to decarbonise. In particular, (net) zero carbon fuels can be used as a high-density energy carrier for long-distance transport, with the interesting advantage that the existing distribution infrastructure can still be used, as well as the existing engines. Consequently, (net) zero carbon fuels (also known as synfuels or e-fuels or power-to-liquid PtL fuels[21]) are considered in many strategies as an important solution for the aviation and maritime sectors.

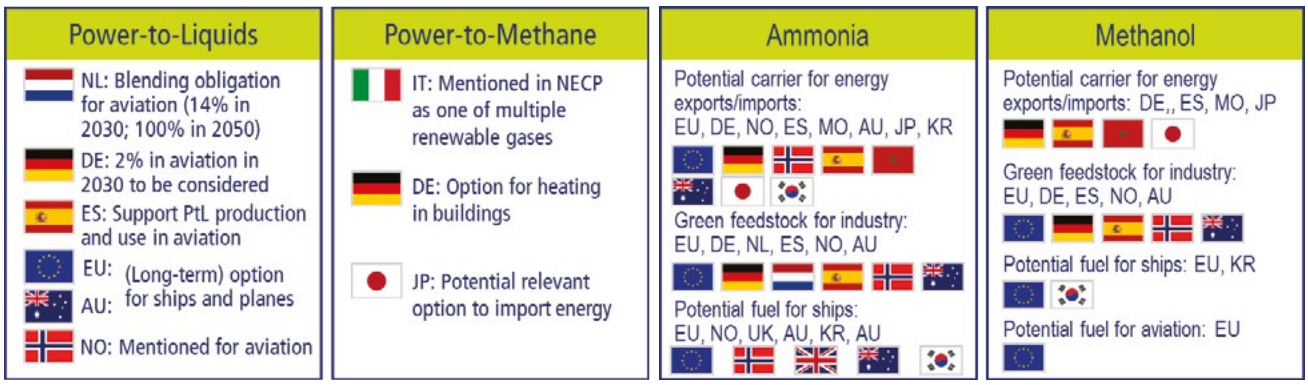


Figure 3.3: The role of various (net) zero carbon fuels in different countries' hydrogen strategies – maritime shipping is playing a key role, but is not the only economic activity in demand for these fuels

Source: Based on World Energy Council and Ludwig Bölkow Systemtechnik, International Hydrogen Strategies, 2020

The large-scale transport of hydrogen could enable importing countries to tap into the abundant low-cost production capacity of exporting regions. Major investment is needed to establish the supply chain for the transport of hydrogen or hydrogen derivatives: in production facilities in the exporting countries, in logistics infrastructure and in port and bunkering facilities in the importing countries. To start the development, bilateral agreements are currently the preferred solution. Possibly the best-known cooperation is between Australia and Japan with the "Hydrogen Energy Supply Chain Pilot" project. The first phase of this project will mainly explore the logistics by transporting liquid hydrogen from Hastings in Australia by ship to Kobe in Japan. The ship "SUISO Frontier" arrived on 25 February 2022 with its first cargo from Australia.

21 Synfuels is a term used for synthetic fuels, and e-fuels is used to emphasise the origin of these fuels from electricity. Power-to-Liquid (PtL) similarly emphasises the use of electric power to produce liquid fuels. Power-To-Gas (PtG) is used to describe the production of synthetic methane (or e-methane), for example.

3.1.5 Bilateral partnerships as a nucleus for global trade

it is expected that bilateral partnerships can become widespread in the near future and set the scene for a truly global market. The bilateral partnerships have the advantage of ensuring that the infrastructure is financed via a reliable contractual arrangement. After a while, these bilateral contracts would then evolve and merge into a global hydrogen market. Some observers, for example HyXChange, emphasise that long-term contracts will not become a serious threat for a liquid wholesale market because it may be possible for the buyer to resell (net) zero carbon fuels without restrictions.

> Bilateral hydrogen cooperation is expected to increase rapidly in the near future before a truly global market develops.

3.2 Biofuels

Biofuel production is complicated to assess, especially with regards to volume, as it is part of a complex environment where variables such as food production, the availability of land and social acceptance play an important role. Some land resources are also connected with a high level of uncertainty, e.g., energy crops on marginal lands. The focus in this report is on first-generation biofuels, although there may be a role for second-generation biofuels in the future.

An assessment of the annual production of biofuels was performed by IEA Bioenergy in 2017:[22]

- Biodiesel potential based on existing oil crops and animal fats < 45Mt
- Used cooking oil 3–6Mt
- Tall-oil production (pulp mills) 2.6Mt
- Lignocellulosic feedstocks 400–750Mt

This leads to a global potential of roughly 450–800Mt of biofuels per year.

With annual fuel consumption of 330Mt for maritime fuels and 220Mt for aviation fuels – i.e., 550Mt in total – biofuels could in slightly optimistic scenarios cover the fuel demand of maritime transport and aviation. However, this also means that biofuels would not be used for other purposes such as road transport, heating/cooling and electricity production.

This leads to the conclusion that biofuels could play an important role in maritime transport, but will most likely not serve as a single fuel solution for decarbonisation. Technically, this can be solved, for example:

- By using a blend of fuels such as bio-methanol with e-methanol (a synfuel); and
- By using alternative fuels for specific transport by vessel (electricity for inland waterways, nuclear propulsion systems for long distances).

22 IEA Bioenergy, *Biofuels for the marine shipping sector*, 2017

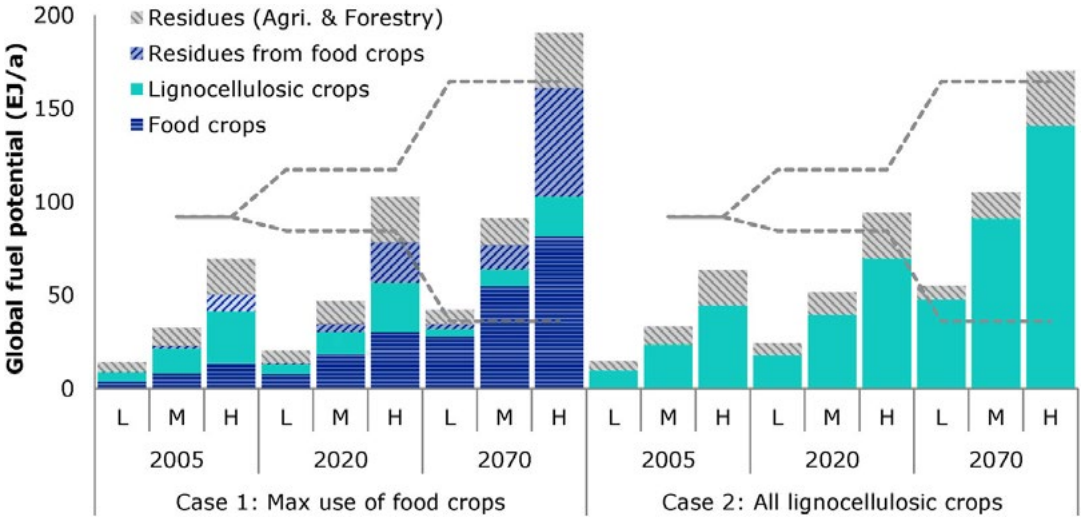


Figure 3.4: Projected global biofuel production per year. The dotted lines indicate the range of projected global transport fuel demand across a range of scenarios

Source: Deng et al., Country-level assessment of long-term global bioenergy potential, 2015

KEY POINT:

The range of expected annual demand for biofuel production by 2050 varies by around 100EJ. This variance in future biofuel production is equal to the total amount the transport sector currently uses.[23]

3.2.1 Global trade and future prices of biofuels

To match regional demand and supply for biofuels, trading between main supply and demand areas is needed. As Deng et al (2015) state, biomass as a global energy supply depends strongly on trade[24], because trade helps to export biofuels from surplus areas or regions to demand areas. Deng et al (2015) also found that, by 2070, around a third of the world's population is expected to live in countries such as India and Vietnam, that have bioenergy potentials less than half the global average. By contrast, only 10% of the world's population will live in countries with bioenergy potentials that are greater than twice the average, such as Russia and Brazil, making global trade an important factor to balance energy supply and demand of biofuels.

Consequently, countries such as Russia and Brazil have an advantage in exporting biofuels in comparison to other regions.

As production increases, biofuel prices are expected to decrease according to the IEA scenario: future biofuel production technologies could become more competitive with fossil fuels in a range between $45 and $70 per barrel. Furthermore, next-generation biofuels are expected to have significantly lower impact on the environment and increase the availability of biofuels.

23 Yvonne Y. Deng, Michele Koper, Martin Haigh and Veronika Dornburg, *Country-level assessment of long-term global bioenergy potential*, Biomass & Bioenergy, Vol. 74, pp. 253-257, 2015

24 Also Yvonne Y. Deng et al., 2015

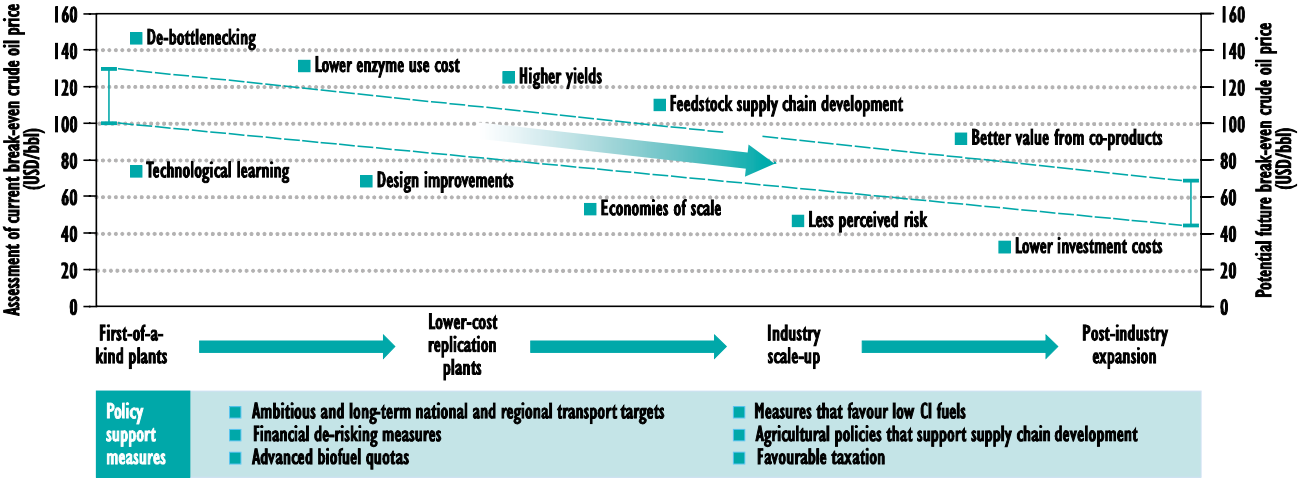


Figure 3.5: The IEA expectation for biofuel production costs

Source: IEA, Medium-Term Renewable Energy Market Report 2016, 2016

The IEA is less optimistic in its Net Zero by 2050 Scenario than the IPCC:[25] the IEA assumes a biofuel supply of 102EJ annually by 2050, whereas the IPCC indicates a range between 118EJ and 312EJ. With their less optimistic approach, the IEA acknowledges potential constraints due to other uses of land, typically food production and biodiversity protection. Additionally, several governments intend to phase out the use of certain biofuels, e.g. palm oil, affecting the total volume of biofuels that can be expected.

> Biofuels can deliver a substantial contribution to the global fuel supply at competitive cost. Global biofuel trading will be essential to balance supply and demand.

The demand for biofuels is considered to be mainly driven by the expected large growth in Asia and Africa, as seen in Figure 3.6 both of these regions outweigh the demand from Europe and the Americas. However, for advanced bioenergy, developed countries are the most favourable markets. As already indicated in Chapter 2 on scenarios for 2050, the use of (net) zero carbon fuels are expected to take place in various sectors: as feedstock for industry, as fuel for the transport sector, and as an energy carrier for the energy and buildings sectors.

Consequently, in order to trigger competition on the supply side, other (net) zero carbon fuels, such as hydrogen-based fuels can help to meet consumers' need for secure supply of (net) zero carbon fuels at competitive market prices.

In the case of the maritime sector, shipping companies are increasingly gaining experience with biofuels. Singapore-based Eastern Pacific Shipping, for example, has appointed GoodFuels to supply biofuel bunkers for its 2010-built 47,377 deadweight tonne medium-range tanker M/T Pacific Beryl. And Ocean Network Express performed trials with sustainable marine biofuel on board the containership MOL Experience. These trials will help to increase understanding of biofuels' potential impact (also as a blend) on engine and storage systems.

25 IPCC, Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels, 2018

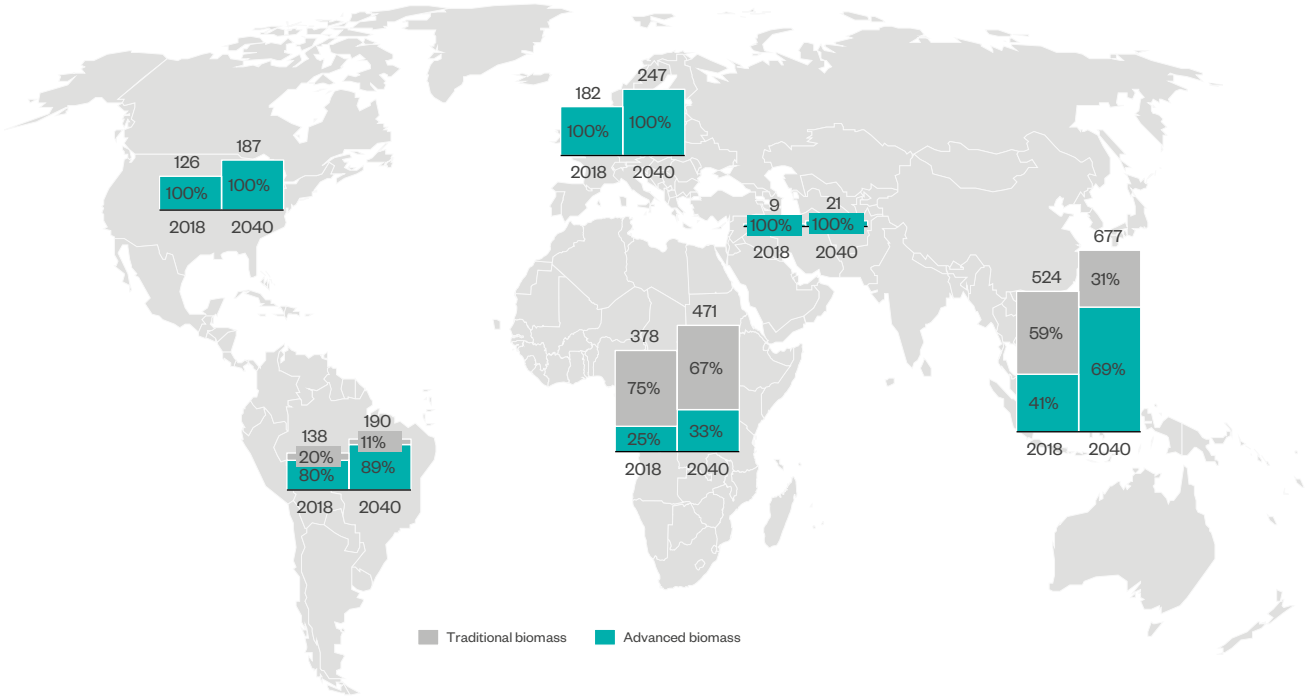


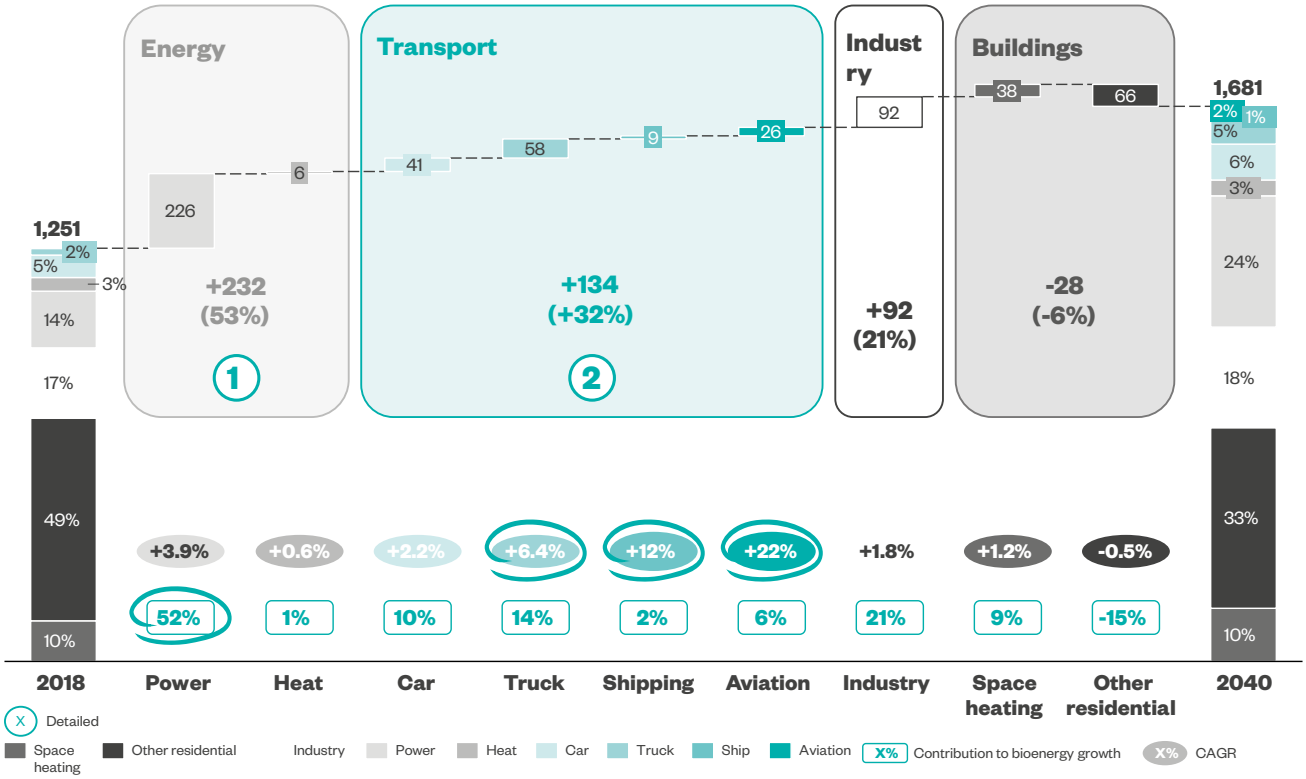
Figure 3.6: Bioenergy primary energy demand by continent, 2018 and 2040

Source: Kearney Energy Transition Institute, Biomass to energy, 2020

KEY POINT:

The demand for bioenergy increases globally in all continents, suggesting a very stable demand outlook, however it is expected that Asia and Africa will have the largest growth

World bioenergy consumption by sector
Mtoe, 2018–2040, world [1] – stated policies scenario



[1] Excluding "Other" which gathers the energy used for transformation activities (for example, energy industry own use) as well as the final energy used in sectors other than industry, transport, and buildings (~8% of total bioenergy consumption in 2018)

Note: Percentages may not resolve due to rounding.

Figure 3.7: World bioenergy consumption by sector, 2018–2040 – maritime shipping will use an increasing share of biofuels, however, this will not be sufficient to replace the fossil fuel basis

Source: Kearney Energy Transition Institute, Biomass to energy, 2020

KEY POINT:

The demand for bioenergy is driven by end-use cases across many sectors.

Although it is expected that shipping will have a growing consumption of biofuels towards 2040 (see Figure 3.7), the share of shipping in biofuel consumption is rather small (2% of the growth) in comparison with the biofuel consumption expected of other sectors such as industry, power and aviation.

3.3 Hydrogen-based Fuels

3.3.1 Production and export potential of hydrogen-based fuels

Synthetic fuels are based on hydrogen, where the hydrogen is produced with climate-neutral energy sources. One example of (net) zero carbon fuels based on hydrogen is ammonia (NH_3). One way to produce hydrogen-based fuels is to use electrolysis with renewable electricity. The LCOE[26] of the electricity supply is a key criterion for potential hydrogen production sites. Hydrogen can be produced using various electricity sources, and for a future world, the climate-neutral ones such as hydro power, PV, wind onshore and wind offshore are key. The World Bank gives for instance an indicative LCOE for PV electricity production for various countries, thus allowing an easy comparison. For a detailed project assessment, however, one needs a site-specific analysis. Additionally, other area-specific resources are needed, such as sufficient availability

26 LCOE = levelised cost of electricity. The LCOE measures the average net present cost of electricity generation for a specific type of power plant.

of water. For large-scale projects, the local political and administrative situation can also be decisive: the political stability in the region politically and whether the government administration makes large-scale projects feasible matters for making investment decisions on such projects. Since these technical projects also have a rather long lifetime, these stability and predictability criteria should also be considered for a sufficiently long period of time, e.g. 10–20 years.

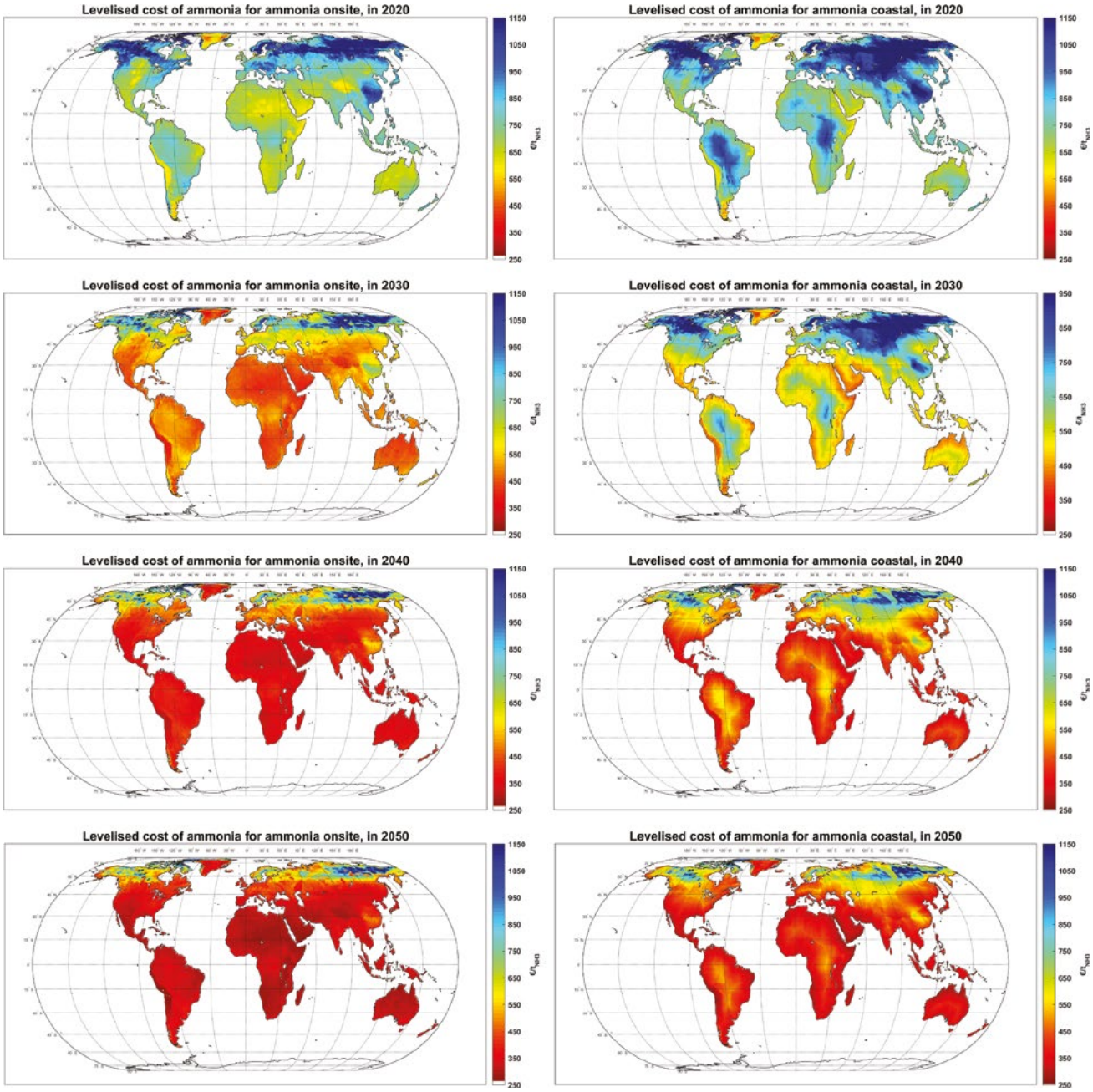


Figure 3.8: Levelised cost of ammonia production onsite (left) and coastal (right) for 2020 (top), 2030 (upper centre), 2040 (lower centre) and 2050 (bottom) based on hybrid wind and photovoltaic generation. The near-coast production will ideally take place in proximity of a port to allow easy shipping

Source: Mahdi Fasihi et al., Applied Energy Volume 294, 15 July 2021, Global potential of green ammonia based on hybrid PV-wind power plants

KEY POINT:

The production costs for (net) zero carbon fuels based on solar and wind electricity are much lower in the Southern hemisphere in comparison with the Northern hemisphere, and lower inland than on the coast.

Figure 3.8 shows the global map of levelised cost of ammonia production worldwide and the expected development over time. There are remarkable potential cost benefits of the Southern hemisphere in comparison with the countries in the Northern hemisphere.

Frontier Economics, an energy economic think tank, used the below criteria to find ideal country candidates for Power-to-X (PtX) production, i.e. countries most suited to producing hydrogen-based, (net) zero carbon fuels. The "X" stands here for the different potential products created by using electricity: liquid fuels (PtL), gaseous fuels (PtG), heat (PtH) or other products. The general idea is that climate-neutral electricity will be used to produce substitutes for the currently used fossil fuels.

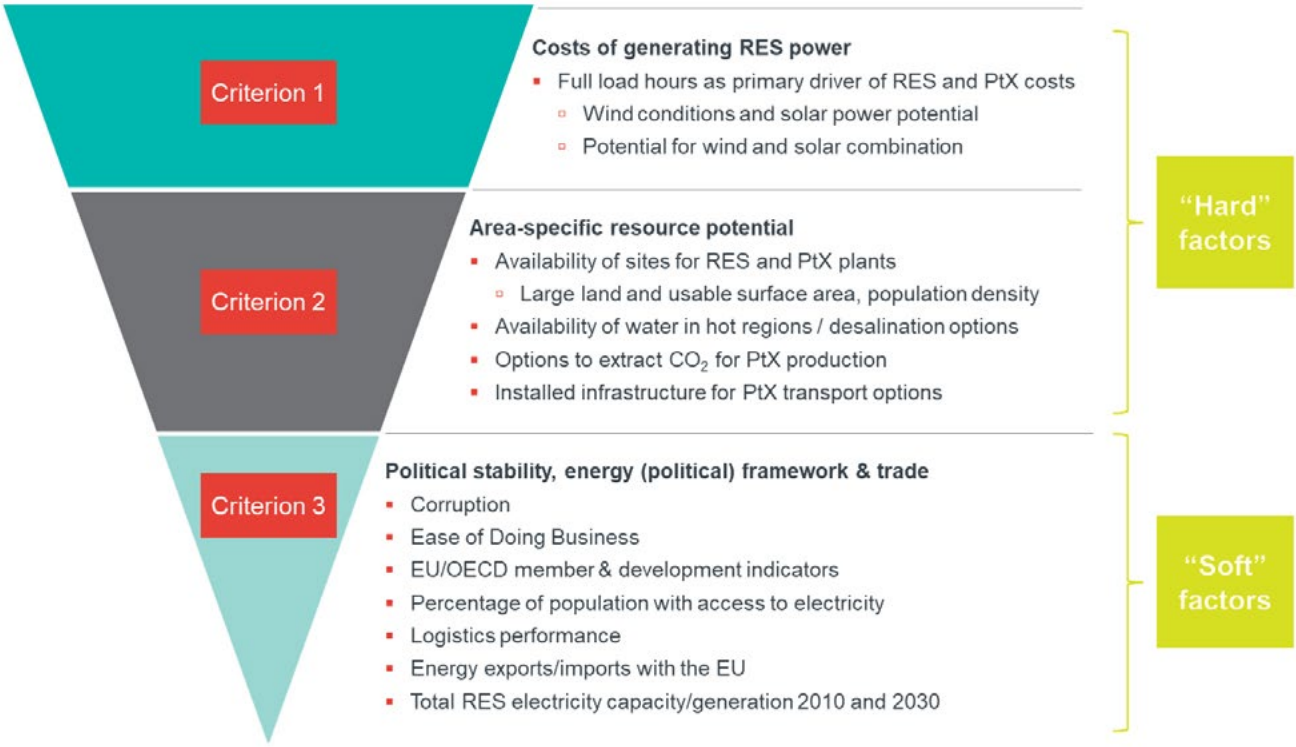


Figure 3.9: The three criteria used by Frontier Economics to assess countries' suitability as a PtX producer

Source: Frontier Economics, International Aspects of a Power-To-X Roadmap, report prepared for the World Energy Council Germany, 2018

Applying Criterion 1, Frontier Economics identified countries with the best electricity production costs using PV, wind and a hybrid system consisting of wind and PV. It focused its analysis on renewable generation by wind and PV. Other carbon-neutral production sources such as hydro and nuclear were not part of its analysis, a situation that in most instances does not change the outcome in individual countries.

However, producing electricity at low cost is only one important requirement. Other infrastructure components are also of interest (Criterion 2):

- Availability of sites for renewable generation (and PtX plants), e.g. uncultivated areas without protection status;
- Availability of water (desalination plays an important role in this context);
- Availability/recoverability of CO_2; and
- Potential transport options.

The soft factors in Criterion 3 have the following dimensions:

- Political stability;
- Development indicators;
- Business environment;
- Energy infrastructure and logistics; and
- Trade relationship with the European Union or Germany.

Summing up, this analysis led to a shortlist of 23 countries, as shown in Figure 3.10.

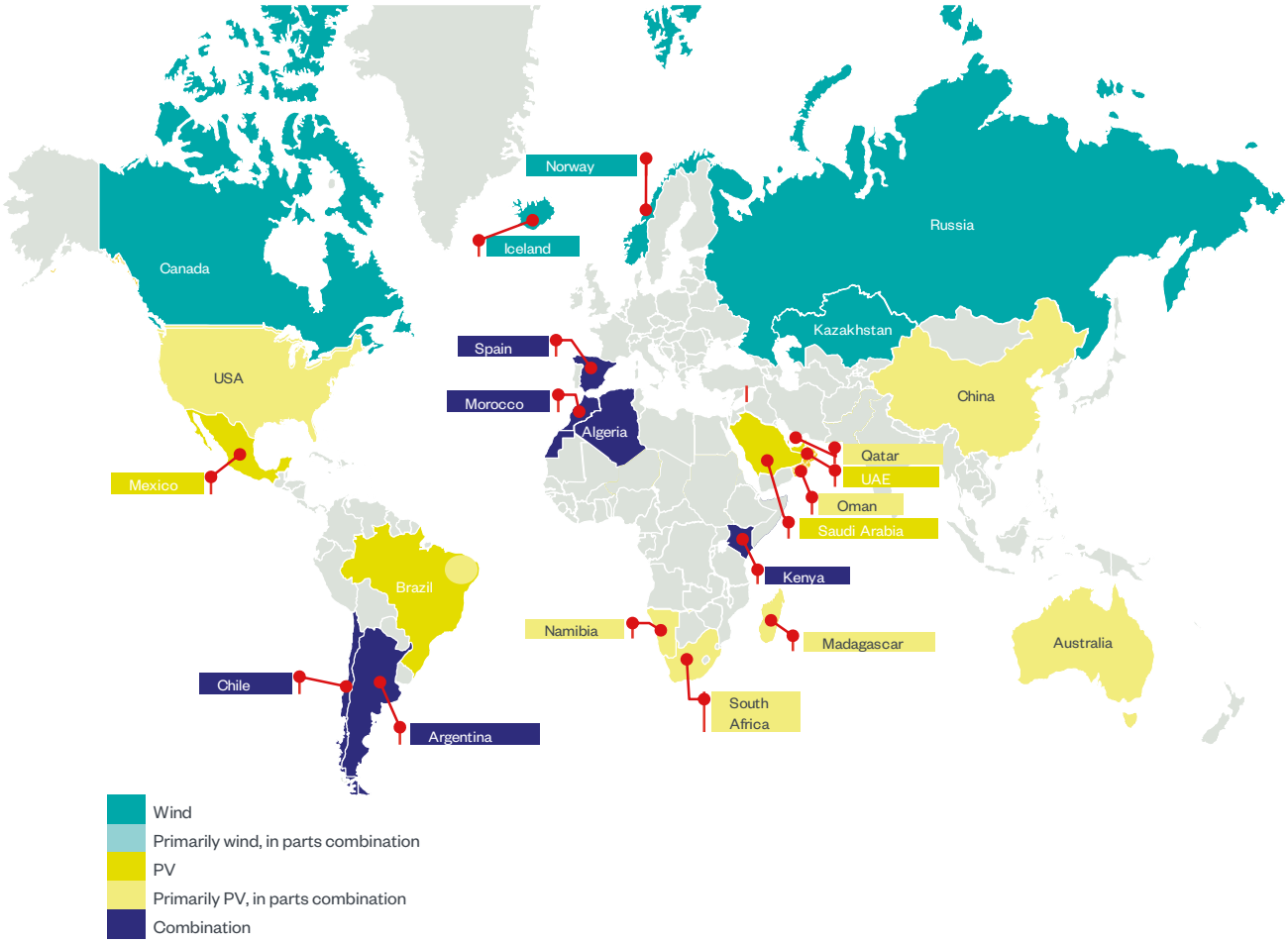


Figure 3.10: Countries with strong PtX-potential, i.e. a high likelihood to export

Source: Frontier Economics, International Aspects of a Power-To-X Roadmap, report prepared for the World Energy Council Germany, 2018

> The potential for (net) zero carbon fuel production depends not only on electricity production costs, but also several other dimensions that need to be considered.

Interestingly, these countries are already well equipped for global trading, so from this perspective it will be less likely that currently countries -not highlighted in the map above- will enter the list of energy carrier exporting countries. The countries in Figure 3.10 benefit from existing transport infrastructure, such as harbours, storage for some liquid and gaseous (net) zero carbon fuels (e.g. ammonia and LNG), pipelines and terminals that can be expanded, retrofitted or adapted for additional types of (net) zero carbon fuel exports.

It should be noted that many countries have excellent sites for hydro generation and biomass production, and excellent solar or wind conditions, but the political stability and the administrative situation in these countries are not seen as enablers for long-term investment. This means, however, that if the administrative situation in these countries improves substantially, they might enter the list of exporting countries. Countries currently subject to global sanctions might also enter this list of exporting candidates if circumstances change and, vice versa, some countries might become subject to global sanctions and substantially reduce their exporting potential.

Generally, the situation is beneficial for global trade, since competition between a number of countries and companies can be expected. The sometimes perceived oligopolistic situation in oil and natural gas markets – leading to discussions about the political power of the "strategic ellipse"[27]–, can be expected to become less important. Security of supply concerns can also be addressed by local production of hydrogen, although typically at higher cost than market prices. Again, using maritime shipping as a mode of transport for (net) zero carbon fuels will also increase the security of supply since failure to supply by one party can easily be solved and, from a supplying country perspective, there is also a multitude of potential customers to ensure security of demand. Furthermore, the high storability of (net) zero carbon fuels also reduces economic risks due to short-term supply interruptions.

> The potential for global (net) zero carbon fuel production is high in numerous regions, especially in the Southern hemisphere. Consequently, international trade in synthetic fuels can help industrial centres meet their demand.

The Fraunhofer Society published its PtX Atlas in August 2021.[28] This describes potential exporting countries in more detail, giving figures for their export potential and the exporting costs to various EU countries, including transport and the political situation. The countries mentioned in Table 3.1 have a total potential synfuel production capacity of roughly 74,000TWh per year. This is definitely higher than the total gas supply worldwide in 2018 (37,937TWh).[29] However, to replace all fossil fuel consumption by synthetic fuels would require roughly 135,000TWh to meet today's energy demand, as the IEA data reveals: the total energy supply in 2018 was 134,873TWh (coal 44,646TWh, crude oil 52,300TWh). For comparison, 100EJ biofuel potential as indicated by the IEA corresponds to 27,777TWh. Consequently, the combined potential of synthetic fuels and biofuels would not be enough to meet even today's energy demand for fossil fuels. Of course, energy efficiency measures can help to reduce this demand substantially and large parts of fossil fuel consumption can be replaced by renewable energy sources as hydro, wind and PV. Nevertheless, the figures indicate a high potential demand for (net) zero carbon fuels.

During the presentation of the PtX Atlas, Fraunhofer researchers also mentioned the hard-to-abate transport sectors, aviation and maritime transport. Their demand forecast is 6,700TWh for aviation and 4,500TWh (corresponding to 16.2EJ) for maritime transport by 2050. As Table 3.1 shows, the total potential production of hydrogen-based fuels, produced in the coast or close to the coast by renewable energy sources could relatively easily match the demand of hydrogen-based fuels of maritime transport by 2050. Fraunhofer indicates in their research the production potential for hydrogen, methanol, Fischer-Tropsch fuels and synthetic natural gas (SNG). In the following, the focus is on SNG to avoid repetitions.

27 The so-called "strategic ellipse" describes a region stretching from the Middle East to the North of West Siberia, where about 70% of global conventional oil and natural gas reserves are concentrated. The term was introduced by the German political sciences magazine "Osteuropa" in 2004.

28 https://maps.iee.fraunhofer.de/ptx-atlas/

29 Data from the IEA.

	Coast			Inland			
SNG (l) in TWh	Hybrid	Wind	PV	Hybrid	Wind	PV	Sum
Saudi Arabia	593	-	1,176	29	-	96	1,894
Australia	769	23	778	3,348	98	7,620	12,636
Chile	21	299	1,239	91	408	57	2,115
Russia	5	1,384	2	-	7,354	-	8,745
USA	40	25	161	13,288	3,431	7,553	24,498
Ukraine	-	10	-	-	-	-	10
South Africa	118	16	436	2	-	61	633
India	10	-	7	-	-	-	17
Iran	-	-	762	-	-	-	762
Brazil	198	17	235	1	-	9	460
Argentina	610	1,019	-	6,644	1,876	778	10,927
Peru	272	-	798	-	-	27	1,097
Mexico	209	1	1,839	-	-	309	2,358
Kazakhstan	-	256	-	-	838	128	1,222
Egypt	1,461	-	589	1,485	-	199	3,734
Libya	1,478	-	128	796	-	20	2,422
United Arab Emirates	-	-	474	-	-	-	474

Table 3.1: Potential for the production of synthetic natural gas (SNG) as a liquid produced by wind and/or PV (photovoltaic) in coastal and inland regions

Source: Fraunhofer Society, PtX Atlas

KEY POINT:

Many countries have substantial potential to produce (net) zero carbon fuels by wind and solar energy.

> The country-specific socio-economic potential for (net) zero carbon fuel production is already assessed for many countries and can be used as a starting point for further analysis.

However, one should note that Fraunhofer only considered a limited number of countries, so additional countries could increase the production potential. The PtX Atlas also considered only wind and PV production of synthetic fuels and no other climate-neutral sources such as hydropower or nuclear, nor low-carbon sources utilising CCUS. Additional demand can be expected for non-energy uses. Thus, it becomes clear that additional countries with high potential to produce synthetic fuels are needed and additional climate-neutral technologies for electricity production could help significantly.

> The combined energy potential of (net) zero carbon fuels, both biofuels and hydrogen-based fuels (as covered by the IEA and Fraunhofer), would not be enough to cover today's total demand for fossil fuels.

Additionally, offshore wind might play a more prominent role in the future. Currently, a pilot project by Ørsted and Siemens Gamesa is expected to produce hydrogen offshore and transport it to shore.[30] The project is to be developed off the coast of north-east England. In Germany, legislation for offshore

30 Ørsted press release, 8 January 2021, *Consortium receives funding to investigate offshore hydrogen production*

hydrogen production entered into force on 1 October 2021.[31] Research to improve existing technologies for offshore hydrogen production is also being carried out, as for example in several H2Mare research initiatives in Germany. Other projects, such as in Denmark, transport offshore wind power to the coast and operate the electrolysers on land.

Should the offshore production of hydrogen succeed at reasonable cost, the next development step of floating offshore hydrogen production would pave the way to enormous production potential (sometimes called "hydrogen islands"). Again, in this case maritime transport will enable the transport of hydrogen from the offshore production facilities to the land-based consumers. This would offer enormous potential: estimates by ESMAP assume a global potential of 71,000GW from offshore wind, comprising 20,000GW in shallower water with fixed offshore wind turbines, and 50,000GW from floating offshore.[32] For comparison, the world's total offshore wind installed capacity stands at 2,799GW.[33] Hence, the floating offshore potential is roughly 17 times higher.

Manufacturers and producers are also preparing for a future with hydrogen and synthetic fuels by building larger-scale projects. For example, Mitsubishi and Shell have agreed on a hydrogen project where ammonia will be exported from Canada to Japan and on a 100MW project in Germany with local use cases. Shell started the operation of a 10MW electrolyser in its chemical park in the Rhineland (Germany) in 2021, and plans to build a 100MW unit due to the high demand. The refining site will be transformed from an oil refinery to a chemical and energy park. In the port of Rotterdam, three projects with a total size of 550MW are being explored or planned.[34]

In the first quarter of 2022, the global hydrogen project pipeline reached almost 300GW, i.e. more than three and a half times higher than the 80GW in December 2020 (source: Green Hydrogen Leaders). For comparison, a large coal-fired power station typically has a capacity of 1GW.

IHS Markit expect a further 40% decrease in the cost of low-carbon hydrogen through to 2025, both due to lower renewable electricity production costs and the declining cost of electrolysers. The greater the demand for electrolysers globally, the more manufacturers will produce them as standard units in automated production lines. Additionally, IHS Markit also notes the political support, reflected in around $44 billion of funding in a few European countries alone, which is five times more than the global investment in research, development and demonstration from 2005 to 2018.[35]

31 Press release of the German Federal Ministry for Economic Affairs and Energy on 24 September 2021

32 https://esmap.org/esmap_offshorewind_techpotential_analysis_maps

33 IRENA, *Renewable Capacity Statistics 2021*, March 2021

34 Argus, Rotterdam port confident on hydrogen pipeline, 11 August 2021

35 IHS Markit, *10 Cleantech Trends in 2021*, 2021

3.3.2 Demand for synthetic fuels

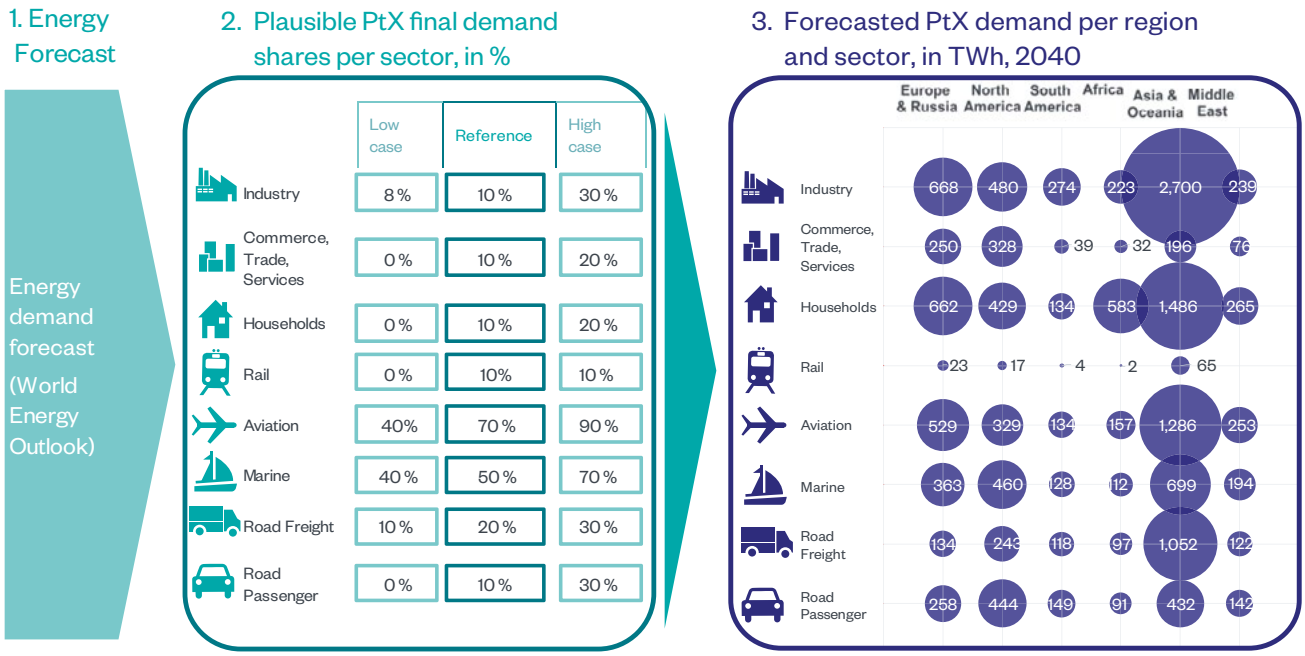


Figure 3.11: Sectoral and regional consumption of hydrogen-based fuels by 2040. Frontier economics expects a global demand of 20,000 TWh in the base case and 41,000 TWh in the high case.

Source: Frontier Economics, International Aspects of a Power-To-X Roadmap, report prepared for the World Energy Council Germany, 2018

The demand outlook for synthetic fuels – as already indicated by the scenario analysis – is very positive. In particular, the anticipated industrial and household demand, as well as the expected demand from Asia, show a very promising future. Figure 3.11 clearly shows that maritime shipping will only play a limited role as a consumer of hydrogen-based fuels in comparison with industrial use cases, households and other transport modes. Consequently, maritime shipping will experience more competition when it comes to sourcing fuel for ships.

> Most scenarios expect a strong demand for hydrogen-based fuels from Asia. Sectors other than shipping will consume the lion's share.

For the future, as hydrogen production costs are expected to decrease because of investment in RD&D projects together with an expected increase in total electrolyser capacity, and the costs for transporting and distributing hydrogen will become increasingly important. Ultimately these transport costs will also become a factor in deciding whether it is more economical to produce these fuels locally (or nearby) or to import them from locations that are further away. Global transport will then be the key enabler connecting regions that have attractive low-cost climate-neutral electricity with regions that have higher costs. The export opportunities will also be driven by existing infrastructure, such as storage, terminals and harbours.

Additionally, non-economic factors might lead to the need to import (net) zero carbon fuels: social acceptance of renewable projects and electricity grid enhancements is not always given, leading to a situation where the necessary amounts of electricity cannot be produced near the consumption centres. In this instance, imports that can be sourced globally are needed. For many potential consumption centres in Europe, South Korea and Japan, the land use constraint (together with comparatively expensive production costs for (net) zero carbon energy carriers) will lead to the need for imports to meet demand.

Generically, this leads to three types of value chain in a hydrogen economy:

On-site: The required hydrogen will be produced on-site; some storage facilities can be used. This might be a solution for large industrial sites, for example steel manufacturers that source electricity via competitive power purchase agreements (perhaps also on-site in order to save grid fees), and which can also run the electrolysers on their site.

Regional: Apart from hydrogen production, storage and conversion (e.g. to liquid energy carriers to enable transport), the distribution of the energy carriers is also part of this value chain. This transport might typically use trucks or pipeline systems depending on the distance. This solution is needed for households and fuel stations, where on-site production of hydrogen with small-scale electrolysers is not economic.

International: For large amounts of energy, global trade will play a decisive role, especially when the local resource situation for climate-neutral electricity generation is not favourable. Transport of the synfuels will then take place either by pipeline system or by ship.

To transport zero carbon hydrogen, or the energy carriers made with it, there are basically three modes of transport available: trucks, pipelines and ships. The chosen transport mode also strongly depends on the end use of the energy carrier. However – as is also the case with crude oil or natural gas – the transport distance has a strong impact on the chosen transport mode.

Trucks: Ideal for low or volatile demand, e.g. super-peak demand. Trucks can also become interesting for distribution to end consumers.

Pipelines: For short and medium distances, pipelines are economically interesting, especially if existing gas infrastructure can be used or enhanced for hydrogen transport.

Initial projects are being developed in Europe to deliver green hydrogen by pipeline. For example, HyDeal Ambition: green hydrogen produced by PV electrolysis will be transported via a dedicated hydrogen pipeline system in a phased approach, with the first deliveries in Spain, followed by the southwest of France and then eventually eastern France and Germany. Deliveries of 3.6Mt per year are being targeted by 2030. The price goal is €1.5/kg.[36]

Ships: Compete with pipelines for long-distance transport, and offer transoceanic opportunities beyond the capability of pipelines.

Particularly for ship transport, regulation needs to be developed or enhanced to meet safety requirements for transporting energy carriers. The safety regulations for maritime vessels, which also regulate the requirements for issuing certificates, are usually developed by the International Maritime Organization (IMO).

> Safety regulations for maritime vessels are needed to enable safe hydrogen transport.

36 Press release, HyDeal Ambition, 11 February 2021

1. Assuming high utilization
2. Including reconversion to H_2; LOHC cost dependent on benefits for last mile distribution and storage
3. Compressed gaseous hydrogen

Figure 3.12: Overview of transport options to meet consumer demand

Source: Hydrogen Council, McKinsey & Company, Hydrogen Insights – A perspective on hydrogen investment, market development and cost competitiveness, 2021

The use of hydrogen applications is not only driven by the absolute cost of hydrogen supply (including production, transport, distribution and storage), but also by technological development in the end application market and the price differential between the hydrogen applications and other technologies (conventional applications based on fossil fuels and also other climate-neutral solutions, e.g. biofuels in the transport sector). Consequently, the carbon price – either as a traded good, e.g. an EU Allowance or a Chinese Emissions Allowance, or as a tax or levy – also plays a crucial role. Apart from energy uses – either directly as hydrogen or in synthetic fuels built from hydrogen – there are also many feedstock applications in industry in general. Analysts expect a broad range of applications.

> Demand for (net) zero carbon fuels is driven by the need to meet climate neutrality goals and is hence very strong. Technical solutions exist for the transport and distribution of (net) zero carbon fuels.

3.4 Conclusions and Recommendations

Apart from the global demand and supply situation, there are many additional reasons to establish a global trading system with (net) zero carbon fuels. These include enhancing security of supply, managing seasonal production swings, reducing energy costs for importers, and financing projects for exporters.

For countries with a strong export agenda, the outlook for demand for (net) zero carbon fuels is very promising. This should allow them to secure project finance at a reasonable cost given the long-term outlook for increasing demand. A global market would also provide liquid market prices, allowing financial investors to fund projects along the (net) zero carbon fuel value chain.

Individual countries may also make strategic investments in climate-friendly fuel production. However, with regards to reducing market foreclosure and increasing liquidity in the markets, these solutions are less preferable. Consequently, an early ramp-up of global trading activities, with a liquid market and reliable market prices, would help to limit this kind of exclusive arrangement. The risk of market foreclosure emerging from the widespread use of long-term contracts can be reduced by competition authorities banning contract clauses that restrict reselling.

Numerous national hydrogen strategies are addressing the future challenges to create a hydrogen economy by looking at several use cases for hydrogen-based fuels in the industry, for households and for mobility. The strong climate-neutrality agenda is underlying this development.

4 Trade and Opportunities for (Net) Zero Carbon Fuels

4.1 Maritime Transport of Hydrogen-based Fuels

Hydrogen can be transported in many ways. The basic difference between the various energy carriers is the volumetric energy density (energy content by volume, e.g. measured in kWh/litre). For maritime shipping, the options currently discussed are liquid hydrogen (also known as LH_2), hydrogen dissolved in liquid organic substances (also known as LOHC), compressed hydrogen, and chemicals, especially ammonia and methanol.

Liquid hydrogen: For transporting as a liquid, the hydrogen needs to be liquefied by reducing the temperature to -253°C, i.e. much lower in comparison with LNG. Liquefied hydrogen has an energy density that is three orders of magnitude higher than gaseous hydrogen. This energy-intensive process consumes in the best case roughly 6kWh/kg. The liquid hydrogen can then be stored in insulated tanks during shipment. The transport capacity of a maritime liquid hydrogen carrier is expected to be in the order of about 11,000t H2.[37] Similar to LNG ships, gas boil-off will also occur during transport, and might be used as transport fuel. Typical values for boil-off are 0.5% of the vessel capacity per day.

LOHC: Hydrogen can also be absorbed in liquid organic substances. Increasing the temperature of these liquids will then set the hydrogen free again. Examples of LOHC are dibenzyltoluene and methylcyclohexane. The LOHC can then be stored and transported by ships. A tanker filled with 75,000t of dibenzyltoluene corresponds to a usable hydrogen amount of 4,000t, i.e., three times less than liquid hydrogen, albeit with easier transport conditions. The organic material can be used for further transport, after the hydrogen is extracted.

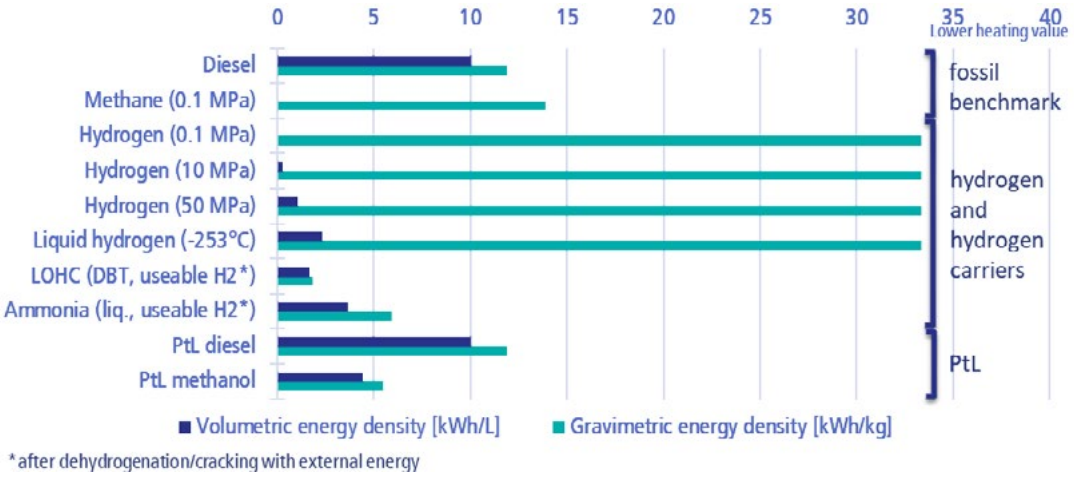


Figure 4.1: Energy density of energy carriers – the advantage of fossil fuels such as diesel or methane is their high volumetric density, which means they take up to less space. Consequently, alternative fuels need to address this challenge.

Source: World Energy Council Germany and Ludwig Bölkow Systemtechnik, International Hydrogen Strategies, September 2020

KEY POINT:

Most energy carriers have a lower volumetric energy density than diesel. Since diesel has a similar volumetric energy density to crude oil, more shipping by volume for the same amount of energy can be expected.

37 The total energy amount for this example is lower than a crude oil supertanker. Assuming a load of 250,000t of crude oil with a density of 11.6kWh/kg crude, the corresponding energy amount is 2.9TWh. The hydrogen ship with 11,000t of hydrogen with a density of 33.33kWh/kg hydrogen contains an energy amount of 0.37TWh, i.e. almost eight times less.

Compressed hydrogen: compressed hydrogen (to 250 bar) needs substantially less volume than at standard pressure, similar to CNG (compressed natural gas). Its energy density is not as high as liquid hydrogen, but the cooling energy is not needed. Initial studies indicate a typical transport amount of 2,000t per ship.

Chemicals: Hydrogen can also be used as a building block for chemicals such as ammonia, methanol and other synthetic fuels. Ammonia can be liquefied to increase its energy density, although temperatures of roughly -33°C are needed. Its typical transport volumes are similar to liquid hydrogen, meaning that using a very large gas carrier (VLGC) with a storage volume of 82,000m^3, roughly 10,000t of hydrogen can be transported. The landed ammonia can then be cracked to produce pure hydrogen for direct use or further hydrogen distribution, or it can be used directly as ammonia, such as for fertiliser production, power generation or as a fuel for ships. Ammonia cracking requires substantial amounts of heat and electricity, resulting in consumption of about 30% of the energy contained in the hydrogen. Due to the toxicity of ammonia,[38] its widespread distribution, especially in populated areas, is a challenge to be implemented as part of future energy import chains. Despite these concerns, ammonia is considered as one of the most promising (net) zero carbon fuels, since this chemical is well-known and there are established processes for transport and storage.

Power-to-Liquid (PtL) fuels are produced from hydrogen and CO or CO_2 via the Fischer-Tropsch or methanol route. After PtL production, the synthetic liquid can be stored, transported and used in the same way as their fossil counterparts.

To produce CO_2-neutral fuels, the hydrogen production and CO/CO_2 supply need to be CO_2 neutral. This can be achieved by using CO_2 from biogenic resources or by capturing CO_2 directly from the air. The first option is usually limited in scale due to available regional biomass potential; the latter option requires a relevant amount of energy and equipment for air separation or direct air capture. PtL fuels are mainly considered as drop-in fuels to (partially) substitute for their fossil-based counterparts in existing applications, such as aviation, that cannot easily be switched to batteries or hydrogen. The main aim is to reduce the carbon footprint. PtL fuels are not used as hydrogen carriers to supply pure hydrogen for use in processes or applications and are thus not directly comparable with hydrogen transport via pipeline, LOHC or in liquid form.

> To trade the same amount of energy with synthetic fuels, a greater volume is typically needed, meaning that more or larger ships are required compared to fossil fuels.

Hydrogen and synfuels are likely to be affected to changes in energy geopolitics. The current focus on the strategic ellipse, where the overwhelming share of oil and gas is produced, might weaken, since more competition and supply alternatives can be expected. Hydrogen and synfuels might also offer business opportunities for energy exporters in MENA and Russia[39].

4.1.1 Hydrogen-based fuel production and import costs

Global trade makes sense if local production costs for hydrogen or synthetic fuels are higher than the imported costs. To put these costs into perspective, we convert them into electricity costs at the import location. We assume that the calorific value of hydrogen is between 33.33kWh/kg and 39.41kWh/kg and that electrolysis requires between 50kWh and 60kWh of electricity to produce 1kg of hydrogen. The electricity prices calculated using this approach can then be compared with the LCOE, which is available for a PV system at the landing site. For example, according to World Bank data, in 2018 in the Netherlands, PV had an LCOE of 12.41¢/kWh (€0.1041/kWh), in Spain 8.10¢/kWh (€0.068/kWh) and in Germany 11.19¢/kWh (€0.0939/kWh).

38 G. Thomas and G. Parks, *Potential Roles of Ammonia in a Hydrogen Economy*, US Department of Energy, 2006

39 Julian Grinschgl, Jacopo Maria Pepe, Kirsten Westphal, A New Hydrogen World, Geotechnological, Economic, and Political Implications for Europe, SWP Comment 2021/C 58 (16 December 2021)

The implicit electricity price compares the import costs for hydrogen with the production costs for hydrogen with an electrolyser in the importing country. According to the study, ammonia can be imported from Chile at €117/MWh(H2) at Rotterdam. From this, an electricity price can be calculated at which hydrogen can be produced by electrolysis in Rotterdam at the import cost. Given the two assumptions that 50kWh of electricity are needed to produce 1kg of hydrogen, and that hydrogen has a calorific value of 33.33kWh/kg, an implicit electricity price of:

$$€117/MWh(H_2) \times 33.33\ kWh/kg(H_2) \div 50kWh(electricity)/kg(H_2)$$

is derived. This implicit electricity price can then be compared with the LCOE for renewable production at the Rotterdam site to determine whether hydrogen production at the landfall site is competitive compared with imports. Since the values for the amount of electricity required vary by 50–60 kWh for electrolysis and the calorific value of hydrogen varies between 33.33 kWh/kg and 39.41 kWh/kg, there is a band width in the implicit electricity cost.

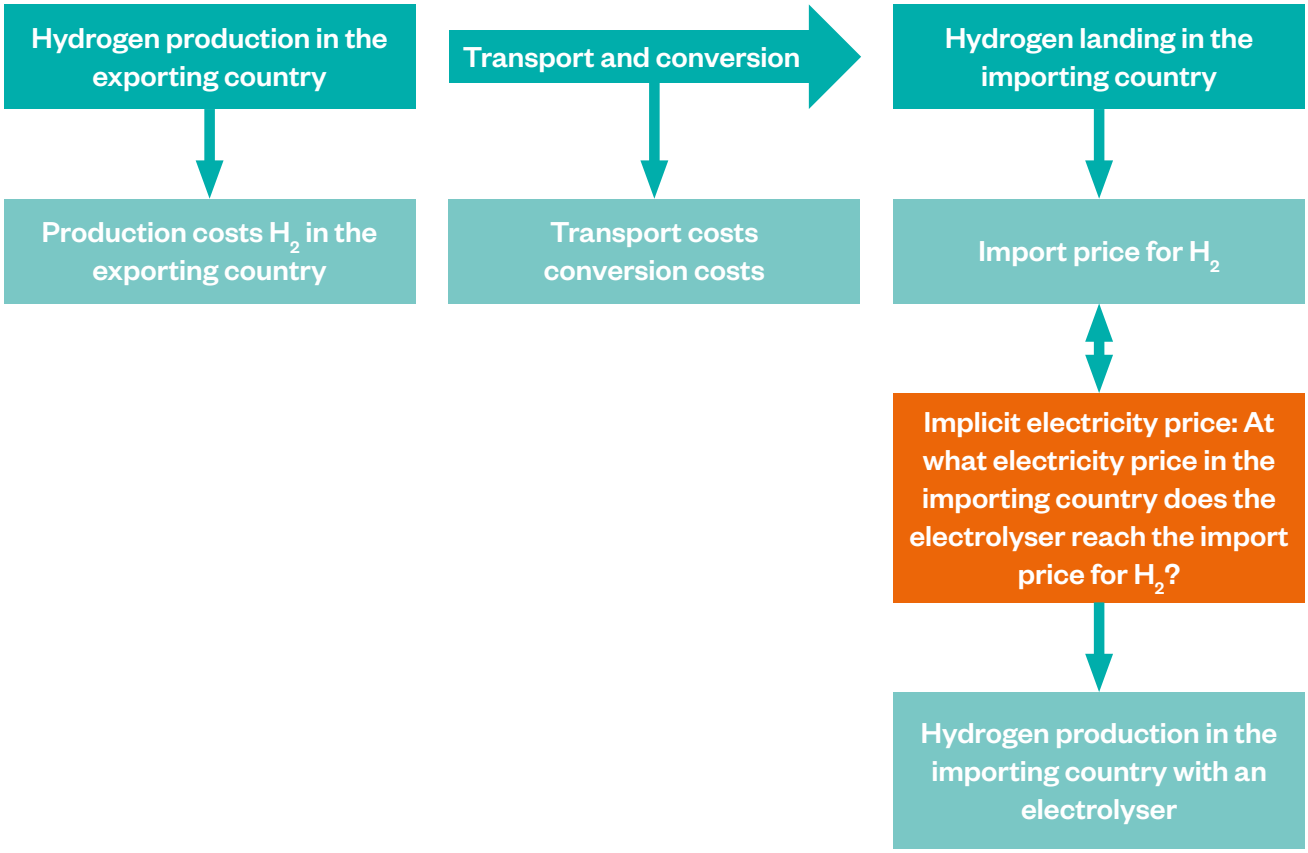


Figure 4.2: Comparison of import costs with production costs for hydrogen using electrolysis in the importing country

Source: Hans-Wilhelm Schiffer and Stefan Ulreich 'Hydrogen – Important Building Block Towards Climate Neutrality', atw: International Journal for Nuclear Power, Vol. 66 (2021), Issue 4

> International trade offers access to low-cost production of synthetic fuels leading to economic benefits for importing countries, as imports are typically cheaper than local production.

Table 4.1 shows that both the Netherlands and Spain already have economically attractive import options for renewable hydrogen in the form of ammonia from Chile. The transport costs are in the best case more than compensated by the lower production costs. Spain, of course, is different from northwest

Europe, thanks to better LCOE for PV: consequently, the production sites for hydrogen in Spain can be more economical.

Import location: costs in €/MWh	Australia hydrogen H_2	Australia ammonia NH_3	Chile hydrogen H_2	Chile ammonia NH_3	Saudi Arabia hydrogen H_2	Saudi Arabia ammonia NH_3
Rotterdam	248	189	161	117	208	169
Rotterdam implicit electricity costs in €/MWh (electricity)	13.78–19.55	10.50–14.90	8.94–12.69	6.50–9.22	11.55–16.39	9.39–13.32
Algeciras	240	186	158	116	200	167
Algeciras implicit electricity costs in €/MWh (electricity)	13.33–18.92	10.33–14.66	8.78–12.45	6.44–12.45	11.11–15.76	9.28–13.16
Note: The import costs for hydrogen are used to calculate the electricity costs that are just competitive for hydrogen production at the import location (Rotterdam or Algeciras): if the actual market prices for electricity at the import location are higher than the calculated value, import is more economical						

Table 4.1: Costs for imported hydrogen and implicit electricity costs at the point of import

Source: Hans-Wilhelm Schiffer and Stefan Ulreich, Hydrogen – Important building block towards climate neutrality, Internationale Zeitschrift für Kernenergie, Vol. 66(4), pp. 19–29, 2021

KEY POINT:

"Make-or-buy" comparison: importing hydrogen into Europe can be cheaper than producing hydrogen in Europe.

> Transport costs by ship for biofuels and synthetic fuels are typically in the range of 2–10% of the total import cost.

In perspective, the costs are likely to fall both for the transport infrastructure – where the reduction in cost is due to technical progress in equipment – and for hydrogen production. A study published by the European Commission[40] shows import costs for 2050 that are significantly lower than the import costs for 2020, assuming that hydrogen is imported into Europe by pipeline from North Africa or Russia. Transport costs are between 2% and 10% of the total costs. Production of hydrogen in Europe therefore faces intense competition if production costs in Europe are 10% higher than in the export regions.

The transport costs of biofuels and synthetic fuels by ship are only a small fraction of the total cost at the landing port, with hydrogen as a notable exception. Typically, the total costs for importing hydrogen are lower than importing synthetic fuels. However, the additional infrastructure costs are not considered here and there might also be additional costs to transform hydrogen to another energy carrier or the necessary feedstock. Consequently, the international trade of methanol or ammonia might in the end be more attractive than hydrogen.

Apart from the cost perspective, the technology readiness level is also of key importance. The IEA assessed this for ammonia bunkering to be high, at 9 out of 10. Consequently, large-scale roll-out is the expected next step. Meanwhile, RD&D is still needed for the transport of ammonia so as to increase the technology readiness from the current level of 4–5.[41]

40 European Commission, *Hydrogen generation in Europe: Overview of costs and key benefits*, 2020

41 IEA, *ETP Clean Energy Technology Guide 2020*, 2020

Fuel: production cost (shipping cost) in €/TWh	From Australia to Germany	From Saudi Arabia to Germany
FT (diesel, kerosene)	126.4 (6.5)	124.7 (3.7)
Methanol	124.7 (12.9)	123 (7.3)
SNG (l)	126.3 (11.1)	124.5 (6.3)
Hydrogen (l)	93 (74.5)	90 (42.3)

Table 4.2: Total fuel costs for transport by ship to Germany from Australia and Saudi Arabia

Source: Fraunhofer Society, PtX Atlas

KEY POINT:

The transport costs from Australia to Germany and from KSA to Germany are almost 50% lower in the case of hydrogen transport than other fuels.

The import costs at the landing port are in a narrow range for fuels from many exporting countries, in other words the available market sources are in competition (no price-setting is possible). If importing countries have access to supply from various markets with high production potential, and all these markets show more or less the same costs, this increases the security of supply.

Additionally, there are options to reduce transport costs and to increase access to further countries by using pipeline transport as an alternative to ships, such as from Russia or Ukraine to EU member states. And again, other climate-friendly electricity production options (hydropower, nuclear, CCUS) will also help to increase the production potential and strengthen the security of supply.

Imports to Denmark	Production incl. transport in €/MWh			
Synthetic fuels (average value)				
Export country	**FT**	**Methanol**	**SNG (l)**	**H_2 (l)**
Chile	114.80	117.70	117.80	128.80
Saudi Arabia	128.40	130.50	131.00	133.20
India	129.70	131.70	132.20	141.70
US	131.50	131.70	132.80	119.10
Iran	133.00	135.30	135.50	136.50
Australia	132.90	137.80	137.60	168.40
South Africa	139.90	142.10	142.90	146.40
Russia	142.20	142.40	143.80	129.50
Ukraine	167.20	167.10	169.10	151.30
Conventional fuels				
Market prices	**Diesel**	**Methanol**	**LNG**	
Aug-21	ARA FOB	Methanex	ARA	
1 USD = 0.85€	581.80 USD/MT	410.00 €/MT	770.00 €/MT	
	41.31 €/MWh	63.17 €/MWh	55.08 €/MWh	
Conventional fuels				
Market prices	**Diesel**	**Methanol**	**LNG**	
Apr-22	ARA FOB	Methanex	ARA	
1 USD = 0.92€	1,028.42 USD/MT	570.00 €/MT	1,738.80 €/MT	
	79.04 €/MWh	87.83 €/MWh	124.38 €/MWh	

Table 4.3: Total synthetic fuel costs (assumptions for 2050) via ship to Denmark from various export countries for Fischer-Tropsch (FT) fuels, e-Methanol and Synthetic Natural Gas (SNG) Market prices as of 15 August 2021 and of 12 April 2022) comparing the 2050 costs for (net) zero carbon fuels with Diesel, Methanol and LNG traded prices.

Source: Fraunhofer Society – PtX Atlas, ICE London, Methanex, Rotterdam Bunker Prices

KEY POINT:

The range of costs for green synthetic fuels is quite narrow between the listed exporters.

> International trade offers access to various exporters with similar total costs and reasonable production potential; this increases the security of supply.

However, one should also note that the current market prices for alternative fuels are still much higher than for current fuels. Efforts are still needed to reduce production costs significantly.

4.1.2 Recent market price movements

Since early autumn 2021, the global market prices for crude oil and especially for natural gas increased strongly due to several reasons, e.g. post-pandemic economic growth, strong demand in North Asia due to expectations for cold winter, military conflicts and supply bottlenecks. The increasing costs for fossil fuel prices lead to a very promising outlook for the economics of the (net) zero carbon fuels. With the market prices in April 2022, synthetic natural gas (prognosis for 2050) is cheaper than the LNG market prices. Depending on the research and development efforts for (net) zero carbon fuels, the switch toward them might come much sooner than expected.

Recent research by the French bank BNP Paribas led to the conclusion that crude oil would need long-term price levels between 10 and 20 US$ per barrel to stay competitive in mobility in comparison with electro-mobility[42]. Consequently, the switch from fossil fuels to alternative fuels might happen faster than anticipated and accelerated by longer periods with high market prices for fossil fuels.

4.2 Market Prices for Hydrogen

The data provided by the Fraunhofer Society contains estimated production costs by 2050 for hydrogen and hydrogen derivatives, as well as an assessment of the annual production potential. The production cost already gives an initial idea about the countries with the lowest estimated production costs (measured in €/MWh). Apart from the expected names, such as Chile, Saudi Arabia and Australia, there are also many promising African countries, e.g., Mauritania, Somalia, Egypt, Jordan and Morocco. However, as already stated, this high and interesting potential also needs administrative and political prerequisites in order to be realised.

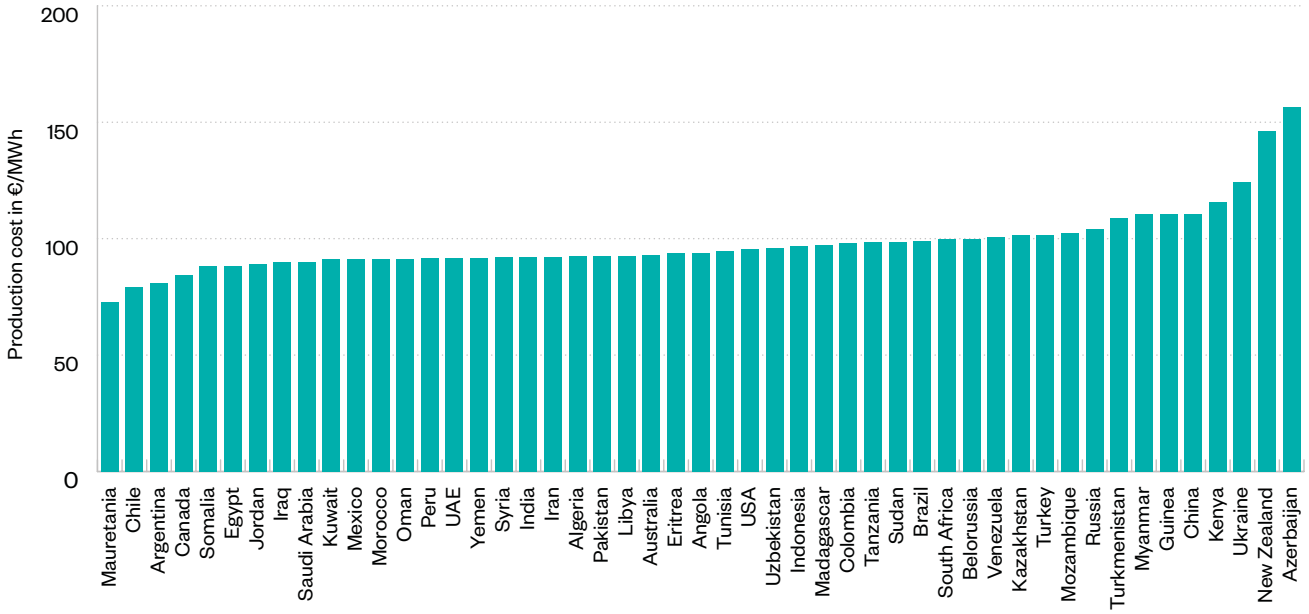


Figure 4.3: Production costs for hydrogen in 2050 in €/MWh, sorted from low to high

Source: Fraunhofer Society, PtX Atlas

Apart from the production costs, the transport costs and the production volume are also relevant. With this data, a merit order curve for a specific importing country can be derived. Price formation for hydrogen will depend on the global demand for it. If it stands at 60,000TWh, from a German importer's point of view the result from the merit order curve would be import costs of €124/MWh. In this instance, low-cost producing countries such as Mauritania would benefit from the difference with the market price and earn more than the cost of production.

42 BNP Paribas, Mark Lewis, Wells, Wires and Wheels – EROCI and the tough road ahead for oil, August 2019

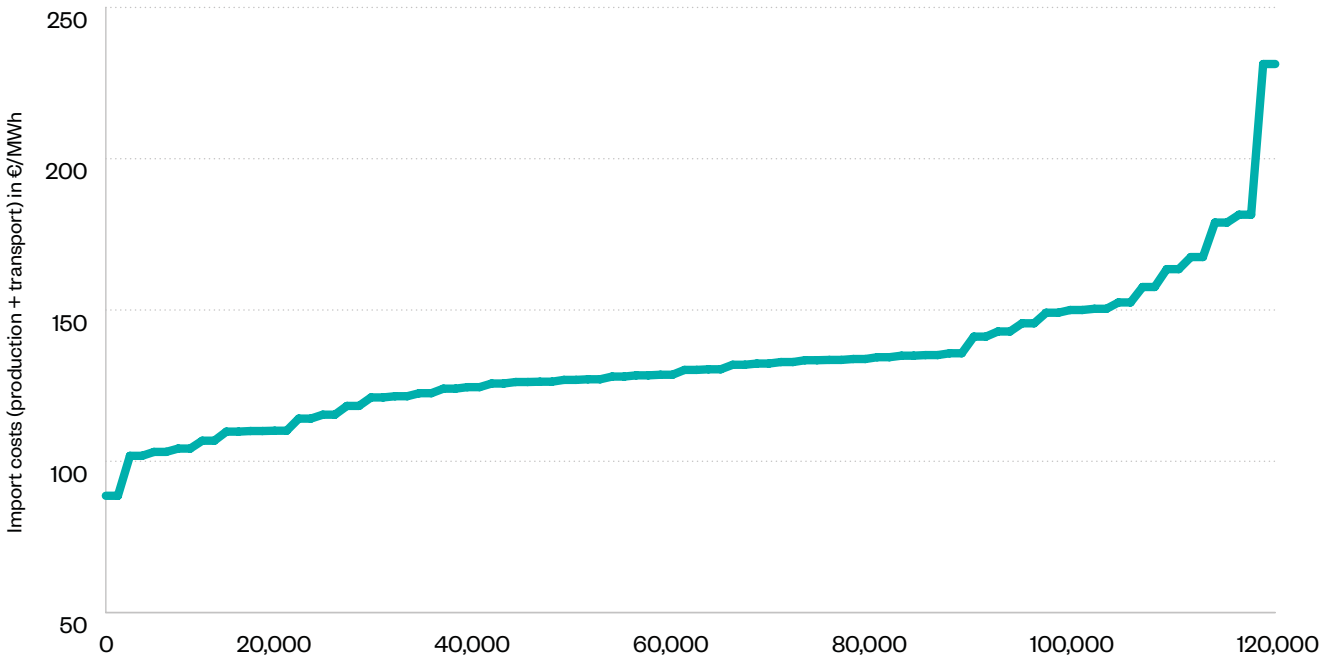


Figure 4.4: Merit order curve for the import of hydrogen to Germany (production costs and transport in 2050 in €/MWh)

Source: Fraunhofer Society, PtX Atlas

Due to the transport costs and their dependence on the travel distance, Fraunhofer expects that there will be no single market price for hydrogen globally, but instead prices will depend strongly on location, as is also the case for LNG imports. Nevertheless, global demand will influence the market price at all potential delivery ports. Again, it is important to emphasise that the strength of a global market is – apart from fair price formation – the ability to ensure security of supply by allowing importers to tap into various global sources.

#	Country	Potential in TWh	Import costs in €/MWh
1	Mauritania	1,007	88.6
2	Morocco	502	101.8
3	Belarus	16	103.1
4	Algeria	596	104.2
5	Canada	3,440	106.8
6	Egypt	4,908	109.8
7	Tunisia	312	110.0
8	Libya	3,663	110.1
9	Jordan	17	114.1
10	Syria	132	115.4
11	United States	29,885	118.3
12	Uzbekistan	622	121.1
13	Yemen	1,066	121.5
14	Argentina	13,080	122.5
15	Eritrea	1,007	124.0
16	Turkey	58	124.5
17	Kazakhstan	1,496	125.7
18	Mexico	2,981	126.2
19	Sudan	490	126.3
20	Somalia	2,839	126.9
21	Angola	492	127.1
22	Chile	2,705	128.0
23	Oman	680	128.4
24	Russia	10,673	128.6
25	Colombia	253	130.2

Table 4.4: Total fuel costs in 2050 for the transport of hydrogen by ship to Germany from various exporting countries, low to high, with hydrogen export potential in TWh also shown by country
Source: Fraunhofer Society, PtX Atlas

KEY POINT:
There are many exporting countries available for Europe – especially if transport by ship is considered – leading to a potential safe supply. The costs for hydrogen landed in Europe is in a reasonable narrow range.

The merit order approach to pricing commodities is a standard methodology in the global commodities market. With this approach, incentives are given to producers to reduce their production and transport costs in order to stay competitive. Similarly, the market prices offer potential consumers the ability to select the solution that is most cost-efficient and, in case of high market prices, to think about more efficient use of the commodities.

> Importing countries can choose between a variety of suppliers for hydrogen-based fuels with similar cost levels.

One should note that the merit order approach results in a theoretical market price. Typically, market prices fluctuate. These price fluctuations can be measured as volatility. Assuming a log-normal model for the price behaviour of a certain commodity, one can estimate ranges for market prices over a given period of time. Assuming a volatility of 50% and potential price movements within a period of 4 weeks, one arrives at Figure 4.5. For comparison, the volatility on the LNG market ranges between 15% and 110%. The figure shows the price ranges that the log-normal model is forecasting (to be precise, 95% of all observed market prices should be in the range between up and down – consequently in 5% of all cases the prices are outside this range).

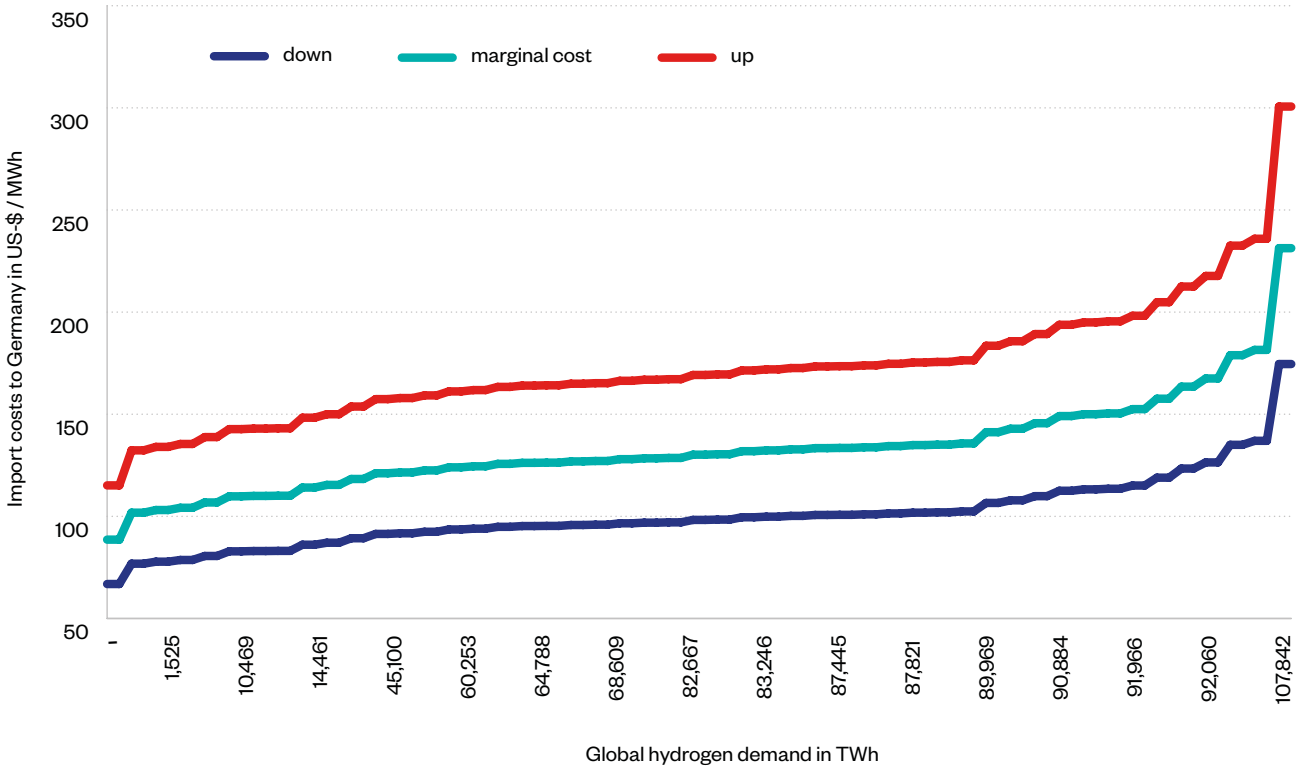


Figure 4.5: Hydrogen import costs to Germany using the log-normal model to identify the potential market price range

Source: Author's calculations

Taking an example, assuming global demand of 10,000TWh for hydrogen would lead to a fair market price of €109.80/MWh at the importing harbour (including freight). If this market price is observed, then within a period of four weeks, the market price should move between €83/MWh and €143/MWh in 95% of all observed cases.

> Variety of importing countries will give hydrogen producers in exporting regions security of demand.

The volatility of the market price is always of huge interest to commodity traders, since reasonably high volatility leads to liquid markets. This ensures that investors and buyers of the commodity will always see a market price signal – in contrast to rather illiquid markets like real estate. The continuous updating of market prices allows investors an easier and more reliable assessment of investment opportunities.

> Liquid hydrogen markets with reliable market price information will help investors and consumers to base their decisions on facts.

In scarce markets with insufficient supply, where the infrastructure still needs to be ramped up, it is likely that prices will be substantially higher than the marginal cost. This ensures that early investors in production capacity benefit from higher returns as a reward for taking on higher risk.

Another benefit of trading markets is the availability of price information, since this increases transparency. In illiquid markets – which is the generic case, when a commodity starts to be traded – a market assessment is typically done by asking for price quotes of market participants. These will be anonymously collected, and an average assessment price will be determined and published. The Commodity Exchange EEX plans to introduce a hydrogen index in 2022[43]. This index could certainly help suppliers and consumers of hydrogen to assess their investments on a more solid ground.

4.3 Opportunities for Production and Exports for Developing Countries

Many developing countries have excellent intrinsic conditions to produce renewable energy by wind, PV systems or hydropower production. One well-known case of unlocked potential is the Grand Inga Project in Africa, which has been under discussion since the 1970s and has slowly gained pace in recent years. The project itself is a set of hydroelectric plants with a total capacity above 40,000MW with an expected production of roughly 370TWh. IRENA points out in its roadmap Africa 2030 that by 2030 100GW of hydropower capacity could be reached in the continent (the current level is 38GW installed capacity) and that around 92% of the technically feasible potential has yet to be developed.[44]

Despite the enormous potential, there are almost no national hydrogen strategies in African countries, with rare exceptions like Morocco and South Africa. Recent estimates show that West Africa alone would be able to produce 165,000TWh of hydrogen per year.[45] For comparison, the total electricity production of Africa is 850TWh, and global electricity production is 26,907TWh.[46]

It is most likely that the gigantic potential of African countries will be tapped by bilateral agreements. Currently, North African countries are concluding these agreements with European importers. These countries have strong experience of oil and gas exporting, which they can apply to hydrogen exports. For other African countries, it might be necessary to start with the development of sea ports and bunkering infrastructure as part of a bilateral agreement. Consequently, the strong strategic interests of the importing country could then determine this partnership, resulting most likely in exclusive hydrogen exports.

43 Reuters, Deutsche Boerse´s EEX to launch hydrogen index in 2022, by Vera Eckert (24 November 2021)

44 IRENA, *Africa 2030: Roadmap for a Renewable Energy Future*, 2015

45 Press release, German Federal Ministry of Education and Research, *West Africa can become the climate-friendly energy powerhouse of the world*, 27 May 2021

46 Enerdata, *Global Energy Statistical Yearbook 2021*

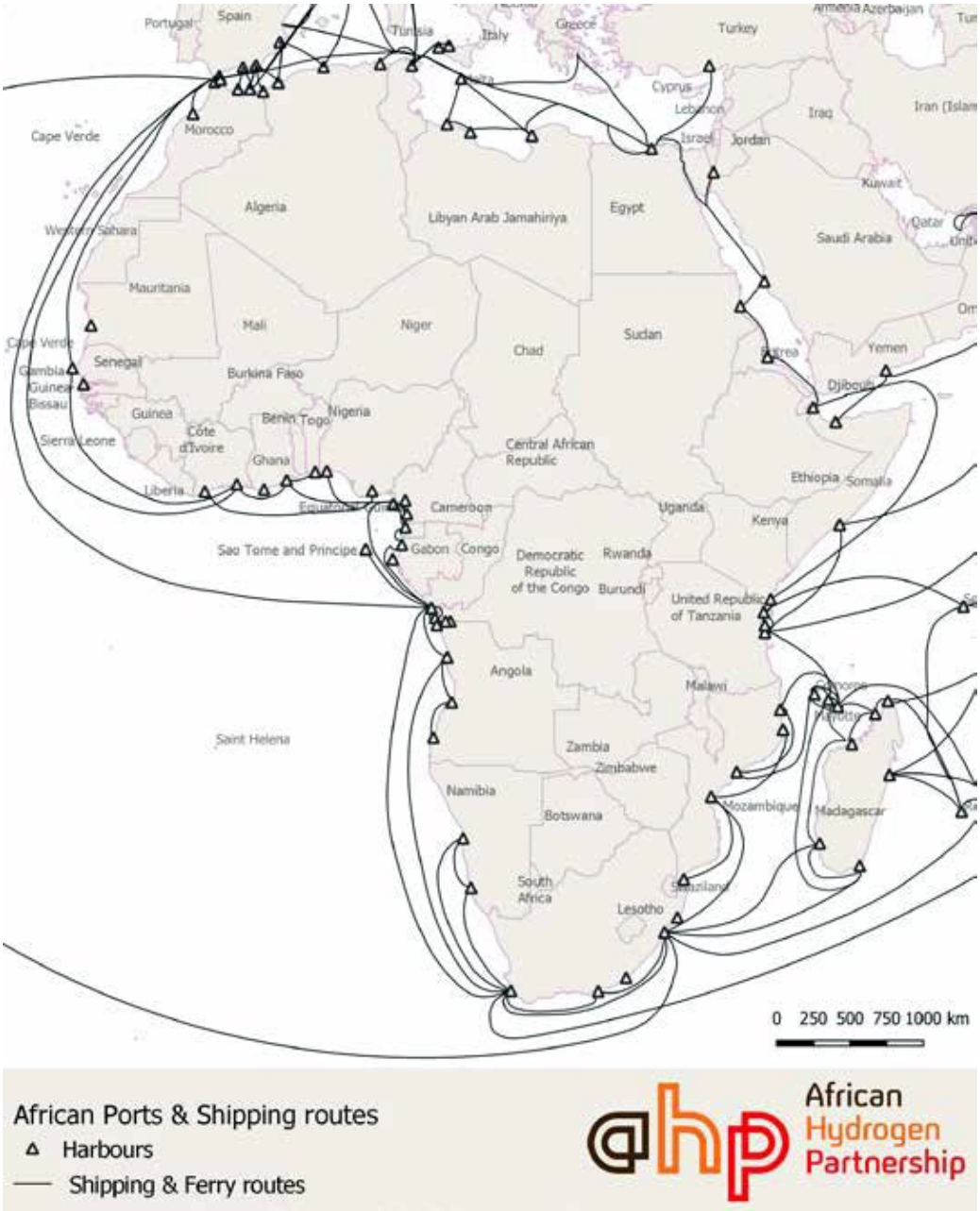


Figure 4.6: Ports in Africa and main shipping routes – Africa benefits from its long coastline when building the hydrogen export infrastructure at sea ports and already existing shipping routes

Source: African Hydrogen Partnership (https://www.afr-h2-p.com/)

Another interesting region for hydrogen production is Latin America, where Chile and Argentina have received significant attention in recent months. As of mid-2021, 11 South American countries have published or are working on a hydrogen strategy: Chile, Argentina, Bolivia, Brazil, Colombia, Costa Rica, El Salvador, Panama, Paraguay, Trinidad and Tobago, and Uruguay.[47] To a large extent, the hydrogen output will be used locally to supply industrial activities in Latin America; however, Latin American countries are focusing strongly on export markets, for example by including five large GW-scale projects in their project pipeline. This should allow both domestic and overseas markets to be well served, where the financial streams due to exporting hydrogen will help to build the local economic activities related to a hydrogen economy. Panama is viewing itself as a potential regional hydrogen distribution hub given its location at the intersection of several maritime routes.

47 IEA, *Hydrogen in Latin America – From near-term opportunities to large-scale deployment*, 2021

Generally, this potential is not exploited due to financing issues. Given the excellent demand prospects for (net) zero carbon fuels and the long-term nature of this demand, the financing concerns should be solved to trigger the development. Financial institutions can use the expected market prices for (net) zero carbon fuels, and/or conventional fuels including a GHG mark-up (for instance, due to a global carbon tax/levy), to evaluate the revenue streams of potential production facilities.

Another financing tool could be strategic investments by importing countries to secure a supply of (net) zero carbon fuels. From a trading point of view this would be less preferential due to possible market foreclosure. However, from the point of view of an exporting country the solution might have some advantages.

These facilities will not only benefit potential exporting countries due to the generation of income, it will hopefully also lead to greater electrification in these countries and might serve as a nucleus for additional industrial activity, sometimes called the "renewables pull". This describes the situation where industrial production facilities are also built in the region due to lower electricity generation costs. Furthermore, this would normally happen where electricity costs play a dominant role in the total production costs, mainly raw materials such as ammonia or methanol. Considerable potential for this exists in Africa in particular.[48]

Again, in this case export infrastructure is needed in the form of storage, bunkering facilities and ports. Consequently, a minimum degree of stability for long-term investment is needed to realise these large-scale projects.

> The long-term global growth expectation for (net) zero carbon fuels can secure financing for export-oriented production facilities in developing countries.

Since transport costs also play a decisive role, not only are production costs relevant from the point of view of the importing country, but also their proximity to the exporting countries. For many European countries, this means that MENA exporters are of great interest, as are exporters from the CIS (Commonwealth of Independent States).

A further consideration is that the scale of hydrogen production in the exporting country should be of sufficient size to justify the investment in the infrastructure. It should be noted that for some years chemicals like ammonia and methanol have been globally traded. Consequently, a degree of global infrastructure is already present – some already in developing economies.

48 McKinsey, *Africa's green manufacturing crossroads – Choices for a low-carbon industrial future*, 2021

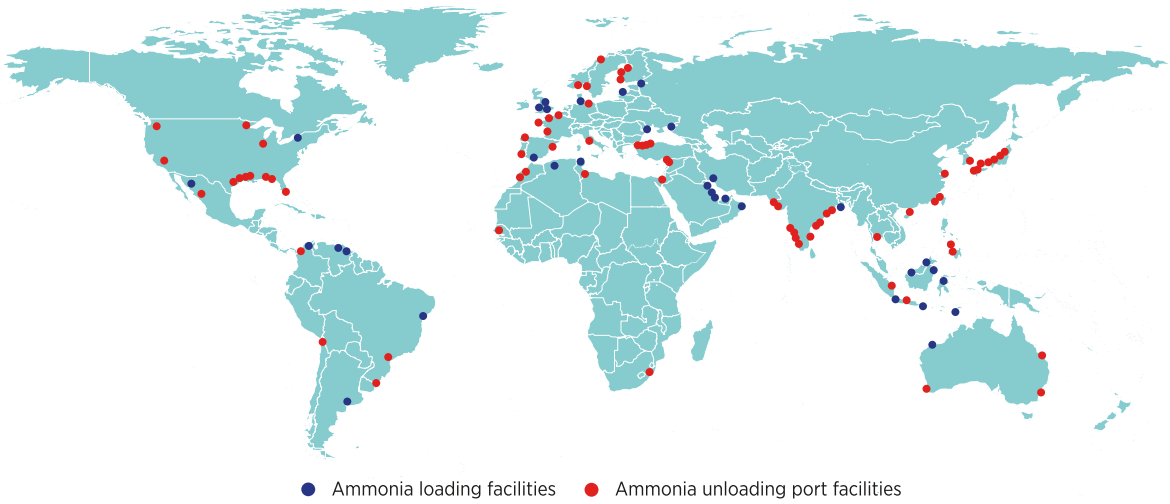


Figure 4.7: Ammonia shipping infrastructure including ammonia loading and unloading facilities

Source: Rodrigue (2020) in IRENA, A Pathway to Decarbonise the Shipping Sector by 2050, 2021

KEY POINT:

Existing ammonia terminals worldwide could be used as a nucleus for ammonia as a marine fuel.

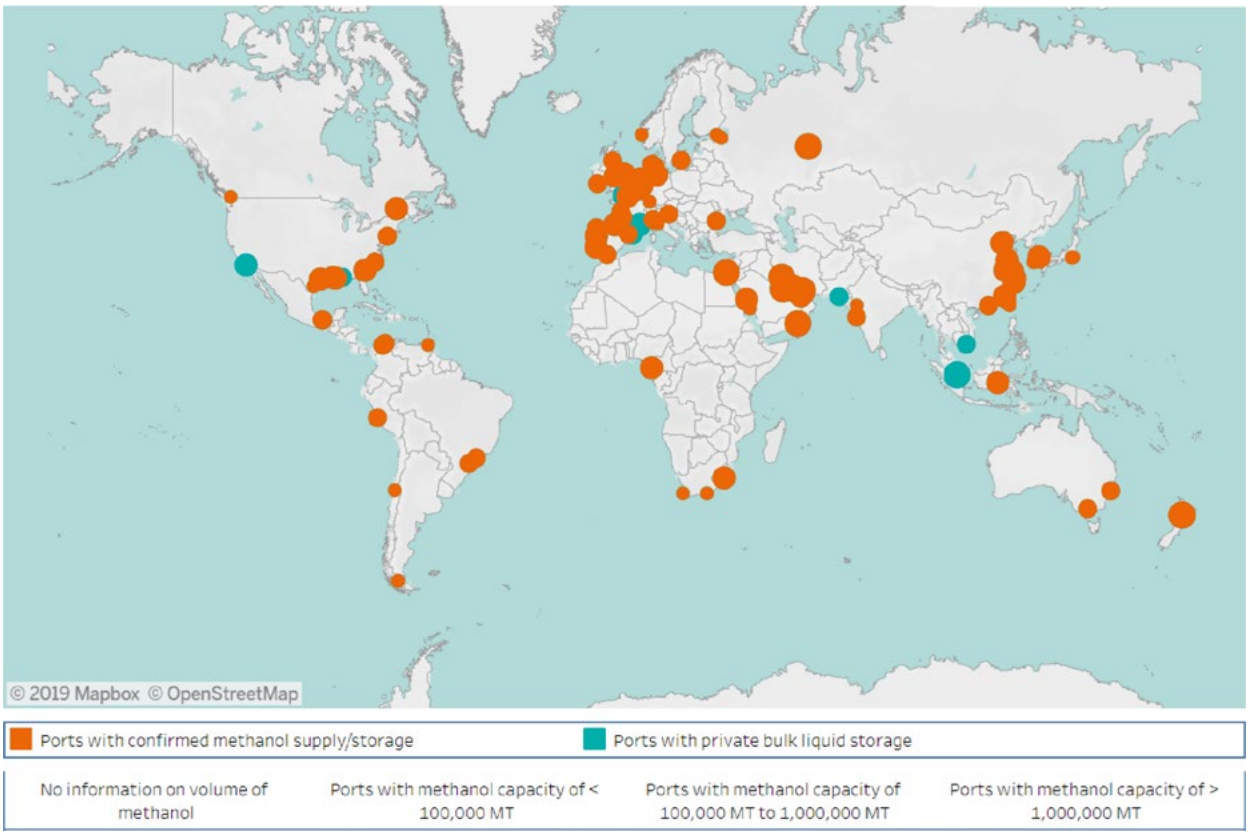


Figure 4.8: Global methanol terminals

Source: Methanol Institute, Methanol as a Marine Fuel, 2020

KEY POINT:

Existing methanol terminals worldwide can assist in the use of methanol as a marine fuel.

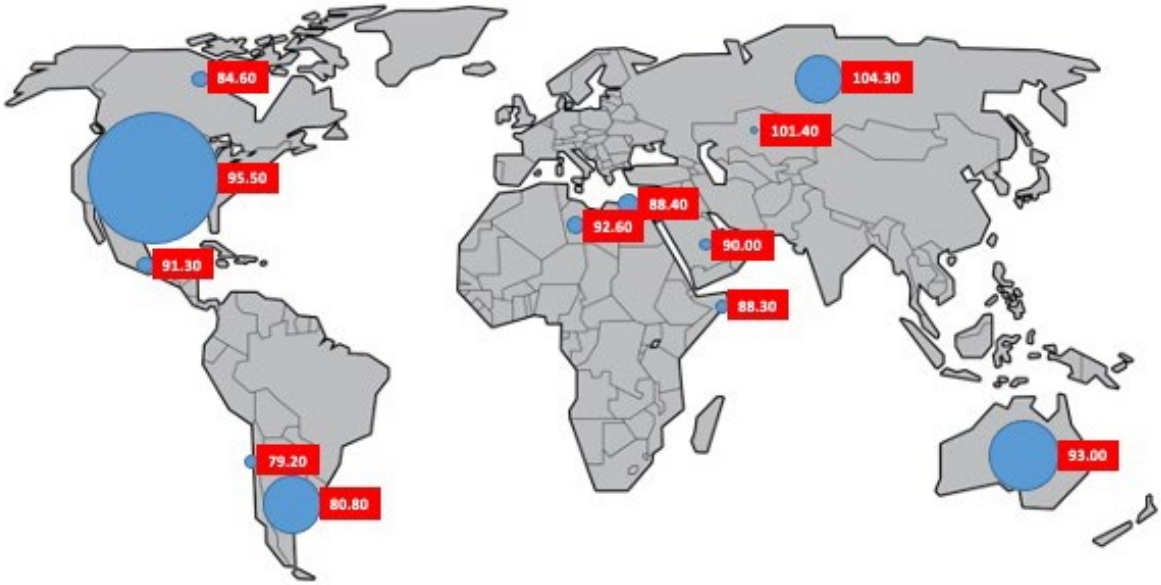


Figure 4.9: Hydrogen production potential based on onshore wind and PV

Note: Other zero carbon sources, e.g., hydropower and floating offshore wind, are not considered by the PtX Atlas.
Source: Fraunhofer Society, PtX Atlas

With regard to the expected production potential, a few countries dominate the global market according to PtX Atlas analysis: the United States, Australia and Argentina. Nevertheless, even for the countries with lower production capacity, the ramping up of hydrogen export infrastructure could make sense.

4.4 Impact of Decarbonisation on the Number of Shipping Vessels

To estimate the fleet size needed to transport hydrogen-based fuels, one can do some simple calculations based on current vessel sizes and their energy load. This estimate helps to understand the challenge of building the vessels required. To complement the estimate, one needs to assess typical travelling times for these freight ships. Table 4.5 shows the number of vessels needed to transport 1,000 TWh per year of each fuel and assuming a travelling time for the single trip of 20 days. The 20 days assumption corresponds to a rather lengthy trip, reflecting that most of the journeys are between the Southern and Northern hemisphere.

Fuel	Hydrogen	Ammonia	Methanol	LNG	Crude oil
Energy load per vessel in TWh	0.300	0.324	0.540	1.104	6.722
Number of ships required to transport 1,000 TWh per year (assuming 20 days travelling time single trip)					
	365	338	203	99	16

Table 4.5: Number of vessels needed to transport 1,000 TWh of fuels per year

It is important to highlight that these figures should be used with some caution, as they merely indicate the magnitude of order. Clearly, due to the lower energy content of a (net) zero-carbon fuel tanker, more ships are needed. However, due to energy efficiency gains there might also be less energy in terms of (net) zero-carbon fuels needed, reducing the need for imports and hence ships. Additionally, local production might play a more important role in comparison with local gas or oil production in many countries.

The import demand for Europe in 2050 is estimated between 20 Mt and 40 Mt of hydrogen[49], corresponding to imports between 667 TWh and 1,333 TWh. Consequently, this would correspond to a magnitude of order of roughly 340 ammonia ships. The current global fleet of ammonia ships is 40, i.e. about eight and a half times the current global fleet of ammonia ships would be needed to meet the European demand in 2050. Given the still ongoing research on ammonia engines and the need to learn from the first-of-a-kind vessels, it is still optimistic to assume that by 2030 a large-scale roll out of these (net) zero carbon ships can be started. This fleet therefore needs to be built within 20 years, i.e. roughly 17 vessels per year. This is not completely unrealistic – despite additional land-based infrastructure that needs to be built in the ports for charging and discharging, production facilities for hydrogen, ammonia, etc. – so guidance to coordinate all these activities could be helpful.

Pipelines could also be an import stream towards Europe – as long as there is either clarity on the transported fuel or the pipelines are able to use several fuels – and also with regards to the needed energy amount. However, the main concerns before entering into such a long-term infrastructure commitment with parties outside Europe are security of supply for the duration of the contract and the lifetime of the pipeline, and how to deal with the enormous amount of (net) zero fuels coming from a pipeline suddenly. Using ammonia or methanol carriers allows an easier and precise matching between supply and demand.

As an example, Korea's Carbon Neutral Strategy assumes that between 80% and 82% of the hydrogen demand in 2050 (27.4 Mt – 27.9 Mt) will be imported[50]. This leads to an estimated import demand of 22.4 Mt of hydrogen, which is around 750 TWh of energy; roughly three quarters of the European import demand.

Japan aims to import between 5 and 10 Mt by 2050 per year[51]. This corresponds to a range between 167 and 334 TWh, which translates into 56–112 ammonia vessels, i.e. one quarter of the European demand.

One should also note that the ships used to transport (net) zero carbon fuels might also be the ships that will generically use (net) zero carbon fuels for their propulsion. These ships have the benefit of enormous fuel storage on board. This might be very helpful when developing first-of-a-kind solutions: for example using an ammonia or methanol carrier as a test for the dedicated ammonia or methanol engine, before doing the large scale roll-out to other vessels.

4.5 Transport of CO_2

Some synthetic fuels (e.g. methanol or Fischer-Tropsch fuels) need CO_2 as raw material.[52] This can be captured at various point sources with CCUS and then be transported to the sites of synthetic fuel production. This could allow the use of freight vessels to transport CO_2 to the production site of synthetic fuel and then return with the synthetic fuel. To this end, vessel design requirements need to be fulfilled: CO_2 is liquid in a temperature range between 31.1°C and -56.6°C and above a pressure of 5.2 bar. If these technical parameters can be provided by the vessel storage system – and are also acceptable for the transport of synthetic fuel – the vessels could be used bidirectionally: transporting CO_2 to the synthetic fuel production site and returning with synthetic fuels.

Currently, early projects with so-called "CO_2 carriers" are being undertaken by Wärtsilä and Danish companies Evergas and Ultragas. With these projects it should be possible to enhance the size of vessels for liquid CO_2. For over 30 years the Norwegian company Larvik Shipping has managed industrial liquid CO_2 tankers, for many years a niche service. However, the technology exists and just needs to be scaled up. The Northern Lights project (participants include Equinor, Shell and Total) plans to build open-access CO_2 transport and storage infrastructure. Transport will take place by CO_2 tanker ships.[53]

49 La Revue de l'Énergie, Decarbonised hydrogen imports into the European Union: challenges and opportunities, October 2021

50 IEA, Reforming Korea's Electricity Market for Net Zero, December 2021

51 Ministry of Economy, Trade and Industry Basic hydrogen strategy key points: Technical Report, Research and Public Relations Office, General Policy Division, Director–General's Secretariat, Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI), Tokyo, Japan (2017) URL: https://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf

52 Some researchers even consider extraterrestrial use cases, i.e. using the CO_2-rich atmosphere of Mars to produce synthetic fuels for astronauts. Michael Miller, *UC reactor makes Martian fuel*, University of Cincinnati News, 22 September 2021

53 https://ccsnorway.com/transport-storage-northern-lights/

4.6 Market Trading

Trading usually starts with bilateral deals that are concluded between two parties, i.e. trading via an over-the-counter market. In order to avoid lengthy legal discussions about contract details and to create risk management benefits by using back-to-back hedging, traders use standardised or master agreements. The standard agreement serves as legal basis for one deal, whereas the master agreement is typically concluded between parties that expect to conclude several deals in the future and the same rules should apply to all their transactions. These agreements help to define very precisely the terms of delivery and quality of the traded good, confirmation details, the sequence of payment streams and force majeure, and are the basis for assessing credit risk and much more. Standardised contracts are popular in the finance sector (ISDA master agreement by the International Swaps and Derivatives Association), freight trading (BIMCO contracts by the Baltic and International Maritime Council) and in energy trading (EFET master agreement by the European Federation of Energy Traders).[54] EFET, for instance, has developed widely used master agreements for electricity, gas and emissions trading. Currently, although there is not an established hydrogen market yet, a standard hydrogen contract is being developed by EFET as a response to traders' expectation of an upcoming hydrogen market.

Traded goods also benefit from places where liquidity is concentrated. This leads to the development of exchanges. Apart from a concentration of liquidity, exchanges also offer additional benefits such as lower credit risk and anonymous trading. To achieve this end they need to define the products very precisely, leading to a higher standardisation (and hence less flexibility) in comparison to the over-the-counter market. Exchanges also have an important function for all actors in the market by giving reliable and trustworthy market price signals. Currently, some European exchanges are working to become a hydrogen market place, such as the European Energy Exchange, where the next steps to implement such a market place have been discussed in workshops with market participants.[55]

Another project to develop a market place is the cooperation between four Dutch sea ports (Amsterdam, Groningen, North Sea and Rotterdam) and the Dutch gas company Gasunie, called HyXchange.[56] The plan is to have a common hydrogen backbone by 2026, with regional trading established earlier. The Dutch ports have a strong interest in maintaining their position as major energy import facilities for Europe, currently dominated by oil and coal imports but then transformed to hydrogen in the long run. Gasunie is preparing for the physical delivery of the traded goods by building underground hydrogen storage facilities. The facility at Zuidwending in the province of Groningen should be fully operational in 2026, with first tests starting in 2022. The hydrogen is expected to be transported through a dedicated hydrogen grid within the Netherlands, including the possibility of transporting it to neighbouring hydrogen grids, e.g. in Germany.

This area – the Netherlands with the neighbouring parts of Belgium and Germany – is a rather interesting area to develop a hydrogen exchange, as there is strong demand from industrial activities and respectively also a need for imports. The anticipated demand for this region is roughly 50TWh, whereas the expected production potential is 39TWh.[57] Hence a supply gap of 11TWh exists, which can be closed by maritime imports.

The products traded on an exchange typically consist of a spot market product, i.e. for immediate delivery of the hydrogen at specified delivery points such as within a pipeline system. Based on these market price signals, an index might develop, which can also be used to define derivative products like futures or swaps. It should be noted that in parallel with the physical and financial transactions, buyers of hydrogen often need and want certification with regard to the quality of the product. In case of green hydrogen, a guarantee of origin is needed that documents the way the hydrogen is generated. These guarantees of origin also need standardisation, which is currently being developed under various initiatives. Guarantees of origin exist

54 EFET agreements can be downloaded from the site www.efet.org.

55 EEX European Energy Exchange https://www.eex.com/en/services/hydrogen.

56 Presentation at an EFET working group, 14 September 2021

57 David Schlund, ewi Cologne, webinar presentation "The Economics of Hydrogen", 28 September 2021

in some energy commodity markets, e.g. electricity and gas. CertifHy is a highly developed certification scheme, now being used as a basis for an Australian scheme, and is an example of current developments with regards to certification.[58]

4.7 Conclusions and Recommendations

Transport costs for synthetic fuels are only a small fraction of their total cost, including production. Hence, transport costs are not prohibitive. For many European countries, total import costs from several exporting countries are within a rather narrow range. This indicates that a highly competitive market can be expected.

Pricing could be very competitive, as there are several (net) zero carbon fuels among biofuels and hydrogen-based synthetic fuels. Furthermore, a market price based on a very liquid market already exists by combining the price for conventional ship fuels (containing carbon) with the cost of carbon offset measures. Thus, a proxy market price, i.e. a price that can be used as a benchmark for economic comparisons, is already in existence.

To facilitate global trading of (net) zero carbon fuels, a standard contract and a master agreement would help to create liquidity in the products and trust in the market. Existing commodity contracts (e.g., the EFET master agreement for LNG deals) serve as an excellent basis to develop such contracts.

A globally accepted certification scheme for hydrogen and hydrogen-based products would provide traders and end consumers with relevant information on the origin of the hydrogen supplied to them and offer transparency regarding the carbon footprint of (net) zero carbon fuels. Again, existing certification schemes for renewable electricity or global standards for GHG abatement projects are a valuable starting point.

The current bilateral agreements and international cooperation on exporting and importing could potentially endanger the liquidity of a trading market. This may occur if long-term contracts are designed in a very exclusive way, for example where the buyer is not allowed to resell (net) zero carbon fuel on the market. Hence, to guarantee liquid global trading, any resale restriction clauses in long-term contracts should be prohibited under competition law. There is a need for multi-stakeholder synergies to be promoted and facilitated to speed up decarbonisation in shipping.

58 https://www.bakermckenzie.com/en/insight/publications/2021/07/update-on-australias-hydrogen-certification-scheme

5 Maritime Emissions

Maritime GHG emissions result from the use of various fossil fuels. Improvements in the efficiency of vessel engines are the target of current measures. However, energy efficiency improvements alone will not be sufficient to reach a climate-neutral maritime transport industry. IMO scenarios indicate that business-as-usual GHG emissions in 2050 are at the same level as today, showing that the existing IMO GHG regulations, and also the IMO GHG regulations currently under negotiation, are critical. The most recent IMO GHG strategy includes a commitment to reduce GHG emissions by at least 50% by 2050 (relative to 2008). This initial strategy[59] is due to be reviewed in 2023.

5.1 Status of Emissions and Fuel Mix

Shipping is responsible for slightly less than 3% of the global GHG emissions. However, international shipping is not attributed to national jurisdictions; hence, these emissions are mainly covered by international agreements decided at the IMO.[60] The signatory countries of the IMO resolutions embody them within their national law, ensuring the legal obligation of ships flying their flag to meet the international regulations. Important players, for example the European Union, also influence the transport sector by placing additional legal obligations on vessels arriving in harbours within their jurisdiction, as is also the case for aviation.

Additionally, many companies are putting pressure on international shipping to reduce emissions. As part of the so-called Scope 3 emissions where freight emissions are considered part of companies' total emissions under the GHG protocol.[61] This creates strong interest among companies to find low-carbon or even climate-neutral vessels for their transport needs.

> Reducing maritime GHG emissions is mainly driven by IMO regulations, but also by companies reducing their carbon footprint voluntarily and increasingly by the interest of investors.

In its recent Fourth GHG Study 2020, the IMO gave an overview of the emissions from shipping (international, domestic and fishing). Emissions of CO_2 grew from 962Mt in 2012 to 1,056Mt in 2018, i.e. an increase of 9.6%. Taking into account also the other relevant GHGs in shipping, principally methane (CH4) and nitrous oxide (N2O), the total GHG emissions from shipping were 1,076Mt CO_2-equivalent (977Mt CO_2eq in 2012). As a proportion of global anthropogenic emissions, the share of shipping was 2.89% in 2018 (2.76% in 2012).

International transport emissions are increasing more than overall global GHG emissions due to growing international trade between global industrial centres. Consequently, the pressure to reduce international transport emissions is increasing. A decrease in carbon intensity, i.e. carbon emissions per unit of distance, has taken place in recent decades in response to increasing fuel prices and efficiency obligations, for example by the IMO. The lower carbon intensity has reduced the growth of transport emissions, but demand for transport services grew faster.

59 https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

60 IMO = International Maritime Organization, a specialised agency of the United Nations responsible for regulating shipping.

61 The Greenhouse Gas Protocol was developed by the WBCSD and the WRI as an international standard for corporate accounting and reporting emissions.

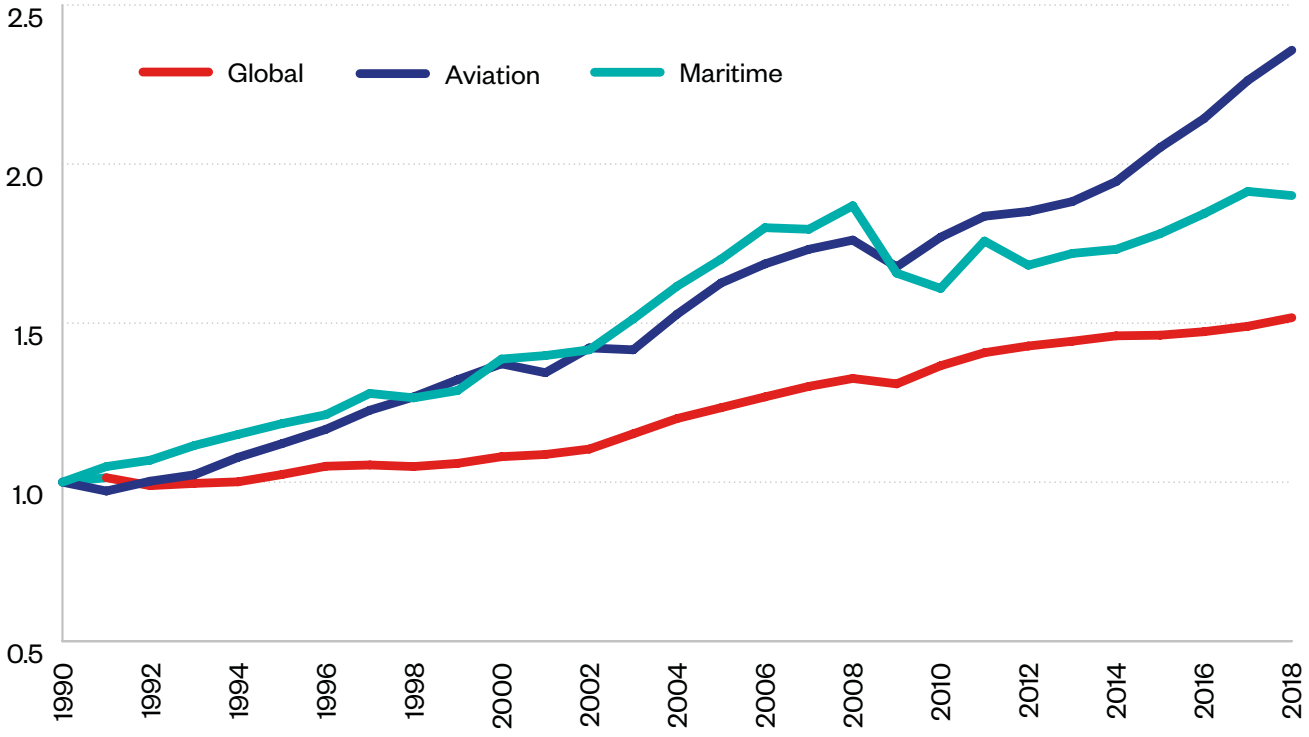


Figure 5.1: The development of global GHG emissions and emissions from international aviation and international maritime transport (Note: 1990 = 1)

Sources: IMO Fourth Greenhouse Gas Study 2020, EDGAR – Emissions Database for Global Atmospheric Research[62], PIK[63]

As is typical for combustion engines running on fossil fuels, CO_2 dominates total GHG emissions. Methane (CH4) and nitrous oxide (N2O) can be transformed using their global warming potential to equivalent amounts of CO_2 emissions. The abovementioned GHG emissions are due to the operation of combustion engines. Additional emissions resulting from the production and the transport of maritime fuels are not considered since these emissions are the responsibility of the fuel producers, i.e. refineries and pipeline operators. Consequently, the maritime industry has very limited impact on these emissions. By contrast, the GHG emissions from operating combustion engines can be influenced by actors within the maritime industry.

The dominant fuel in maritime shipping is HFO (heavy fuel oil), with a 2018 fuel share of 66% (vessel-based), or 79% of total fuel consumption by energy content (voyage-based allocation). However, in recent years a massive shift away from HFO has been taking place: its (vessel-based) share in 2012 was 75%, i.e. 9 percentage points higher. The fuel in second place is MDO (marine diesel oil) at 30% (vessel-based in 2018). LNG is ranked third at 3% (vessel-based in 2018). Interestingly, methanol had already reached a share of 0.5% in 2018 (vessel-based).

> The current fuel mix in maritime shipping is fossil-based with high shares of HFO and MDO.

This change in the fuel mix has already had a beneficial impact on the GHG emissions of the maritime sector, since an increasing share of its fuel has lower specific emissions. However, one should note firstly that these changes are not necessarily economic if the fuel with higher specific emissions is cheaper than the fuel with lower specific emissions. And secondly, in the ideal case of a dual-fuel or even multi-fuel engine, fuel switching can be done easily (assuming that fuel storage is available for various fuels) and without potentially high retrofit costs.

62 https://edgar.jrc.ec.europa.eu/

63 The PRIMAP-hist national historical emissions time series https://www.pik-potsdam.de/paris-reality-check/primap-hist/

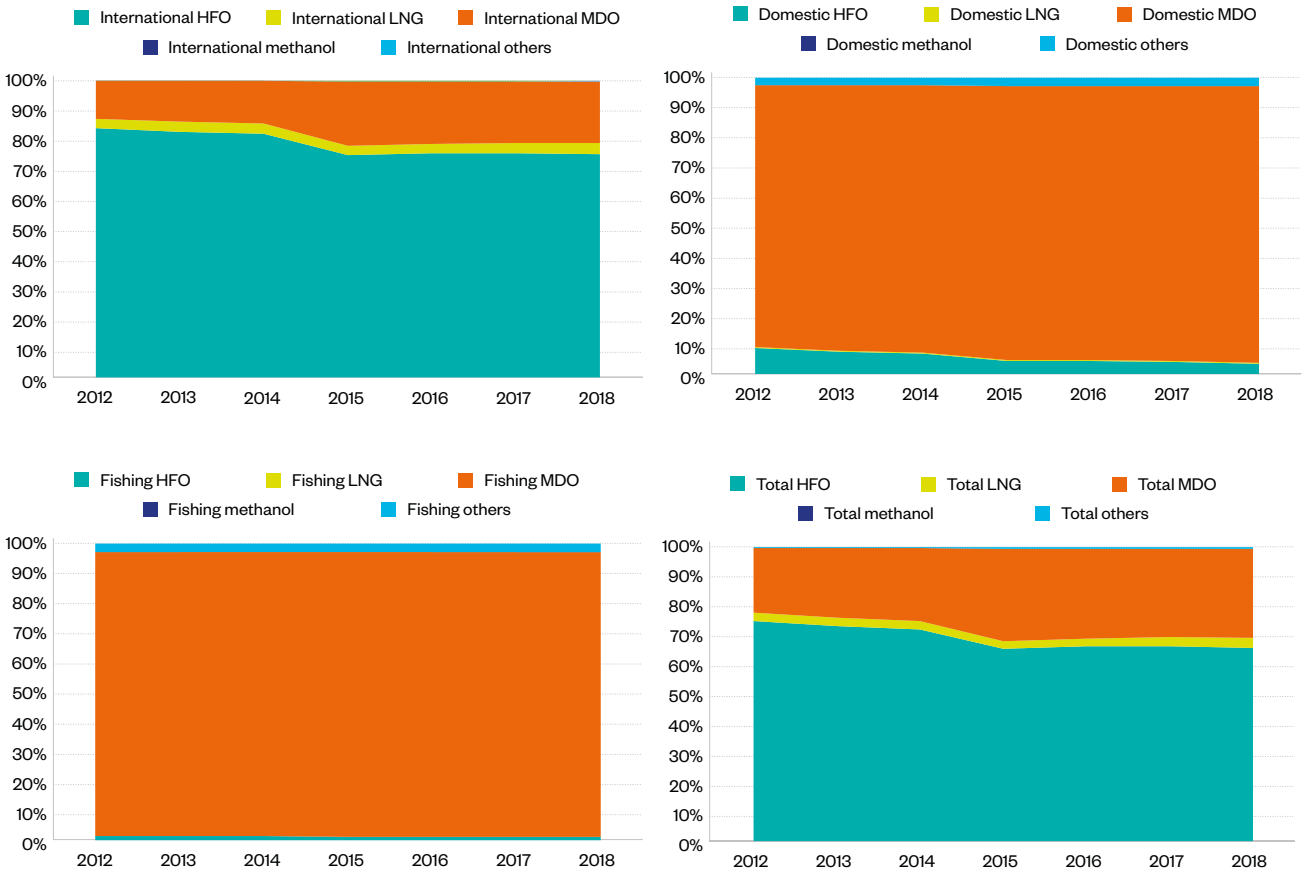


Figure 5.2: Fuel mix for maritime shipping (international, domestic, fishing and total)

Source: IMO, Fourth GHG Study, 2020

KEY POINT:

HFO dominates the fuel mix, but in recent years other fossil fuels have increased their share of the mix.

The short-term forecast from Rystad expects the current rules on fuels to lead to a shift within the range of available fossil fuels, but (net) zero carbon fuels will remain a niche product over the coming years. However, Rystad stated in 2022 that a reaction to the rising fossil fuel prices, green hydrogen and fuels based on it might become economically much more interesting in the future[64]. This could also help to increase security of supply, since the dependency of a limited number of fossil energy exporters is transformed into the opportunity to import hydrogen and hydrogen-based fuels from a multitude of supplying countries.

64 Hellenic Shipping News, Cheap, secure, and renewable – Europe bets on green hydrogen to fix energy woes, 22 March 2022

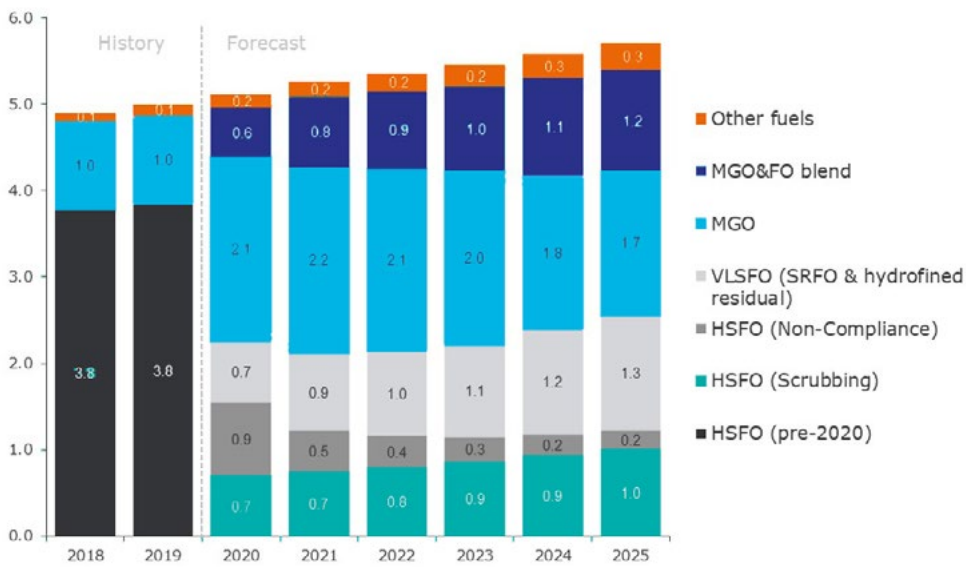


Figure 5.3: Short-term forecast for the fuel mix in marine bunker fuels: by 2025 Rystad expected fossil fuels to continue to dominate maritime fuels

Source: Rystad Energy, Rystad Energy forecasts transitional fuel mix of upcoming IMO 2020, 2019

Interestingly, there is also some concentration in maritime shipping: globally, there are roughly 95,000 ships in use carrying up to 90% of all global trade. However, around 20% of the global shipping fleet is responsible for 85% of the maritime sector's GHG emissions.[65] Consequently, concentrating on a smaller part of the fleet could lead to immediate and substantial emission reductions.

Similarly, bunkering capacity is also highly concentrated: seven countries are responsible for 60% of bunker sales, including Singapore, the United States and the United Arab Emirates.[66] Consequently, developing (net) zero carbon fuel infrastructure at these ports is a key priority.

5.2 Drivers for Reducing Emissions in Shipping

International regulations established by the IMO are a key driver, as is a desire from customers to reduce their carbon footprint. Investors are also increasingly addressing environmental concerns to protect their long-term investments. All these drivers influence investment decisions within maritime shipping.

Driver 1: Regulation

The maritime industry has already responded to the challenge of reducing its GHG emissions. Based on the 2015 Paris Agreement, in 2018 the IMO announced the goal of reducing GHG emissions by 50% by 2050 compared to emissions in 2008. Additional measures aim to reduce other emissions from shipping, such as sulphur dioxide and particulate matter. Examples for these measures are:

- **EEDI** (Energy Efficiency Design Index) for new ships with regard to the specific CO_2 emissions of freight ships. The goal of the EEDI is an improvement in average annual efficiency of 1.5% from 2015 to 2025;
- **SEEMP** (Ship Energy Efficiency Management Plan) for existing ships, aiming to increase their energy efficiency in operations; and
- **IMO 2020** to limit the sulphur in fuel (effective from 1 January 2020).

65 IRENA, *Reaching Zero with Renewables: Eliminating CO_2 Emissions from Industry and Transport in Line with the 1.5°C Climate Goal*, 2020

66 IRENA, *Navigating the Way to a Renewable Future: Solutions to Decarbonise Shipping*, 2019

The IMO estimates that the two measures EEDI and SEEMP alone will reduce the annual emissions of maritime shipping by 420Mt CO_2 per year, i.e. a reduction of up to 25% from the baseline.[67]

In mid-2021 the Marine Environment Protection Committee (MEPC) of the IMO agreed new targets to reduce CO_2 emissions per unit of transport work: by 2030 a 40% decrease and by 2050 a 70% decrease (the baseline is defined as the year 2008). The total GHG reduction required by 2050 is 50%.[68] In order to give additional guidance to shipowners, two new measures (indexes) have been defined:

- **EEXI (Energy Efficiency Existing Ship Index):** this new index is scheduled to come into force on 1 January 2023. The EEXI is like its predecessor, the Energy Efficient Design Index (EEDI), but is applied to existing ships outside EEDI regulations. Emissions are defined per cargo tonne and mile; and
- **CII (Carbon Intensity Indicator)**: the CII provides ship operators with the factor by which they must reduce CO_2 emissions annually to ensure continuous improvement and comply with regulations. The CII must be implemented within each operator's Ship Energy Efficiency Management Plan (SEEMP). The CII will come into effect in 2023. This CII index will be used to rate ships on a five-grade scale: A, B, C, D and E, from best to worst performing. This will lead to a phasing out of the least-efficient vessels, e.g. by technology upgrades.

Market observers such as the Veritas Group expect the impact of EEXI to depend on the vessel type. Anticipated EEXI compliance – due to vessels meet the emissions regulations – is:[69]

- Bulk: 60%
- Tankers: 70%
- Container ships: 30%
- Gas carriers: 55%
- LNG carriers (without steam turbines): 100%
- Cargo ships: 80%

Technically, the reduction path is initially met by optimising operations, reducing speed, retrofitting vessels with energy-efficient technology and innovative propulsion techniques (e.g. wind assistance) and eventually switching to (net) zero carbon fuels.

Driver 2: Voluntary action by freight customers

Apart from the regulatory framework setting the global abatement path for maritime shipping, customers of shipping services are also increasingly asking for climate-neutral transport. This is used to reduce the Scope 3 emissions of a company in line with the GHG protocol.

An example of voluntary action is Volkswagen. The car manufacturer has been operating the two LNG ships SIEM Aristotle and SIEM Confucius for the round trip between Europe and North America since January 2020. LNG has lower specific GHG emissions compared with the usual ship fuels. Consequently, Volkswagen could claim a lower carbon footprint on that basis. As mentioned earlier, however, the maritime industry is experiencing growing concerns relating to methane slip from engines (methane is a highly potent GHG) and fugitive emissions during production, transport and storage. Nevertheless, LNG is still seen by a segment of the maritime industry as an appropriate transition fuel, especially with the view to use (net) zero methane as future fuel, perhaps also blended with biomethane.

Similarly, Shell uses LNG as a fuel for its crude oil fleet. In March 2021, Shell signed agreements to charter ten new crude tankers (VLCCs) powered by dual-fuel LNG engines. Shell also ensures that LNG as a ship fuel is available on global trading routes and at major ports in Europe, Asia and North America. Shell assumes marine LNG demand to reach around 3.6Mt by 2023, with 45 bunker vessels expected to be in service.

67 Jonty Richardson, *Decarbonisation in the bunker market*, Argus, 12 March 2021

68 IMO press release (17 June 2021): Further shipping GHG emission reduction measures adopted

69 Bureau Veritas Group, *BV Solutions M&O*, 2021

Furthermore, BHP announced in 2020 a so-called scope 3 emissions goal to support 40 per cent emissions intensity reduction of BHP-chartered shipping of their products. To this end, BHP intends e.g. in 2022, to use less-carbon intense fuels as LNG and even bio-fuels. Further examples of voluntary action are the fashion group H&M and the furniture company IKEA. Their ambitious climate goals also require reduced transport emissions, e.g. by using increasing amounts of biofuels for their ship transport needs.

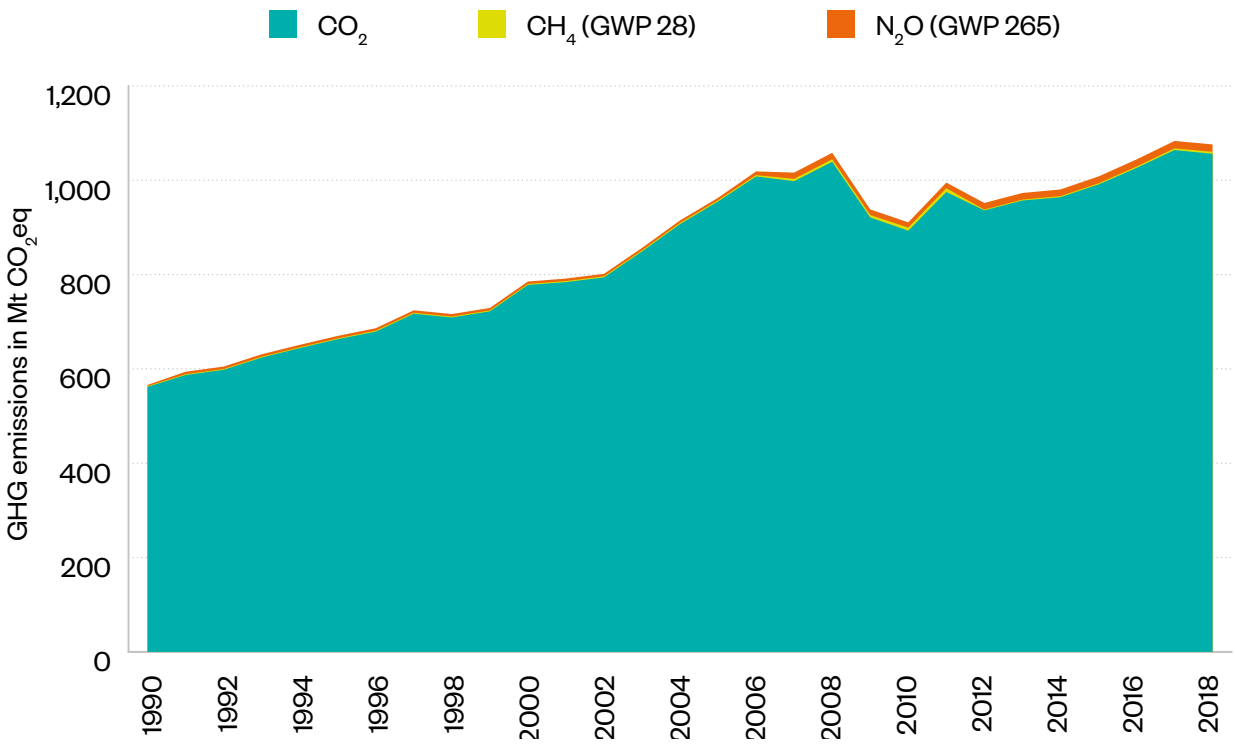


Figure 5.4: Trajectory of maritime GHG emissions (international, domestic and fishing) in Mt CO_2eq for the three main GHGs, CO_2, methane, nitrous oxide

Sources: IMO, GHG Study, 2009, 2014 and 2020

Driver 3: Taxonomy

The third driver for GHG abatement in the shipping sector is related to the financial sector. Many large investors are now looking at environmental, social and governance criteria when assessing investments. In fact, the industry-led and then UN-convened Net-Zero Banking Alliance currently has 100 banks from 40 countries as members. They represent over 43% of global banking assets and are committed to aligning their portfolios with net zero emissions by 2050. Specific to the maritime sector are the signatories of the Poseidon Principles: this initiative aims to link their loans to the shipping industry with decarbonisation ambitions.[70] Currently, 27 banks are members.

In some jurisdictions this is even legally formalised, such as with the EU taxonomy. Consequently, the carbon footprint of business activities is playing an increasingly important role, since investors want to reduce their risk with regard to changes in climate regulation. Hence, some investors have a preference for companies who actively manage their carbon exposure, both with existing assets and even more so with investment in future assets.

70 https://www.poseidonprinciples.org/#home

5.3 Business-as-Usual Scenarios

In pre-Coronavirus (COVID-19) times, the United Nations Conference on Trade and Development (UNCTAD) expected an annual increase in seaborne trade from 2019 to 2024 of 3.4%.[71] Due to COVID-19, these expectations have not materialised. However, UNCTAD's expectation is for expansion of 4.8% in 2021, despite COVID-19 leading to decreases in 2020, as the global economy recovers.[72] Similarly, the OECD expects maritime trade to triple by 2050. Consequently, the IMO expects that, in the long run, the GHG emissions of shipping will rise in some business-as-usual scenarios by up to 50% by 2050. These business-as-usual scenarios assume no further legislation with regard to energy efficiency or emissions; consequently, they are mainly describing the impact of global economic growth in various scenarios and the fleet development with respect to the transported goods.

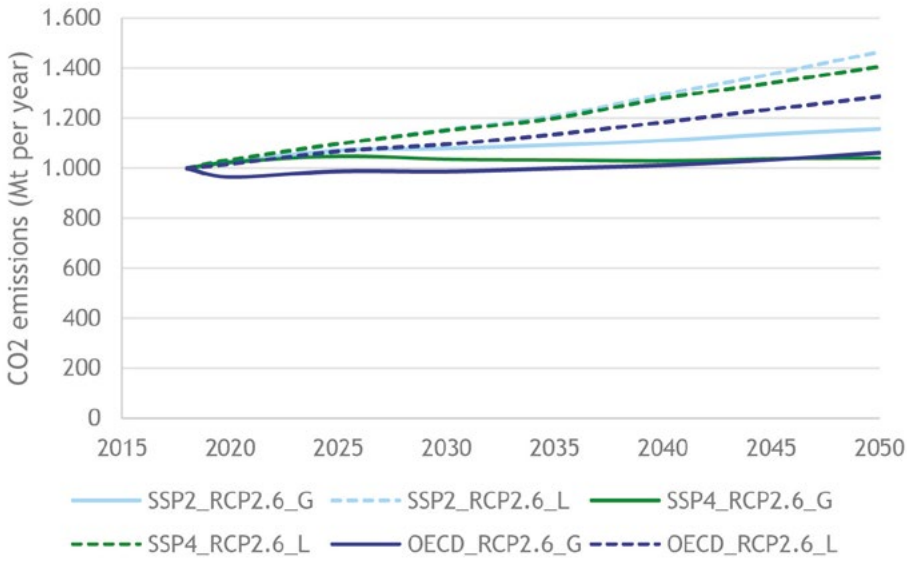


Figure 5.5: Business-as-usual scenarios of the IMO in its Fourth GHG Study 2020: the expected strong demand for global maritime transport would lead to increasing emissions by 2050.
Source: IMO, Fourth GHG Study, 2020

> In IMO scenarios, existing measures on energy efficiency and emission reductions only lead to a sideways move in global maritime shipping emissions to 2050.

The IMO scenarios clearly show that a business-as-usual approach will not be sufficient to achieve climate neutrality in maritime transport. Consequently, in June 2021, IMO agreed to the EEXI and CII additional GHG measures and negotiations regarding a market-based measure are ongoing. The IMO, as a truly global organisation, has the confidence of the key actors in maritime shipping, which is the most important lever to move things forward.

For the overall transport sector, the situation is even more challenging: A business-as-usual scenario provided by the US Energy Information Administration (EIA) indicates the need to replace fossil fuels in the global transport mix. Without further efforts, the transport sector will in the coming decades predominantly use fossil fuels. An increasing share of (net) zero carbon fuels is needed to meet global and national climate targets.

71 UNCTAD, *Review of Maritime Transport 2019*

72 UNCTAD, *Review of Maritime Transport 2020*

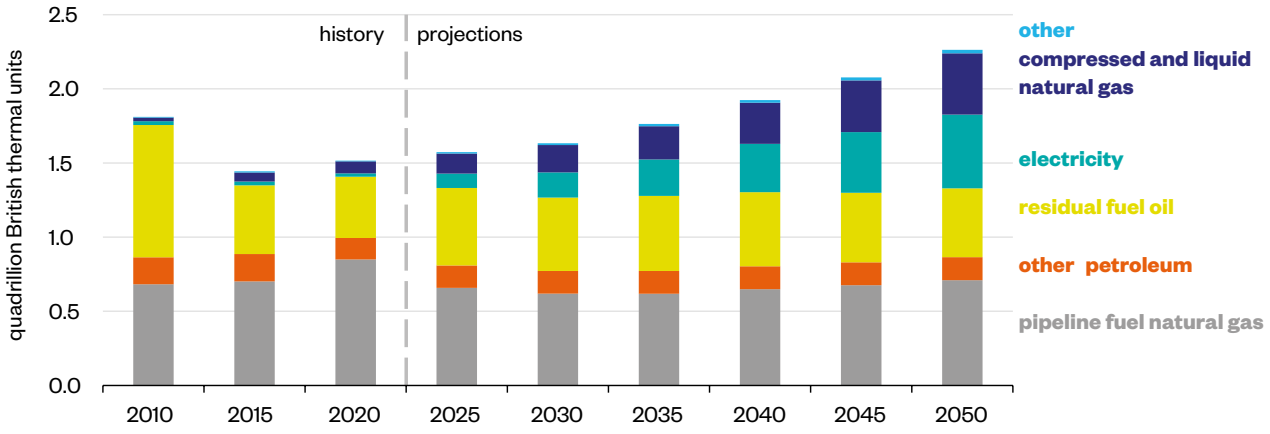


Figure 5.6: Transport sector consumption of minor petroleum and alternative fuels, AEO2021 Reference case (in quadrillion British thermal units)

Source: US Energy Information Administration, Annual Energy Outlook March 2022

KEY POINT:

The Reference case of the EIA describes a business-as-usual scenario: without additional measures, the fuel mix of the transport sector will by 2050 still be dominated by fossil fuels.

5.4 Conclusions

Emissions from the maritime sector have a share of roughly 3% of total global emissions. To reduce these emissions, a shift in the fuel mix towards (net) zero carbon fuels is needed. Energy efficiency is very important in order to achieve net-zero emissions: firstly, since this will reduce emissions currently, and secondly, since this will lead to lower demand for (net) zero carbon fuels in the future. The IMO analysis emphasises that, without additional measures, the GHG emissions of maritime shipping will not be sufficiently reduced.(Net) zero carbon fuels are a major tool to meet this goal. A similar requirement can also be seen in other transport modes, such as road and air. Maritime shipping has an important role as the enabler of climate-neutral mobility by facilitating the delivery of (net) zero carbon fuels from production sites to fuel hubs for aviation, road and rail transport.

In 2021, the IMO adopted regulations on GHG targets for the coming decades, responding to the challenges for maritime transport by setting ambitious targets. However, various technological solutions and their implementation are needed to meet these goals. The IMO has also discussed the introduction of a mandatory levy of \$100/t CO_2 in order to establish a price signal for all actors. This clearly indicates that the IMO is fully aware of its responsibility to bring about emission reductions in maritime shipping.

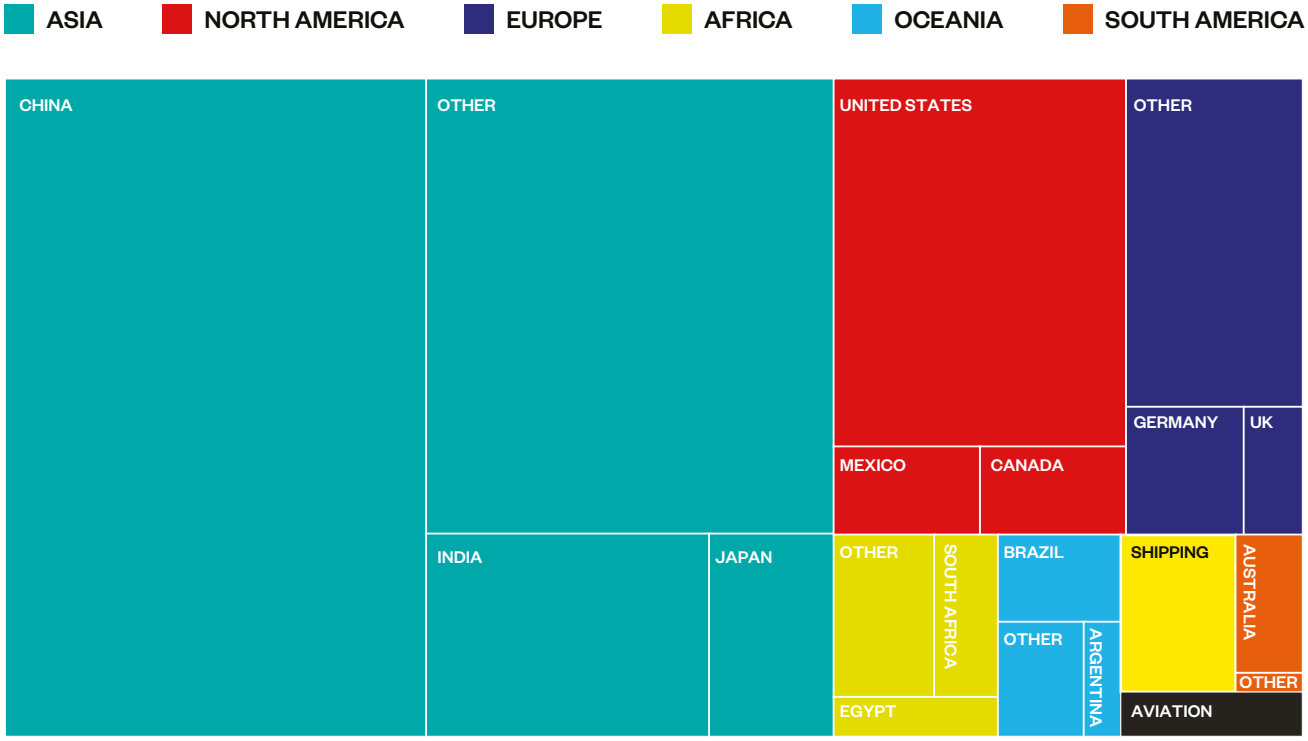


Figure 5.7: Global CO_2 emissions (2020) – the emissions from maritime shipping are rather small compared to other sources, but maritime shipping is fully aware of its responsibility to deliver climate-neutral transport services globally. International shipping and aviation usually have similar emissions but in 2020 international aviation was severely limited during the COVID-19 pandemic.

Data Source: Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Banja, M., Olivier, J.G.J., Grassi, G., Rossi, S., Vignati, E., GHG emissions of all world countries – 2021 Report, EUR 30831 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-41547-3, doi:10.2760/074804, JRC126363.

6 Decarbonising Maritime Transport

Various measures can reduce or even eliminate the GHG emissions of the maritime industry. All of them are needed to achieve climate-neutral shipping at the lowest possible cost. (Net) zero carbon fuels are critical for climate neutrality. Where dual fuel ship engines or engines than can be retrofitted for (net) zero carbon fuels are available at reasonable cost, ship operators will be able to choose between available fuels and reduce the risk of stranded investments.

6.1 Measures for Decarbonisation

6.1.1 Overview: generic measures

The maritime sector will need (net) zero carbon fuels in order to deliver climate-neutral services in the future. This might act as a driver for global green development, since demand from the maritime sector is an excellent reason to start the production of (net) zero carbon fuels at large scale, simultaneously developing solutions for the transport, distribution and storage of these fuels where the existing infrastructure for liquid and gaseous fuels need enhancement.

> Various levers exist to decarbonise maritime transport and they all need to be addressed.

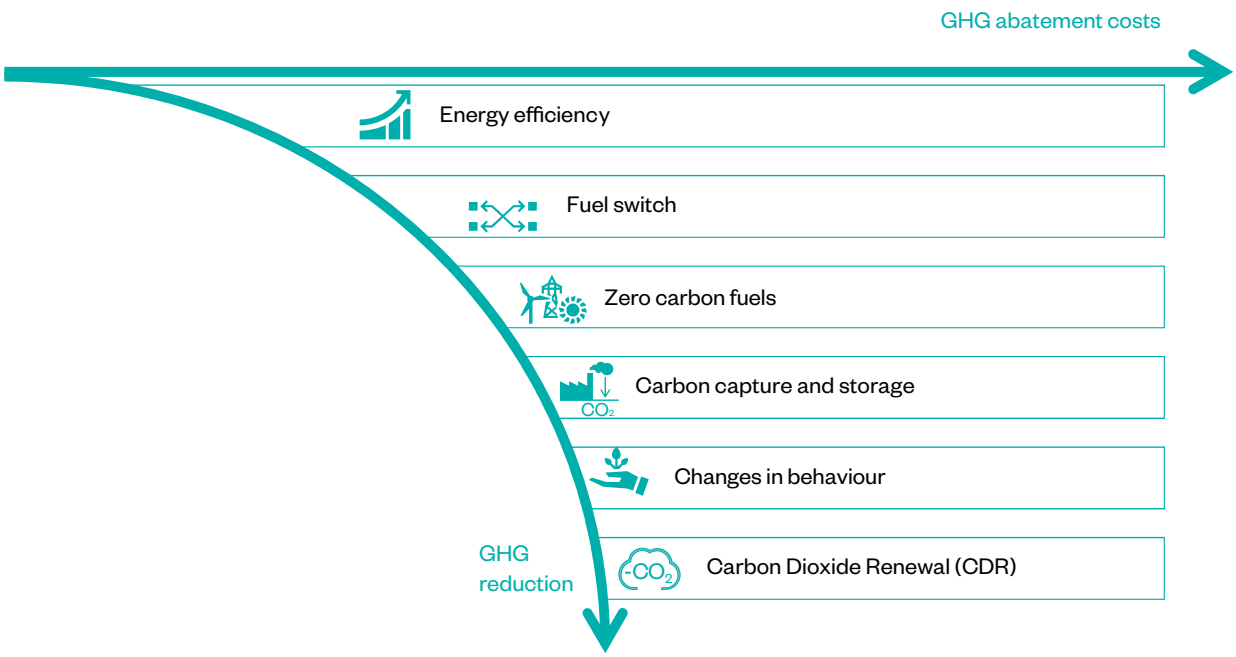


Figure 6.1: The six generic ways to reduce GHG emissions
Source: World Energy Council Germany, Pathways to Climate Neutrality, 2020

KEY POINT:
There are six generic ways to reduce GHG emissions. They can be adopted for use in the maritime sector. The cost of reduction is decisive, however, and this means that the low-hanging fruit should be harvested first.

To decarbonise transport, certain levers reflecting a generic merit order curve for all industrial activities can be used (see Figure 6.1). Typically, at the beginning the most cost-efficient solutions as low hanging fruit will be chosen. As a "backstop technology", CO_2 removal (also called negative emission technologies)73 might be used, where GHGs are taken from the atmosphere and either stored or converted to reduce the GHG impact in the atmosphere. Consequently, industrial decarbonisation starts with energy efficiency measures, followed by fuel switching to less carbon-intense or (net) zero carbon fuels. The different decarbonisation measures sketched in Figure 6.1 will be discussed in more detail in this chapter.

6.1.2 Global carbon price or levy for maritime

Given the truly global nature of the maritime shipping industry, its participation in an emissions trading scheme is rather unrealistic. There are several trading systems in action in various jurisdictions, with very different price levels. Using these different market price levels would significantly distort competition in the maritime sector. Similarly, existing national and regional carbon taxes show a wide bandwidth of related carbon costs, again leading to an unlevel playing field.

Hence, it might be preferable to introduce a global carbon levy just for maritime shipping. The same price level for all ship operators would establish a level playing field, as is currently the case where a global oil market price or a global LNG market price determines the fuel costs for all market actors to the same extent and without discrimination.

Since this carbon levy would only affect the maritime shipping industry, the levy can be chosen to meet several goals without considering distributional effects on other sectors. The carbon levy needs to be high enough to give the incentive for maritime operators to reduce emissions over the coming years. It should not lead to prohibitive transport costs, since this would do harm to global trading activities.

One additional benefit for the maritime shipping industry consists of the reasonable use of carbon revenues, a topic that is often discussed in relation to carbon taxes and the auction income from emission allowances.[74] These funds can and should be used for RD&D and deployment of climate-neutral technologies. In particular, (net) zero carbon fuels could be supported through specific funding for the maritime sector. To enhance the equitable transition, (net) zero carbon fuel projects in developing countries could be promoted by giving investment grants or attractive credits. Via this use of carbon revenues, the maritime sector would trigger the more rapid realisation of global trade powered by (net) zero carbon fuels.

The International Chamber of Shipping has proposed to members of the International Maritime Organization (IMO) the creation of the Climate Fund for Shipping. The proposal will be discussed in the next IMO MEPC meeting this year.

> The revenues from a maritime carbon levy could be used to enhance the development of (net) zero carbon fuel export infrastructure in developing countries, thus contributing to an equitable energy transition globally.

73 Coalition for Negative Emissions, *The case for Negative Emissions*, June 2021

74 Partnership for Market Readiness (World Bank Group), *Technical Note 16 – Using Carbon Revenues*, Washington D.C., August 2019

6.1.3 Energy efficiency

Energy efficiency measures are the natural candidates as the first step in the journey towards climate neutrality. The reduction of energy consumption per unit of distance and per tonne of freight will also reduce the carbon footprint. This is essential to approach climate neutrality, but it will not be sufficient to achieve full climate neutrality. Energy efficiency is also an important prerequisite to consume lower amounts of alternative fuels in the future and is therefore important for the maritime sector to stay competitive. Thus, energy efficiency is a fundamental cornerstone of (net) zero carbon shipping. Nevertheless, investment in energy-efficient engines needs to demonstrate acceptable economic return.

As already pointed out, the IMO has prominently addressed energy efficiency in its recently adopted GHG regulations, showing the high potential of these measures with regard to GHG abatement.

Energy efficiency can be improved in the design phase of a ship, friction can be reduced in various ways and energy can be recovered for heating purposes. For existing ships, there are some operational measures available, such as trim optimisation, improvements in routing, slow steaming or using Wind Assisted Propulsion Systems (WAPS), e.g. sails. Moreover, some retrofit measures can improve the energy efficiency of an existing vessel. Digital solutions show further potential to improve vessel performance and hence increase the economic and environmental performance[75]. Maersk, one of the largest shipping companies in the world, uses digitally enhanced weather forecasting to reroute vessels, thus improving security and efficiency. However, the economics of all these measures need to be carefully considered.

Table 6.1 presents technological measures that can improve energy efficiency and their corresponding fuel saving potential.

Technological measures	Fuel saving potential in %
Light materials	0–10
Slender design	10–15
Propulsion improvement	1–25
Bulbous bow	2–7
Air lubrication and hull surface	2–9
Heat recovery	0–4
Operational measures	**CO_2 mitigation potential in %**
Speed	0–60
Ship size	0–30
Ship–port interface	0–1
Onshore power	0–3

Table 6.1: Typical energy efficiency measures in maritime transport with their fuel-saving or GHG mitigation potential

Sources: L. Kirstein, R. Halim and O. Merk, Decarbonising maritime transport pathways to zero carbon shipping by 2035, International Transport Forum, OECD, 2018; E. A. Bouman et al., State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping–a review, Transportation Research Part D: Transport and Environment, Vol. 52, pp. 408–421, 2017

Example: Slow steaming

In order to reduce fuel consumption and emissions, a vessel might deliberately decrease its cruising speed. Typical speeds for slow steaming are between 12 and 19 knots, in contrast to full speed being up to 24 knots. This measure reduces fuel consumption considerably: a typical container ship normally consumes 200t of fuel per day at 24 knots, whereas slow steaming at 21 knots leads to 125t fuel consumption per day. Slow

75 Yuki Ichimura, Dimitrios Dalaklis, Momoko Kitada, Anastasia Christodoulou, Shipping in the era of digitalization: Mapping the future strategic plans of major maritime commercial actors, Digital Business, Volume 2, Issue 1, March 2022, ISSN 2666-9544

steaming thus helps to save money as a reaction to high fuel prices. Furthermore, it will also help to reduce GHG emissions as an immediately available option to meet environmental requirements. However, there are practical limitations to this approach: perishable goods might necessitate higher cruising speeds, as well as peak demand for certain goods. Because of slow steaming, the overall shipping capacity per year might be reduced by longer travelling times, so at times of globally strong demand for freight transport this option will be used less often.

Slow steaming does not necessarily need a retrofit of the engine, as long as technical requirements are met such as the cruising speed not being too slow. It may lead to additional and higher maintenance requirements. Consequently, future engines should be designed in a way that allows slow steaming with less technical harm to the engine and lower economic disadvantage. Here the IMO EEXI requirements for existing ships should be mentioned: many shipowners are expected to meet these requirements through overridable power limitation. The EEXI requirements are due to enter force in January 2023.

The GHG emissions of a combustion engine consist of CO_2 (the lion's share), methane and nitrous oxide.[76] Black carbon is not considered, since the emission factors still need to be determined. Using the global warming potential of the GHGs, the tank-to-wake emissions can be translated into CO_2 equivalents.[77] Typical values are shown in Table 6.2, where the emissions of CO_2, CH_4 and N_2O are considered, as well as the impact of black carbon.

Fuel	Engine type	Tank-to-wake in g CO_2eq(100) /g fuel	GHG emissions in t CO_2eq per day	
			200t fuel/day	125t fuel/day
HFO	SSD	3.338	668	417
HFO	MSD	3.605	721	451
VLSFO	SSD	3.415	683	427
VLSFO	MSD	3.682	736	460
MGO	SSD	3.298	660	412
MGO	MSD	3.493	699	437
LNG	LNG-diesel	2.879	576	360
LNG	Steam turbine	2.794	559	349

Table 6.2: The tank-to-wake emissions for various fuels and engine types

Notes: SSD = slow speed diesel; MSD = medium speed diesel. Methane slip for LNG is included.
HFO = heavy fuel oil, VLSFO = very low sulphur fuel oil, MGO = marine gas oil, LNG = liquified natural gas
Source: ICCT Briefing, Accounting for well-to-wake CO_2 equivalent emissions in maritime transportation climate policies, March 2021

KEY POINT:

Slow steaming reduces the GHG emissions during operation.

The table illustrates the GHG emissions of the fuel and the impact of slow steaming. Of course, the consumption per day might vary depending on the fuel type and the engine efficiency. Nevertheless, it shows the potential impact of slow steaming on the GHG emissions of a vessel.

> Energy efficiency is the first step towards climate-neutral shipping: it reduces GHG emissions immediately and will improve affordability of (net) zero carbon fuels.

76 Bryan Comer and Liudmila Osipova, *Accounting for well-to-wake CO_2 equivalent emissions in maritime transport climate policies*, International Council on Clean Transportation, March 2021

77 The overall emissions connected with using fuels in shipping can be viewed as well-to-wake emissions, i.e. considering upstream and downstream emissions, or as tank-to-wake emissions, i.e. only the emissions connected with the ship operations.

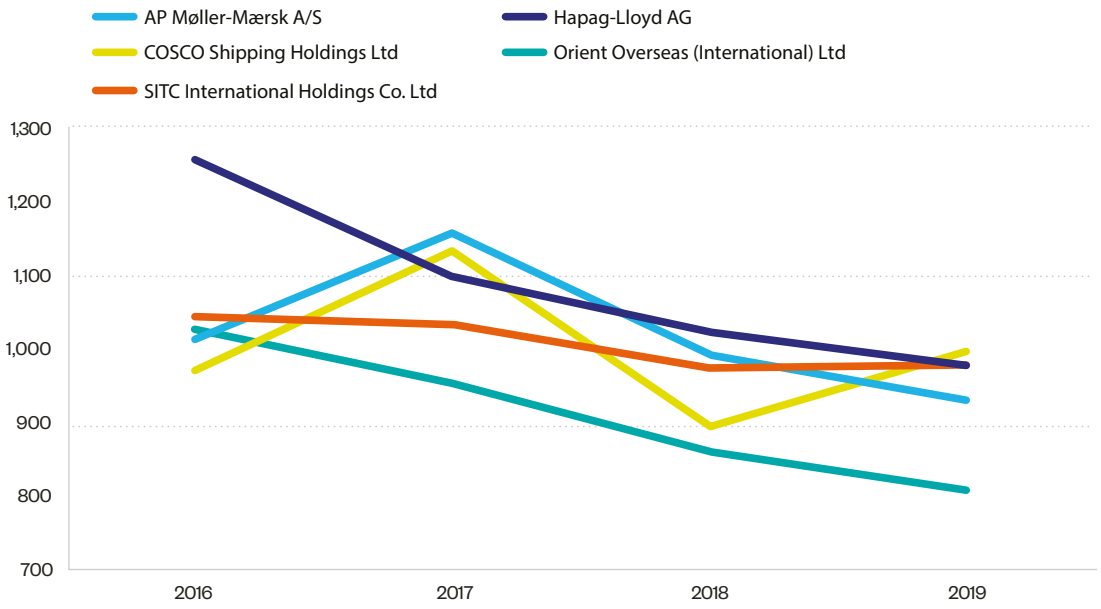


Figure 6.2: The decreasing GHG intensity of maritime shippers

Note: Data as of April 2021. Greenhouse gas emissions intensity [...] is measured per metric tonne of carbon dioxide-equivalent emissions per million US dollars in revenues. Companies were selected by market cap size of those with their primary business in maritime transportation of freight.

Source: Esther Whieldon, Your climate change goals may have a maritime shipping problem, S&P Global Sustainable1, April 2021[78]

In recent years, the major maritime shippers have implemented some energy efficiency measures and reduced their GHG intensity successfully. Partially, this was an economic response to increasing ship fuel prices. Slow steaming, however, also needs to meet the requirements of the customer with regard to delivery times.

6.1.4 Fuel switching and the role of a carbon tax or levy

Fuel switching mainly describes the use of less carbon-intense fuels to run an engine. As with energy efficiency, this is an important step to reduce emissions, but it will also not be sufficient to make shipping climate neutral unless the fuels are effectively climate neutral.

The source of the GHG emissions in maritime transport is fuel consumption. In 2018, roughly 339Mt of HFO equivalent were consumed (overwhelmingly as HFO or MDO). This corresponds to roughly 13.7EJ (assuming 40.4MJ/kg). Replacing these fuels should not only aim to reduce GHG emissions, but also reduce emissions of sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM) as covered by MARPOL.[79] Consequently, the use of (net) zero carbon fuels in the maritime sector is not only driven by GHG abatement, but also by other environmental goals and by fuel economics.

> Fuel switching to (net) zero carbon fuels is another option to reduce GHG emissions, because dual-fuel engines can perform it without retrofitting. This opportunity also defines carbon price switch levels.

With fuel switching, GHG emissions can be reduced during operations, especially when the engine is dual-fuel or even multi-fuel. The basic idea is that depending on fuel prices and carbon costs (from market prices for allowances or from taxes or a levy) the most economic fuel (including the potential costs of GHG emissions) is chosen. With increasing carbon costs, the less carbon-intense fuel is chosen. This simple consideration also allows us to assess critical carbon prices where a fuel switch will take place. However,

78 https://www.spglobal.com/esg/insights/your-climate-change-goals-may-have-a-maritime-shipping-problem

79 Maritime Agreement Regarding Oil Pollution (MARPOL) Annex VI is a regulation covering emissions of air polluting substances such as SO_x, NO_x and PM.

one has to bear in mind that fuel prices change over time and so does the fuel switching level. There could also be periods of high volatility in fuel prices.

Perhaps the best-known example of fuel switching is given by power generation in the EU ETS. Carbon-intense power generation at coal-fired power stations was switched to gas-fired power stations with lower intensity. The coal and natural gas prices set the fuel switching price level that was heavily used by traders as a benchmark for the EU Emissions Allowance market price. With the rather high emission prices in the EU ETS, ongoing for more than a year, a strong decrease in coal-fired generation and in parallel an increase in gas-fired generation resulted One should observe that this switch is only possible within existing assets as an immediate response to the carbon price signal. However, the price signal is also noted by investors in power generation and will thus lead to investments in low-carbon or even zero carbon power generation.

Furthermore, for an operator of a vessel the total cost of one unit of useful energy is connected with fuel costs and carbon costs, assuming there is a carbon price or a carbon tax. With potentially increasing carbon costs, the less carbon-intense fuel will become more economic at some critical carbon price: this then defines the fuel switching level. In Table 6.3 the LNG-diesel engine shows the lowest GHG emissions, i.e. if the carbon price (which may also be defined by a carbon tax or levy) is high enough, this would be the most preferred fuel and engine type. Of course, the fuel costs also have an impact. (Net) zero carbon fuels would have zero emissions; consequently, only their fuel costs play a role, independent of the carbon price (or carbon tax).

To calculate the carbon price where the fuel switch will take place, one needs technical parameters describing the engine, and market prices (current and future) that will reflect the costs for the operator.

Fuel type	Engine type	Tank-to-wake in g CO_2eq(100) /g fuel	To produce 1 kWh of useful energy one needs ... g of fuel	This leads to ... g of CO_2 emissions
HFO	SSD	3.338	175	584
HFO	MSD	3.605	185	667
VLSFO	SSD	3.415	167	570
VLSFO	MSD	3.682	177	652
MGO	SSD	3.298	165	544
MGO	MSD	3.493	175	611
LNG	LNG-diesel	2.879	135	389
LNG	Steam turbine	2.794	285	796

Table 6.3: The tank-to-wake emissions per unit of useful energy for various fuels and engine types

Source: ICCT Briefing, Accounting for well-to-wake CO_2 equivalent emissions in maritime transportation climate policies, March 2021

KEY POINT:

In addition to the tank-to-wake emissions, the typical efficiency of the engine plays a decisive role in calculating total GHG emissions.

Example calculation:

The following market prices are used for this example calculation:

- HFO $360/tonne
- VLSFO $430/tonne
- MGO $530/tonne
- LNG $550/tonne

Fuel costs to produce 1GWh of useful energy with HFO are:

$$\$360/\text{tonne}_{HFO} \times 175\ \text{tonne}_{HFO} = \$63{,}000\ \text{(engine type SSD)}$$

A carbon price (or carbon tax or carbon levy) of $\$50/\text{tonne}_{CO2}$ leads to carbon costs of:

$$\$50/\text{tonne}_{CO2} \times 584\ \text{tonne}_{CO2} = \$29{,}200$$

Varying the carbon price allows us to identify the most economic fuel for the given market prices. One can show that the critical carbon price is $57.55/t; below this price HFO SSD is most economic, and above this price LNG-diesel is the economic solution. One should note additionally that to the benefit of GHG emissions, LNG also reduces the emissions of SO_2, NO_x and PM substantially.

		0	10	20	30	40	50	60	70	80	90	100
HFO	SSD	63,000	68,842	74,683	80,525	86,366	92,208	98,049	103,891	109,732	115,574	121,415
HFO	MSD	66,600	73,269	79,939	86,608	93,277	99,946	106,616	113,285	119,954	126,623	133,293
VLSFO	SSD	71,810	77,513	83,216	88,919	94,622	100,325	106,028	111,731	117,434	123,137	128,841
VLSFO	MSD	76,110	82,627	89,144	95,661	102,179	108,696	115,213	121,730	128,247	134,764	141,281
MGO	SSD	87,450	92,892	98,333	103,775	109,217	114,659	120,100	125,542	130,984	136,425	141,867
MGO	MSD	92,750	98,863	104,976	111,088	117,201	123,314	129,427	135,539	141,652	147,765	153,878
LNG	LNG-Diesel	74,250	78,137	82,023	85,910	89,797	93,683	97,570	101, 457	105,343	109,230	113,117
LNG	Steam turbine	156,750	164,713	172,676	180,639	188,602	196,565	204,527	212,490	220,453	228,416	236,379
Most economic		HFO SSD	HFO SSD	HFO SSD	HFO SSD	HFO SSD	HFO SSD	LNG-Diesel	LNG-Diesel	LNG-Diesel	LNG-Diesel	LNG-Diesel

Table 6.4: Fuel costs for 1 GWh including CO_2 emission costs (author's calculations)

KEY POINT:

Increasing the carbon price makes LNG-diesel economically attractive. With the assumed market prices and technical parameters, the fuel switch takes place at $57.55/t CO_2.

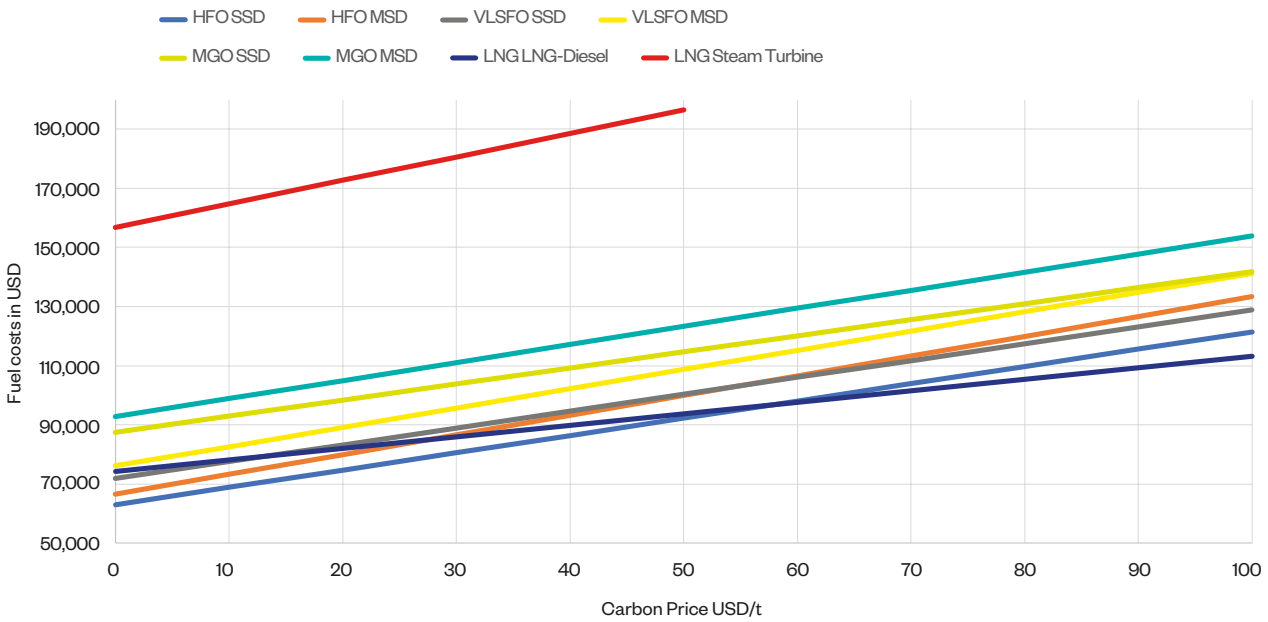


Figure 6.3: Fuel costs including CO_2 emission costs (author's calculations). Fuels with lower specific carbon emissions benefit from high CO_2 prices.

Source: Author's calculations

KEY POINT:

Looking at the fuel costs for the examples described in the text, with higher carbon prices the LNG-diesel engine becomes the most competitive solution based on currently available technologies.

The switching level changes over time due to the market price development of the shipping fuels. Where there is a relevant carbon price/carbon tax for shipping, this level will then decide the most economic fuel.

Fuel switching between various fossil-based shipping fuels is currently driven by IMO regulation, but affects in first place SO_x emissions. LNG is increasingly being used, but mainly for LNG transport, where the LNG boil-off is used as fuel. Again, it should be emphasised that the fuel switch has an immediate impact on existing vessels and, via investment decisions, an impact on future vessels.

Market prices for conventional fuels are continuously changing and some dramatic changes were visible in 2021 and 2022. Whereas at the end of 2020 LNG Diesel engines were very competitive and did not need any carbon costs to be more economic than HFO, by April 2022 a carbon cost of almost 500 USD/t CO_2 would have been needed to make an HFO SSD competitive with an LNG engine.

Nov-20	HFO SSD	HFO MSD	VLSFO SSD	VLSFO MSD	MGO SSD	MGO MSD	LNG Diesel	LNG Steam
HFO SSD	-	-	942	-	852	-	-	-
HFO MSD	-	-	151	1,121	265	950	-	-
VLSFO SSD	942	151	-	-	760	-	-	-
VLSFO MSD	-	1,121	-	-	87	796	-	-
MGO SSD	852	265	760	87	-	-	-	-
MGO MSD	-	950	-	796	-	-	-	-
LNG Diesel	-	-	-	-	-	-	-	-
LNG Steam	-	-	-	-	-	-	-	-

Apr 22	HFO SSD	HFO MSD	VLSFO SSD	VLSFO MSD	MGO SSD	MGO MSD	LNG Diesel	LNG Steam
HFO SSD	-	-	2,942	-	3,702	-	483	-
HFO MSD	-	-	535	3,486	1,273	4,107	379	-
VLSFO SSD	2,942	535	-	-	4,475	-	340	-
VLSFO MSD	-	3,486	-	-	813	4,667	242	-
MGO SSD	3,702	1,273	4,475	813	-	-	90	-
MGO MSD	-	4,107	-	4,667	-	-	16	-
LNG Diesel	483	379	340	242	16	16	-	-
LNG Steam	-	-	-	-	-	-	-	-

Table 6.5: Comparison of the fuel switch levels in US$/t CO_2 in November 2020 and April 2022 for typical bunker prices at Rotterdam port

Source: Author's calculations (market price source: Ship & Bunker)

To illustrate this change, Figure 6.4 shows the development over time. Consequently, there is some difficulty in defining such a carbon cost level by a levy or a tax, since market price movements might change the overall situation considerably; from being not necessary at all to high carbon prices needed for a change.

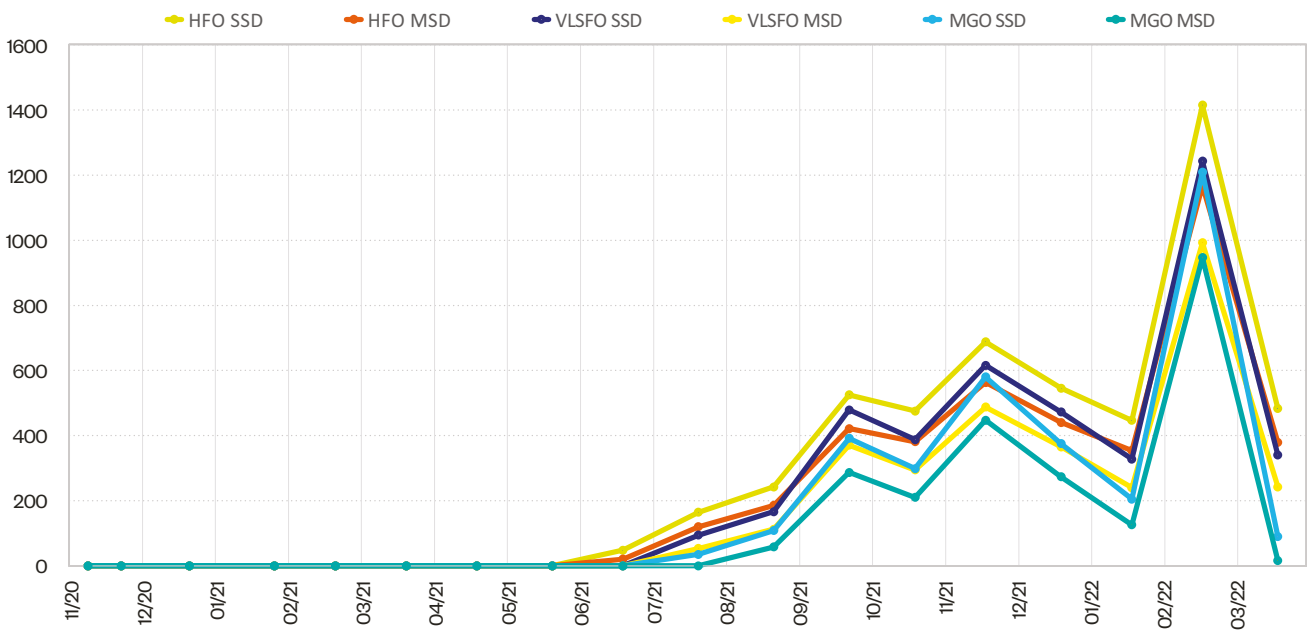


Figure 6.4: Development of the carbon fuel switch level to use LNG as a replacement fuel between November 2020 and April 2022

Source: Author's calculations (market price source: Ship & Bunker)

6.1.4.1 Integration of (Net) Zero Carbon Fuels

The fuel switching explained in the previous sections helps to reduce GHG emissions. However, using carbon-neutral fuels, such as biofuels, electricity or synfuels (the latter two from climate-neutral sources), will eventually make the maritime sector climate neutral. Here we assume again a vessel engine that can use conventional fuels as well as carbon-neutral fuels.

(Net) zero carbon fuels – which can be sourced from renewable energy, but also from other climate-neutral energy sources – have no carbon costs.[80] Consequently, their total costs are just the fuel costs, meaning that with increasing carbon prices the conventional fuels become less economic.

Example calculation:

Market prices of fatty acid methyl esters (FAME) biodiesel are quoted, by Neste[81] for example, as $1,340/t in April 2021 ($1,930/t in April 2022). Due to the slightly lower calorific value of FAME, one can assume that 195g of fuel are needed to produce 1kWh of usable energy. Using the same data as before for HFO SSD, the critical carbon price can be calculated as $339.47/t CO_2 in April 2021 and $455.05/t CO_2 in April 2022. Again, price changes on the fuel market heavily influence the fuel switch level.

It can be seen that the switch to a (net) zero carbon fuel leads to much higher carbon price levels. This indicates that the switch towards (net) zero carbon fuels will not be used as an initial step to achieve climate neutrality, but instead at the later stages. This delay might be economically beneficial, since the learning curve for producing (net) zero carbon fuels will help to reduce their production costs. To make this happen, R&D on the construction of production units is needed.

	0	50	100	150	200	250	300	350	400
HFO	63,000	92,208	121,415	150,623	179,830	209,038	238,245	267,453	296,660
FAME	261,300	261,300	261,300	261,300	261,300	261,300	261,300	261,300	261,300

Table 6.6: Fuel switching between HFO and FAME: with higher CO_2 prices (first row in $/t), FAME becomes more economical (author's calculations) (considered amount of energy 1 GWh)

Source: Author's calculations (market price sources: Ship & Bunker for HFO, Neste for FAME).

KEY POINT:

Increasing the carbon price could favour the increasing use of carbon-neutral fuels, in this case FAME biodiesel (omitting life cycle analysis (LCA) emissions). The critical carbon price for fuel switching is $339.47/t CO_2.

> (Net) zero carbon fuels are not currently the first choice to reach climate neutrality due to high abatement costs. However, climate neutrality will become nearly impossible without them.

FAME biodiesel prices, however, will also react to market price developments for conventional fuels, as could also be seen in the past. Consequently, the critical carbon price for switching fuels will also change over time, which presents a challenge for a rational investor and also a challenge to determine a fixed level for a carbon tax or levy. Consequently, one should not compare the costs to produce alternative fuels as FAME with the market prices, but always keep in mind, that alternative fuel producers also observe the markets for conventional fuels in order to determine their price offers.

80 This calculation omits emissions for cultivation, processing, transport and distribution of the zero carbon fuel. In case these emissions need to be considered, the fuel switching calculations of the previous section apply. In this section, however, economic consideration of a zero carbon fuel is the focus.

81 https://www.neste.com/investors/market-data/biodiesel-prices-sme-fame#16f9eed2

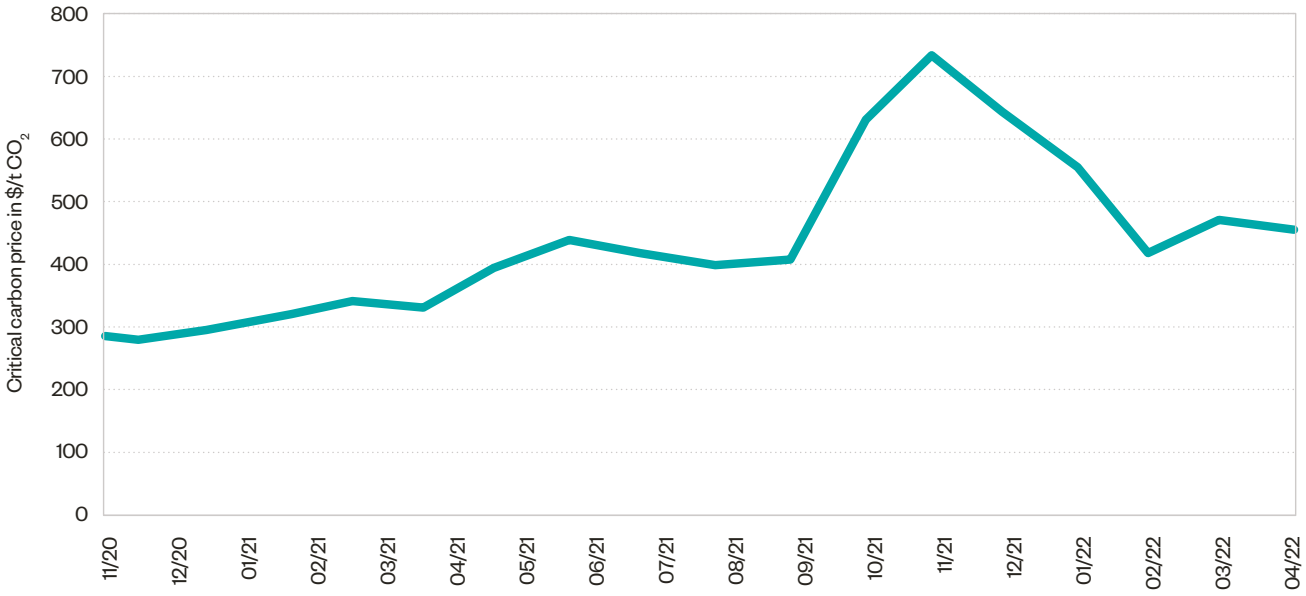


Figure 6.5: Development of the carbon fuel switch level (critical carbon price) to replace HFO by FAME November 2020 and April 2022

Source: Author's calculations (market price source: Ship & Bunker and Neste)

Similar considerations can be done for other (net) zero carbon fuels such as ammonia or methanol: critical carbon prices can be determined. Currently no engine consumption data is available based on experience, so only rough estimates could be done in this case.

The first initiatives to use (net) zero carbon fuels are on their way: A. P. Møller-Mærsk announced in March 2021 plans to run a container vessel with net zero carbon green methanol by 2023. One challenge is the procurement of sufficient amounts of green methanol for the vessel. To this end, a new facility will be established in Denmark to produce the 10,000t of e-methanol it is assumed the container vessel will consume annually[82]. This facility will run on renewable energy and use biogenic CO_2. This example shows that, especially at the beginning of climate-neutral operations, close cooperation between suppliers and users is needed to start the development process for (net) zero carbon fuels. Maersk now seems confident about the methanol procurement and in August 2021 ordered eight large ocean-going vessels[83]. In response to the expected methanol demand, in September 2021 A. P. Møller-Mærsk invested in the US-based methanol producer WasteFuel[84]. The first vessel (capacity of approx. 16,000 containers) is planned to start operations in the first quarter of 2024.

On 29 September 2021, the first commercial container ship was fuelled with net zero carbon LNG (produced with renewable energy) in the German harbour of Brunsbüttel. This fuel was produced using renewable electricity. The amount of synthetic LNG was 20t. Together with roughly 20t of conventional LNG, the fuel should be sufficient for the 20-hour trip to St. Petersburg in the Russian Federation. The ship Elbblue (former name Wes Amelie) has a rather small size of 1,036 TEU. The engine is retrofitted for dual-fuel use and should be able to run on HFO or LNG.

Similarly, the 35-metre-long research cutter Uthörn started its Arctic mission in June 2021 with methanol as a fuel. The methanol is produced in a pilot plant combining CO_2 produced from a nearby sewage plant with green hydrogen produced by electrolysis, which is powered by an 8MW wind turbine. Since methanol has roughly half of the energy density of conventional ship fuels, the tanks need to be much larger.

82 Maersk Press release, "Maersk secures green e-methanol for the world's first container vessel operating on carbon-neutral fuel", 19 August 2021

83 https://www.maersk.com/news/articles/2021/08/24/maersk-accelerates-fleet-decarbonisation

84 https://www.maritime-executive.com/article/maersk-invests-in-u-s-start-up-to-develop-methanol-supply

Research projects are also on their way, e.g., the ShipFC consortium led by Norwegian cluster organisation NCE Maritime CleanTech with 14 European companies and institutions, aiming to install an ammonia fuel cell system in the vessel Viking Energy in late 2023.

One should note that (net) zero carbon fuels could help meet climate neutrality requirements. To find the optimal fuel for vessels, other requirements also need to be met, as shown in Figure 6.6. where the criteria for a fuel assessment are described.

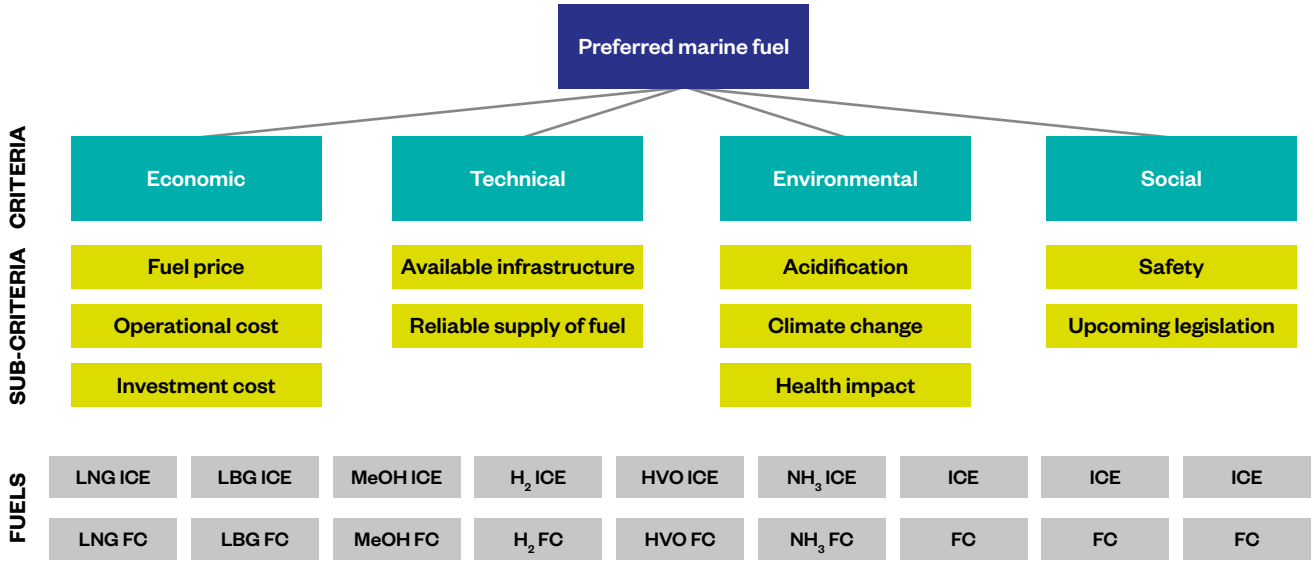


Figure 6.6: Criteria to assess fuels: climate change concerns are a very important driver, however other areas of concern also need to be addressed to achieve viable solutions

Notes: FC = fuel cell; ICE = internal combustion engine; LBG = liquefied biogas; MeOH = methanol.

Source: Julia Hansson et al., Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders, Biomass and Bioenergy, Volume 126, pp. 159–173, July 2019

KEY POINT:

While (net) zero carbon is an important quality for marine fuels, other criteria also need to be met.

6.1.5 Carbon Capture and Storage

Carbon capture and storage (CCS) technologies are also under consideration for ships. The SINTEF project, CCShip, aims to develop cost-effective on board solutions for ships by means of solvents.[85] These solvents are liquids that extract CO_2 from the exhaust gases of the engine. These approaches will help to reduce the GHG emissions of a ship. However, one should note that CCS technologies are not completely GHG-free, since the capture rate is typically not 100%: for solvent-based technologies reductions of over 50% are targeted, although higher values can be obtained. The capture costs are roughly $50/t.[86] However, additional costs of loading/unloading the solvent and additional equipment might lead to higher total costs.

CCS with solvents also require additional infrastructure at ports: the solvent "filled" with CO_2 needs to be unloaded at the harbour and replaced by a fresh solvent, and then the CO_2 contained in the solvent needs to be unloaded. In both cases, infrastructure for loading, unloading, storing and transporting solvents or CO_2 is needed. However, this also has the benefit that CCS ships could provide a valuable source for stored CO_2, which might become a feedstock for synfuel production.

85 https://www.sintef.no/en/projects/2021/ccship-deploying-carbon-capture-and-storage-for-ships-to-enable-maritime-CO2-emission-mitigation/

86 https://www.pnnl.gov/publications/driving-down-carbon-capture-costs-506-tonne

The EverLoNG project led by Dutch TNO aims to demonstrate CO_2 capture on board of two LNG-fuelled ships. These ships are owned and operated by the two project partners TotalEnergies and Heerema Marine Contractors. In the end, the readiness of this approach is targeted[87]: a capture rate of more than 90% with marginal abatement costs between 75 and 100 US$ per tonne CO_2. Similar magnitude of orders for the price range was reported in a case study for RoPax ferries by Finnish Ultramarin, published in October 2021[88].

> Ships with on board CCS are currently under consideration at the initial project stage. The future will show their competitiveness and readiness.

6.1.6 Changes in behaviour to shift mode of transport

Changes in behaviour may also lead to substantial GHG reductions; however, these measures are often connected with convenience losses and are hence often not the preferred choice, mainly in the private sector. We have already touched on one behavioural change: slow steaming in the energy efficiency section. Another important option in the maritime industry is modal shift (as an opportunity for the maritime sector), meaning switches between the various transport modes such as from road freight transport to domestic maritime.

Maritime transport covers roughly 90% of the volume of globally traded goods. Generally this is good news, since seaborne transport emits fewer GHGs per unit of mass and distance than other transport modes. Despite this comparative advantage, however, the maritime sector still needs to reduce its emissions until the sector is climate neutral. Nonetheless, it also shows the opportunity offered by modal shift, choosing ship transport in preference to more GHG-intense alternatives.[89]

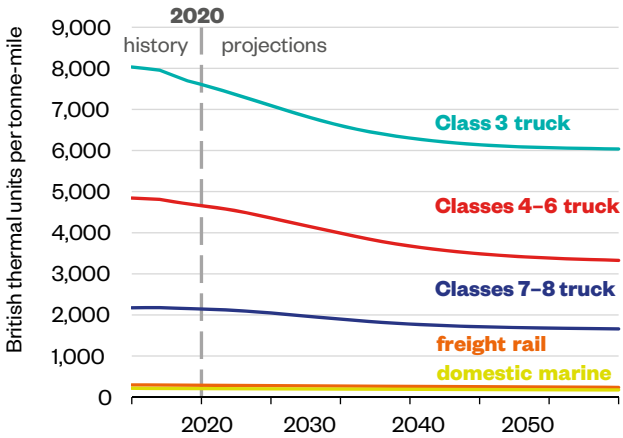


Figure 6.7: Transport freight travel energy intensity by mode in British thermal units per tonne-mile: clearly maritime transport shows the lowest energy intensity per tonne-mile

Source: US Energy Information Agency, Annual Energy Outlook 2021 with projections to 2050, February 2021

KEY POINT:

Maritime transport has extremely low values for freight travel energy intensity.

> In comparison with other transport modes, the maritime sector has very low values for freight travel energy intensity. Thus, a modal shift towards vessels helps to reduce GHG emissions.

87 https://everlongccus.eu/partners/project-partners

88 https://deltamarin.com/blog/carbon-capture-case-study-for-a-ropax-ship/

89 US Energy Information Administration, *Annual Energy Outlook 2021 with projections to 2050*, February 2021

Figure 6.8: Comparison of typical CO_2 emissions between modes of transport

Source: ICS based on IMO, Second GHG Study, 2009

**AP Møller-Maersk, 2014*

KEY POINT:

Maritime transport has lower emissions in comparison with other transport modes; consequently, a shift towards maritime transport is beneficial for the climate.

Another behavioural change – potentially triggered in the aftermath of the COVID-19 pandemic and the Russia-Ukraine conflict – is a less globalised world, i.e. more regional production and consequently less global trading. This change will reduce the need for transport and hence also reduce the GHG emissions. One should, however, be cautious about demanding less international transport as a goal: restricting global trade will also reduce the benefits of economic growth. In fact, in many cases trade cannot be avoided, since many raw materials are localised in certain areas of the world. Examples include rare materials that are needed in the energy sector for electricity production and storage equipment.

6.1.7 Carbon dioxide removal

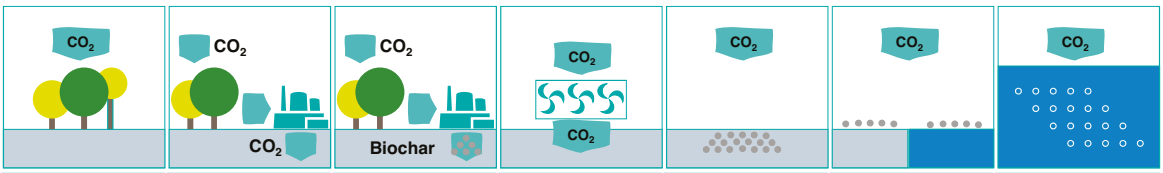
Carbon dioxide removal (CDR) technologies are considered as a solution of last resort. The maritime sector emits up to 1.5Gt per year by 2050 according to IMO scenarios. This means that the CDR's potential (as shown in Figure 6.8) easily meets the volume requirements, provided other sectors will not heavily use CDR as part of their climate-neutral future and provided that all mentioned CDR options fully materialise. Using CDR would allow the maritime sector still to use conventional fuels such as HFO, MDO, MGO and LNG, and compensate the GHG emissions completely with activities such as afforestation or BECCS (biomass with CCS).

Apart from the major uncertainties with regard to the potential of CDR and unwanted side-effects, public perception and social acceptance of CDR solutions are key. A recent study by Cox et al. (2020) concluded that:

> *"While research under well-controlled conditions is likely to be acceptable, at-scale deployment without corresponding efforts to reduce emissions may represent a red line for many people."*[90]

Consequently, the maritime sector might use CDR where other approaches such as (net) zero carbon fuels have been used extensively, but prove not to be sufficient.

90 Cox, E., Spence, E. and Pidgeon, N., *Public perceptions of CO_2 removal in the United States and the United Kingdom*, Nat. Clim. Chang., Vol. 10, pp. 744–749, 2020, https://doi.org/10.1038/s41558-020-0823-z



Negative emissions technology	Afforestation and reforestation	Biomass-energy with carbon capture and storage	Biochar	Direct air carbon capture and storage	Soil carbon sequestration	Enhanced weathering & ocean alkalinity[1)]	Ocean fertilisation[1)]
2050 potential	0.5-3.6 Gt CO_2/p.a.	0.5-5 Gt CO_2/p.a.	0.3-2 Gt CO_2/p.a.	-	2.3-5.3 Gt CO_2/p.a.	1-16 Gt CO_2/p.a. 0.1-10 Gt CO_2/p.a.	0-44 Gt CO_2/p.a.
Costs	USD 5-50/t CO_2	<USD 200/t CO_2	USD 30-120/t CO_2	USD 100-300/t CO_2	USD -45-100/t CO_2	USD 15-40/t CO_2 USD 14-500+/t CO_2	USD 2-457/t CO_2
Features	• High land and water usage • Lower period of storage than geological storage • Saturation of forests over decades/ centuries • Storage threatened by fire, drought, and pests	• Limited by availability of sustainable biomass and secure CO_2 storage • High nutrient and energy consumption • Uncertainties regarding scalability • Land use conflicts	• High land use • Limited maximum storage period determined by available soils • Positive effects on soil fertility	• Costs currently high • Technological challenges • Low land use	• Soil saturation after 10-100 years • Increases soil fertility	• Problematic scalability and side effects • Higher pH values, release of heavy metals, changes to ecosystems	• Major side effects on existing ecosystems

Figure 6.9: Potential and costs of GHG carbon sinks

Source: World Energy Council Germany, Pathways to Climate Neutrality, April 2020

KEY POINT:

As these technologies are at a very early stage of development, the potential and costs can only be broadly estimated.

CDR technologies could also be a valuable bridge technology for the maritime sector: as long as biofuels or synthetic fuels are too expensive or their production is still in the ramp-up phase, conventional fuels combined with CDR measures could be used to achieve a net zero solution. In the long run, fewer or even no CDR measures might be needed by the maritime sector, if the learning curve for biofuels and synfuels reduces their production costs sufficiently.

> CDR combined with conventional ship fuels offers a possible intermediate solution for the maritime sector to reach climate neutrality.

Currently, the approach of offsetting emissions is used for LNG.[91] The LNG importer association GIIGNL views this as a premium product and as a differentiator among the competition.

Offsetting is also used in the CORSIA programme (Carbon Offsetting and Reduction Scheme for International Aviation). The aviation industry plans to use carbon offsets generated in several schemes (e.g. CDM, REDD+ and VCS) to reduce their carbon footprint over the coming years.

Carbon offset was recently introduced in maritime shipping, e.g. by Charles R. Weber Company[92] or KPI OceanConnect[93]. It might become an important part of the solution towards climate neutrality as long as conventional fuels cannot be replaced fully within a reasonable time-scale.

91 Vincent Demoury, *LNG carbon offsetting: Fleeting trend or sustainable practice?*, The International Group of Liquefied Natural Gas Importers (GIIGNL), 18 June 2020, giignl.org

92 https://www.bluesource.com/press-releases/crweber/

93 https://kpioceanconnect.com/news/kpi-oceanconnect-completes-first-carbon-neutral-fuel-supply-to-boost-sustainability-in-the-supply-chain/

6.1.8 Conventional fuels with carbon sinks

Conventional fuels might still be used in a climate-neutral future, provided regulation allows full compensation via carbon offsets or with CDR projects. This would mean that the existing global infrastructure for conventional fuel trading could be used further – to a lesser extent, since the global demand for fossil fuels is set to fall.

The ongoing use of conventional fuels depends on the availability and the price of carbon offset solutions, and also the market price or tax level for GHG emissions. Technically, the potential for using carbon offsets is sufficiently high. However, the limiting factor might be regulation that does not accept these solutions. The same holds true with regard to the expected price: trading systems or tax systems accepting carbon sinks will set the price for the use of conventional fuels in each carbon pricing region. Currently, these prices vary significantly between various jurisdictions, as shown by the World Bank carbon pricing dashboard[94], leading to cherry picking by using the cheapest available fuel to meet local regulation.

Fossil fuels climate-neutralised by carbon sink projects could also work for an intermediate time as a bridge process in the maritime transition, until enough synthetic fuel capacity has ramped up to the amount needed. This could help to reduce pressure on the technology supply side and allow the benefits of a learning curve to be reaped. A massive addition of synthetic fuel production capacity in a short time might not only lead to an over-heated supply side, but also lock in technology at the current state of the art.

> Conventional fossil fuels combined with carbon sinks might also be part of the solution until enough synthetic fuel and biofuel production is available. This also leads to a proxy price based on existing liquid markets.

Carbon pricing can either be realised with:

- A carbon tax or levy, i.e., a fixed price for the emission of 1t of CO_2. This has the advantage of predictable costs, although the total emissions per year are not capped; or
- An emissions trading scheme, i.e. the price is determined by supply and demand and the total emissions per year are capped. This has the advantage of meeting climate targets, although investors have to cope with price volatility.

Voices from the maritime sector recently suggested a carbon tax or levy of $150/t.[95] At this price level, carbon-neutral fuels will certainly become economically more attractive (see section 6.1.4). Many of the details of such a levy would need to be discussed, e.g. the redistribution of tax income. Nevertheless, this price indication is interesting to note, being higher than the current market prices in the EU ETS. This underlines that decarbonisation in the maritime sector might not be as easy as in the sectors that are currently captured within the EU ETS. Moreover, the International Chamber of Shipping (ICS) has proposed a levy of $2 per tonne of fuel to create the International Maritime Research Fund (IMRF), however member countries at the IMO had not yet approved the measure, making a higher levy difficult to envision.

94 World Bank Carbon Pricing Dashboard https://carbonpricingdashboard.worldbank.org/

95 https://www.bloomberg.com/news/articles/2021-06-02/shipping-giant-maersk-seeks-150-a-ton-carbon-tax-on-ship-fuel

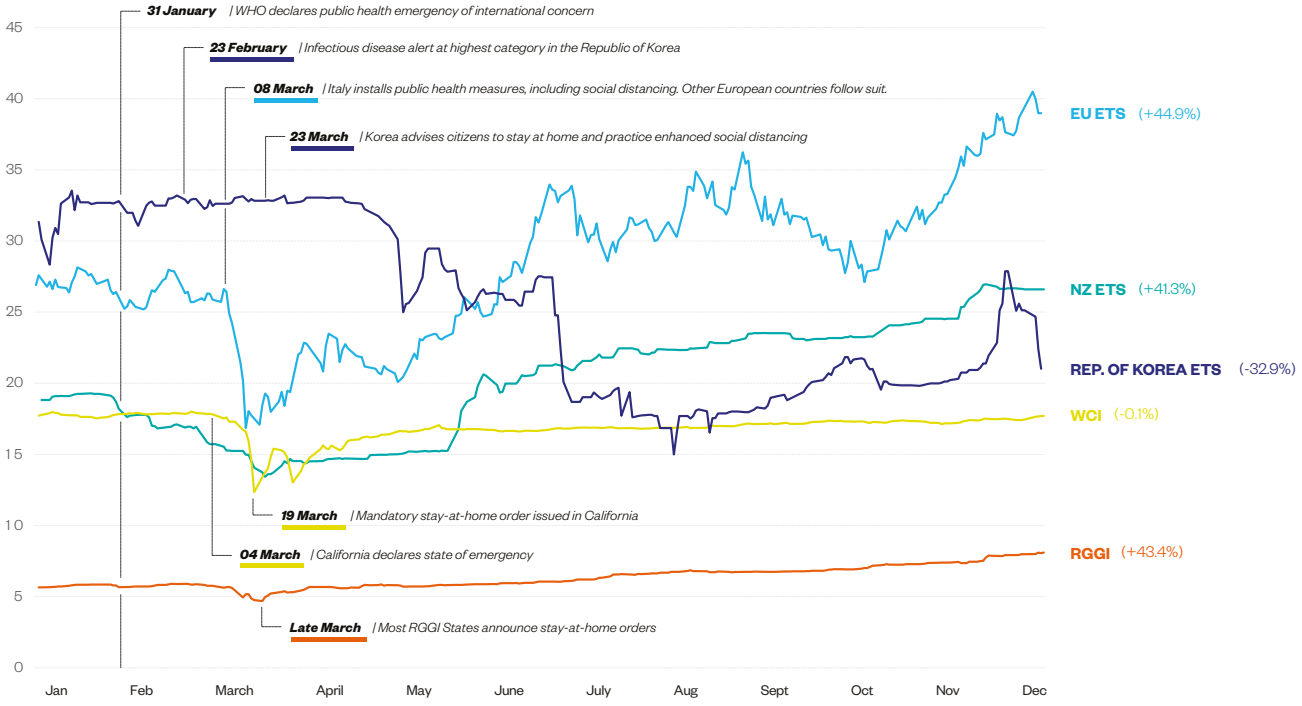


Figure 6.10: Market price history for various emission trading systems in 2020 – market prices can substantially change as reaction to several influence parameters

Source: World Bank, State and Trends of Carbon Pricing 2021

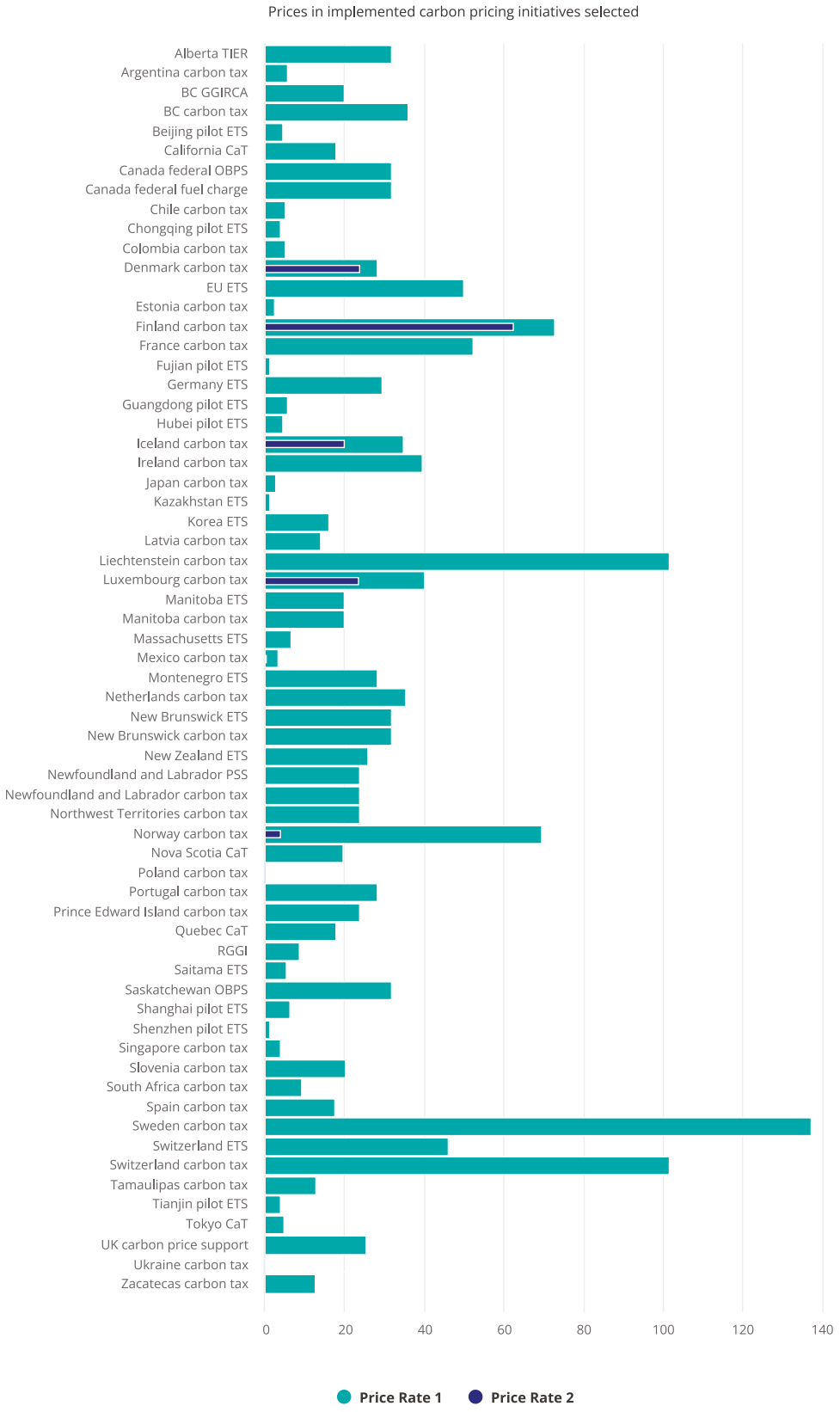


Figure 6.11: Global market prices/taxes for one tonne of CO_2 equivalent in various countries – the suggested 150 US$/t for the maritime sector would become the highest price in this chart

Source: World Bank, Carbon Pricing Dashboard, April 2021

KEY POINT:

Carbon tax levels and emission allowance prices vary significantly around the world.

6.2 Merit Order for GHG abatement

So far we have seen examples of various measures to reduce – partially or even to a large part – the GHG emissions of the maritime sector. The technological potential to reduce the sector's emissions is important to consider, as it will show if there is "enough technology" out there to do all the necessary reductions in practice.

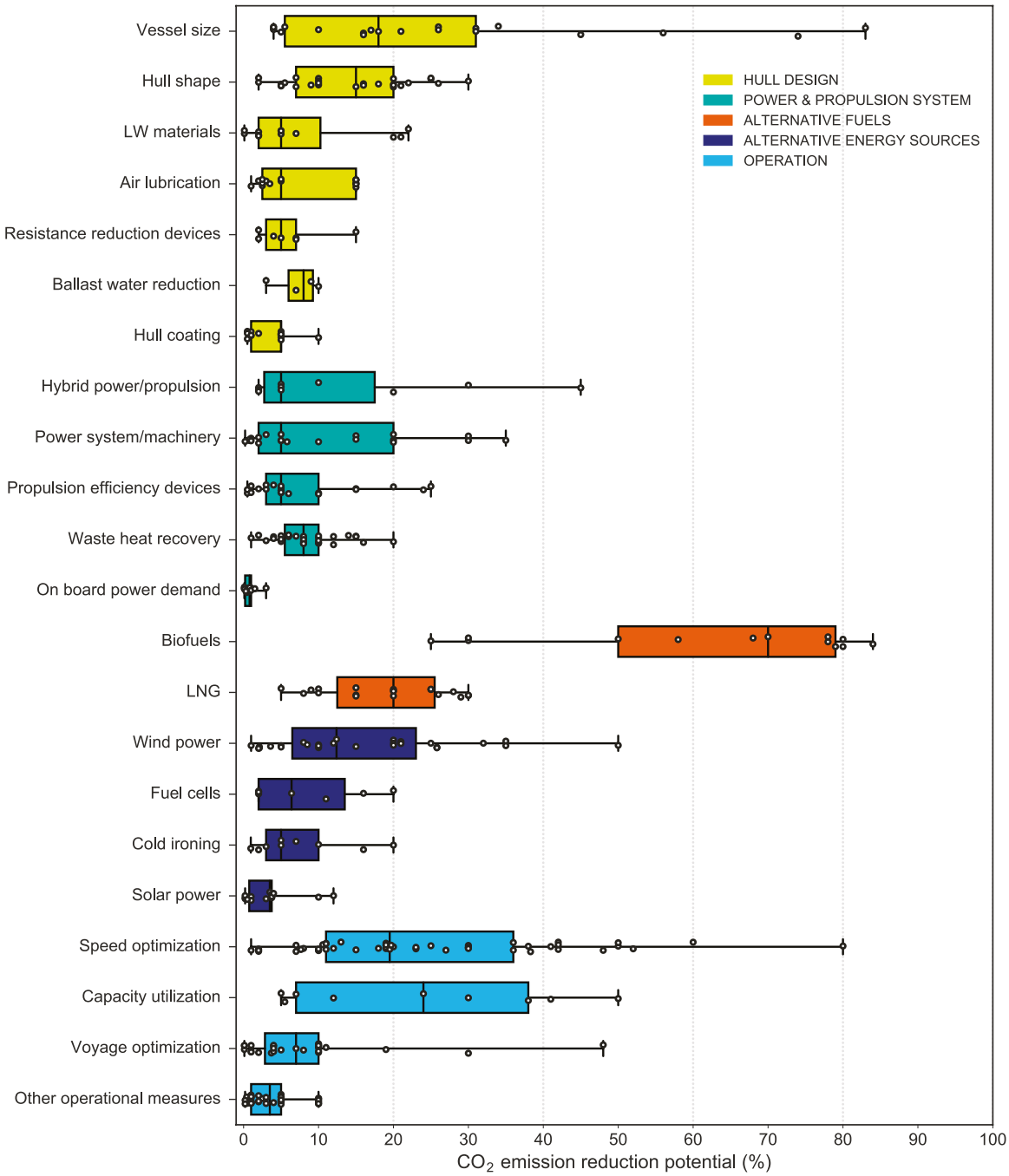


Figure 6.12: CO_2 emission reduction potential of various measures in the maritime sector

Source: E. A. Bouman et al., State-of- the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review, Transportation Research Part D: Transport and Environment, Vol. 52, pp. 408–421, 2017

Apart from the technical levers (energy efficiency and fuel substitution), there are also options to influence modal shift and total transport demand. However, one should note that influencing total transport demand might not be a sustainable solution, since this demand will always vary over time and suppressive measures

are not always convincing. Hence, the technical solutions should be preferred, since this is a more robust approach to handling future changes in transport demand.

In addition to the technical potential, the associated costs play a decisive role. The merit order curve describes this relationship by showing clearly which options are the cheapest and should be done first (the low-hanging fruit). This relationship is depicted in Figure 6.12 and can be elaborated by economic calculations of the abatement costs. The IMO did this work in their fourth report and calculated the GHG abatement curves for various scenarios by 2030 and 2050.

> (Net) zero carbon fuels are inevitably needed to achieve climate neutrality in the maritime sector.

The IMO used two approaches to calculate the marginal cost curve: net present value (NPV) and capital recovery. The technical potential for both abatement curves was more or less identical, however for the abatement costs strong differences emerge. The basic reason for this strong difference is due to discounting. This means that, especially for investments, the results can be very different. For existing ships with dual-fuel the decision is much easier, since only current fuel prices need to be considered. Investment decisions, on the contrary, cover periods of roughly 30 years, and therefore the impact of discounting is rather high.

Group	Technology	2030		2050	
		MAC (USD/tonne -CO_2)	CO_2 abatement potential (%)	MAC (USD/tonne -CO_2)	CO_2 abatement potential (%)
Group 3	Steam plant improvements	-28.0	1.30%	-25.3	2.13%
Group 10	Optimization water flow hull openings	-27.1	1.64%	-25.6	3.00%
Group 6	Propeller maintenance	-26.0	2.20%	-23.1	3.95%
Group 9	Hull maintenance	-21.9	2.22%	-20.2	3.90%
Group 8	Hull coating	-5.9	1.48%	-14.3	2.55%
Group 12	Reduced auxiliary power demand	27.6	0.40%	-9.9	0.71%
Group 13	Wind power	36.5	0.89%	4.2	1.66%
Group 2	Auxiliary systems	42.4	0.87%	-4.4	1.59%
Group 1	Main engine improvements	42.5	0.25%	-2.6	0.45%
Group 5	Propeller improvements	54.1	1.40%	5.6	2.40%
Group 16	Speed reduction by 10%	60.3	7.38%	6.7	7.54%
Group 7	Air lubrication	108.0	1.35%	29.1	2.26%
Group 4	Waste heat recovery	123.3	1.68%	22.6	3.09%
Group 15B	Use of alternative fuel without carbons	126.6	0.10%	46.4	64.08%
Group 11	Super light ship	135.3	0.28%	20.2	0.39%
Group 15A	Use of alternative fuel with carbons	156.9	5.54%	---	---
Group 14	Solar panels	631.4	0.18%	241.5	0.30%

Table 6.7: The marginal abatement cost (MAC) to abate 1t of CO_2 (with the NPV method)

Source: IMO, Fourth GHG Study, 2020

KEY POINT:

The IMO calculates the marginal abatement costs with the NPV method.

Additionally, the marginal abatement costs vary strongly with fuel prices. Consequently, it cannot be expected that this analysis will deliver a simple single figure, but will instead deliver somewhat broad ranges.

However, some general conclusions can be drawn by considering all scenarios and results.

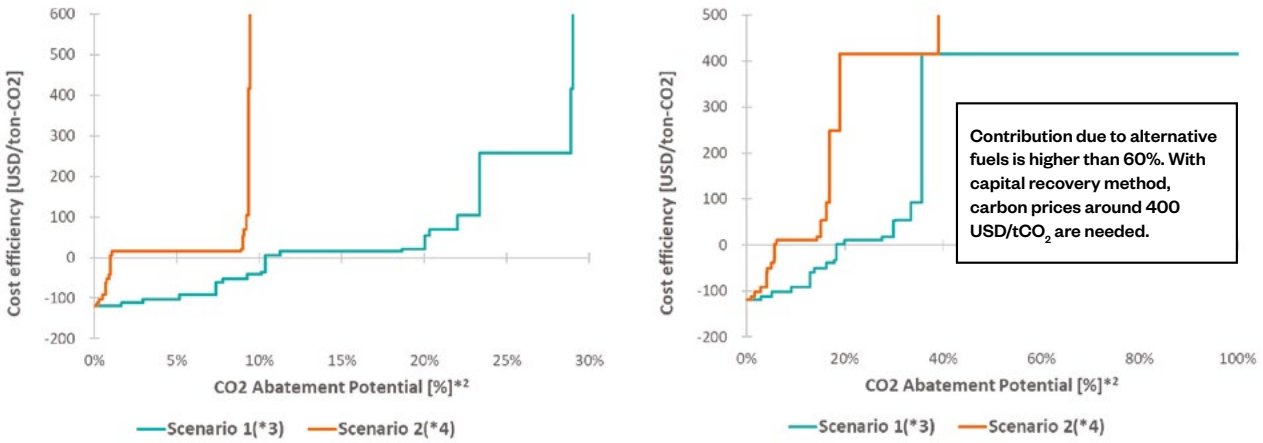


Figure 6.13: Merit order for GHG abatement: to achieve climate-neutrality in maritime shipping by 2050, (net) zero-carbon fuels are needed following the IMO study of 2020

Source: IMO, Fourth GHG Study, 2020

KEY POINT:

In the merit order for GHG abatement, the capital recovery method shows higher carbon prices compared with the net present value method.

The main conclusion is that without alternative fuels, climate neutrality cannot be reached. More than 60% of the abatement potential by 2050 will be due to alternative fuels with(net) zero carbon content. The associated carbon costs range roughly between \$50/tCO_2 and \$500/tCO_2. One should note that this broad price range was already observed in the past months for the fuel switch levels of conventional fuels, as explained in section 5.1. So it should not be interpreted as exaggeration, but as part of the reality.

This huge uncertainty cannot be reduced easily, since the variation in fuel prices, interest rates, the global economic situation and so on heavily influence the outcome of the calculations. Consequently, investors might use scenarios with different market prices for CO_2 (consistent with the assumed scenario prices for the fuels), in order to find out which investment portfolio is most robust under various scenarios. This approach might only give a limited basis for sound investment decisions, so most investors might prefer to wait until it is clearer which market solution will become the most successful.

> Abatement costs for (net) zero carbon fuels broadly range between \$50 and \$500/tCO_2. Investors might hence prefer to use scenarios to make the most robust decisions.

As a second conclusion, in line with the generic marginal cost curve, energy efficiency will deliver emission reductions first and hence pave the way for the later use of the more expensive alternative fuels. This can be seen by the negative abatement cost for efficiency measures, i.e. energy efficiency is usually an investment that pays off in the short term.

One technical note: synthetic fuels in an ICE diesel engine will most likely also need a pilot fuel in the future in order to trigger combustion, as will be the case for ammonia-fuelled engines. Only if the pilot fuel is also carbon-neutral (e.g. biodiesel or syndiesel) can the operation of the engine be completely climate neutral.

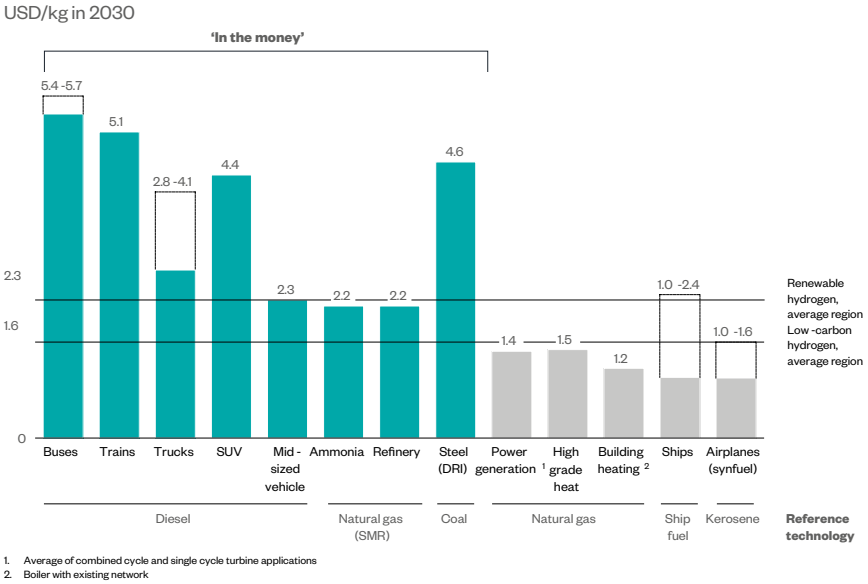
Comparing the abatement costs of climate-neutral solutions in the maritime sector with the abatement costs in other hard-to-abate sectors leads to the third conclusion: it is more economic for society to use

initially climate-friendly hydrogen and hydrogen-based synthetic fuels as an industrial feedstock and for road transport before large-scale deployment in international aviation and international shipping. It should be emphasised that this does not mean the maritime sector hesitates in its actions to fight climate change, it just means that it is more economic to abate GHG emissions in the sectors with lower marginal abatement cost and not in the sectors with the highest marginal cost.

One caveat needs to be considered with the economic reasoning in the third conclusion: not all decisions are based on mere economics. Public pressure, international and national regulations, access to finance and customers' decarbonisation strategies all influence decisions as well and might overrule the economics. Similarly, the willingness to pay might lead to unwanted side-effects. Within the European Union, heavy industry strongly opposed the integration of private vehicles into the EU ETS. Existing carbon taxes for road vehicles indicate an enormous willingness to pay for private transport, leading to substantially higher market prices for emission allowances.

In order to make international shipping ready for climate-friendly fuels, it is imperative to increase the ambitions of the sector to enhance energy efficiency. Eventually, this will reduce the demand for hydrocarbon based fuels and will hence make (net) zero carbon fuels competitive at an earlier stage. Additionally, RD&D on engines and fuel storage needs to be undertaken to develop the best solutions and have them available when economic implementation makes perfect sense.

The IMO scenario calculations underline this approach: the marginal abatement costs for (net) zero carbon fuels in 2050 are substantially lower than in 2030. Consequently, economically it makes much more sense to increase the maritime sector's ambitions in RD&D and deployment projects on (net) zero carbon fuels in order to move the learning curve forward rapidly, and then start with the large-scale deployment of climate-friendly fuels. Environmentally, this also makes more sense, since it is important to abate GHGs and this should take place primarily in those sectors with lowest abatement costs and highest total emissions.



1. Average of combined cycle and single cycle turbine applications
2. Boiler with existing network

Figure 6.14: Required hydrogen production cost for breakeven with conventional solutions at assumed carbon costs of $100/t CO_2eq. Many hydrogen use cases in industry are already economical at relatively high hydrogen production costs, whereas maritime shipping would need hydrogen costs at comparatively low levels.

Source: Hydrogen Council and McKinsey & Company, Hydrogen Insights – A perspective on hydrogen investment, market development and cost competitiveness, 2021

KEY POINT:

For other sectors (e.g. heavy industry), hydrogen is economical at an assumed carbon price of $100/t, but this is not the case for shipping.

Road transport and industrial applications offer attractive abatement costs for hydrogen use cases. Maritime transport could benefit at a later stage from lower hydrogen market prices.

6.3 Conclusions and Recommendations

Maritime shipping will need to use several levers in order to reach carbon neutrality. Initially, the journey towards carbon neutrality will start with energy efficiency, since this measure will deliver immediate GHG reduction and pave the way for the later use of (net) zero carbon fuels. The (net) zero carbon fuels are inevitable in order to meet the goals of the Paris agreement: without these fuels, maritime shipping will not be able to reduce the GHG emissions to (net) zero.

Carbon taxes and carbon levies can enhance investment in (net) zero carbon technologies, as long as they are implemented globally to avoid cherry picking and ensure all ships operate under the same rules.

Maritime shipping will enter into competition with regards to (net) zero carbon fuels. Other hard-to-abate sectors – industrial use cases such as steel, or transport use cases such as aviation – will also need these fuels. The regulatory pressure and the ability to pass the costs to customers will in the end decide which of the hard-to-abate sectors will use (net) zero carbon fuels in the beginning the most. After a while, when enough production capacities are available, all hard-to-abate sectors could have sufficient access to (net) zero carbon fuels. In any case, maritime shipping will become an enabler of this development as a supplier of transport capacities for these fuels.

7 (Net) Zero Carbon Fuels: How Will They Work?

7.1 Introduction

This section shows the basic ways that (net) zero carbon fuels work, i.e. how the produced GHGs will become part of a carbon cycle, or how the production of GHGs will be avoided. However, this also means that there are various solutions. To mitigate the risk of a stranded investment in a certain vessel type with a certain (net) zero carbon fuel, it might be preferable to have the option of using several fuels with the same vessel: this type of hedge will reduce the risk of a stranded asset tremendously, provided this is technically possible. An example use case of (net) zero carbon fuels is the aviation industry with their adoption of sustainable aviation fuel (SAF).

Biofuels benefits from the short-term CO_2 cycle: the CO_2 emitted by burning the biofuel is assumed to be captured during the growth period of the plants that are used to produce the biofuels. Consequently, there is a closed carbon cycle that results in a net-zero emission solution.

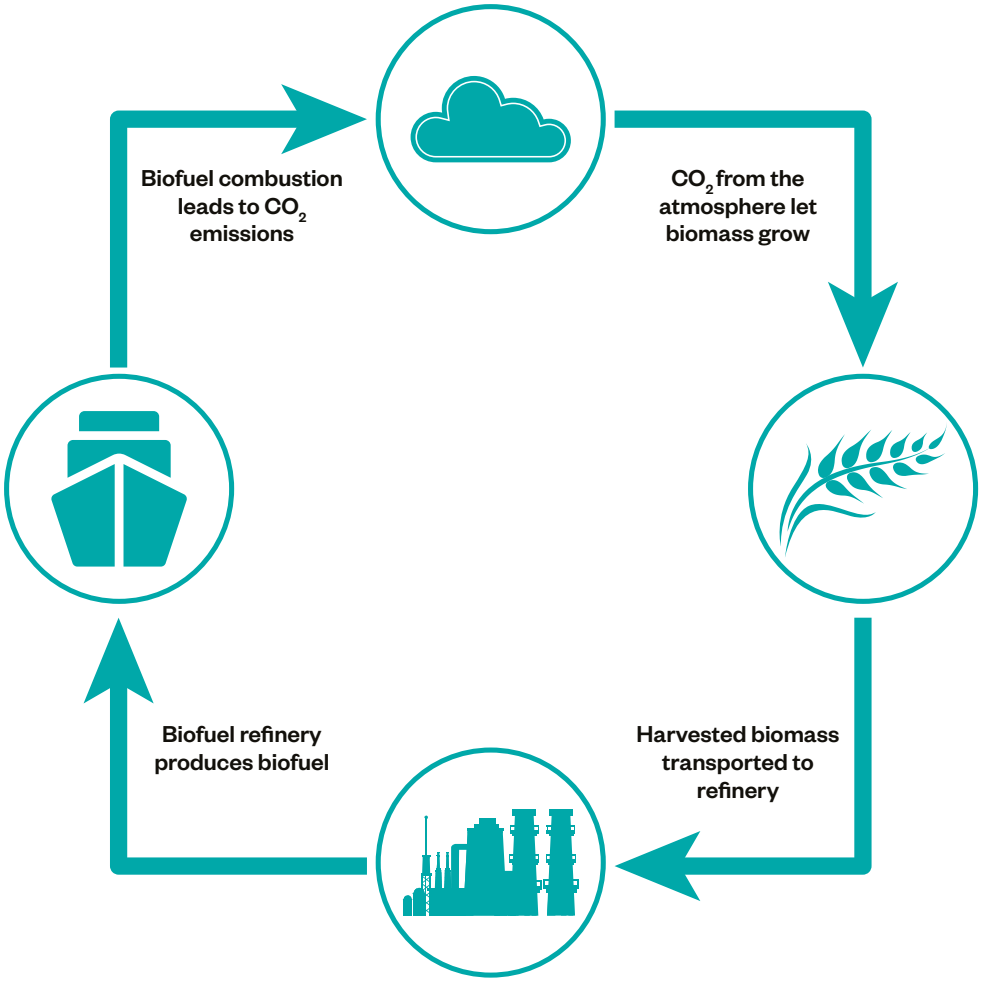


Figure 7.1: Climate neutral cycle: biofuels. Due to a closed carbon cycle their climate neutrality is guaranteed

KEY POINT:
A carbon-cycle ensures the climate neutrality of biofuels.

Synfuels with carbon essentially perform the same cycle as biofuels: the CO_2 capture in this case is performed by technological solutions. For the ship operator, this fuel is climate neutral, as the synfuel producer acts as a carbon sink and will pay for the costs incurred.

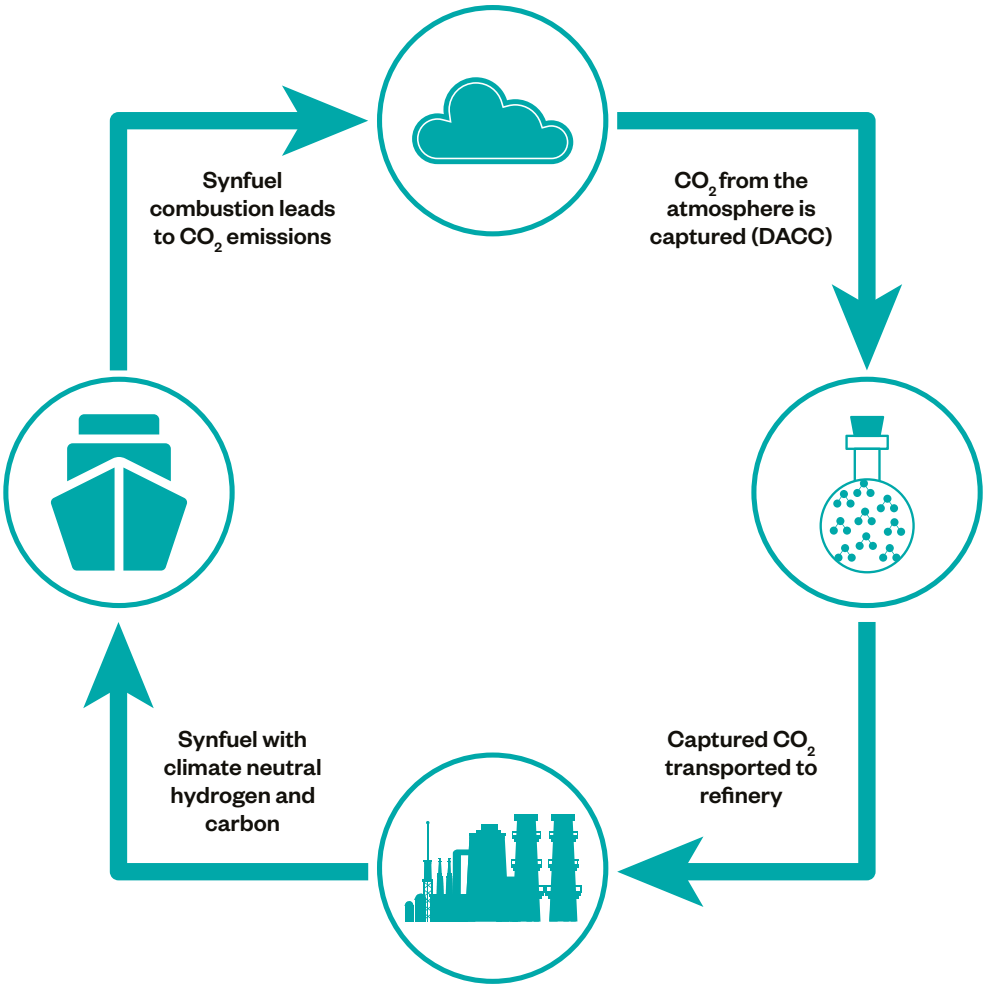


Figure 7.2: Climate neutral cycle: synfuels with carbon. Synfuels with carbon content simulate the carbon cycle of biofuels by technology

KEY POINT:

A carbon cycle ensures the climate neutrality of synfuels with carbon.

Synfuels without carbon do not contribute to GHG emissions, since their combustion does not lead to GHG emissions. Synfuel production is based on using climate-neutral electricity. Hence, the complete cycle is climate neutral.

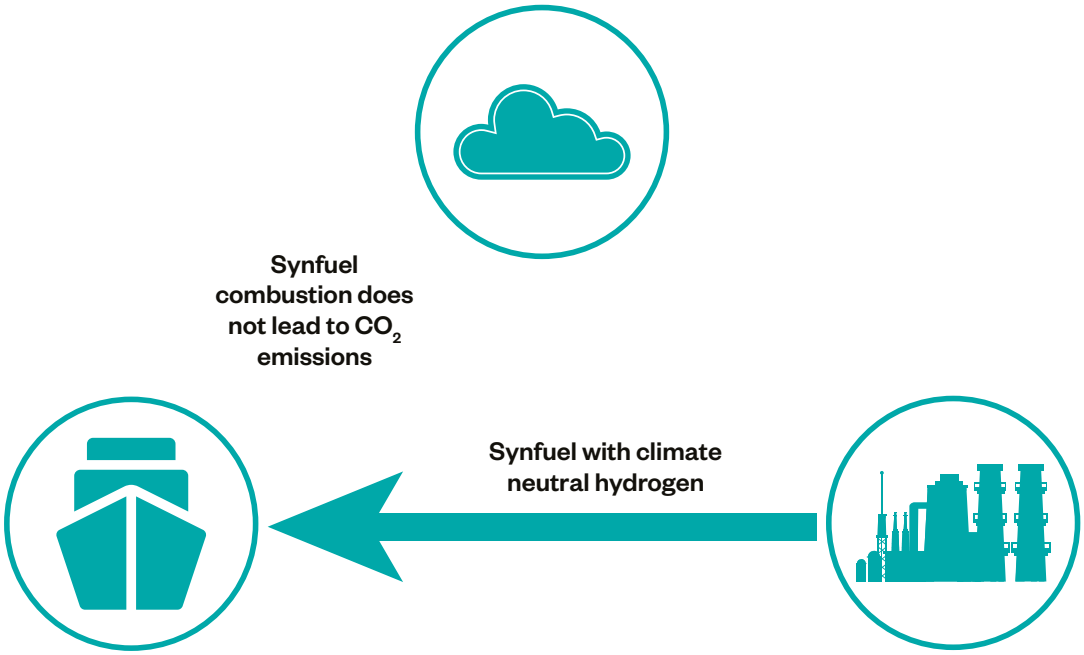


Figure 7.3: Climate neutral cycle: synfuels without carbon. Synfuels without carbon content, e.g. ammonia, do not lead to CO_2 emissions at all

KEY POINT:
Synfuels without carbon emit no GHG emissions during production and combustion.

Conventional fuels can be combined with CDR measures: this results in a net zero solution if the captured CO_2 is stored permanently.

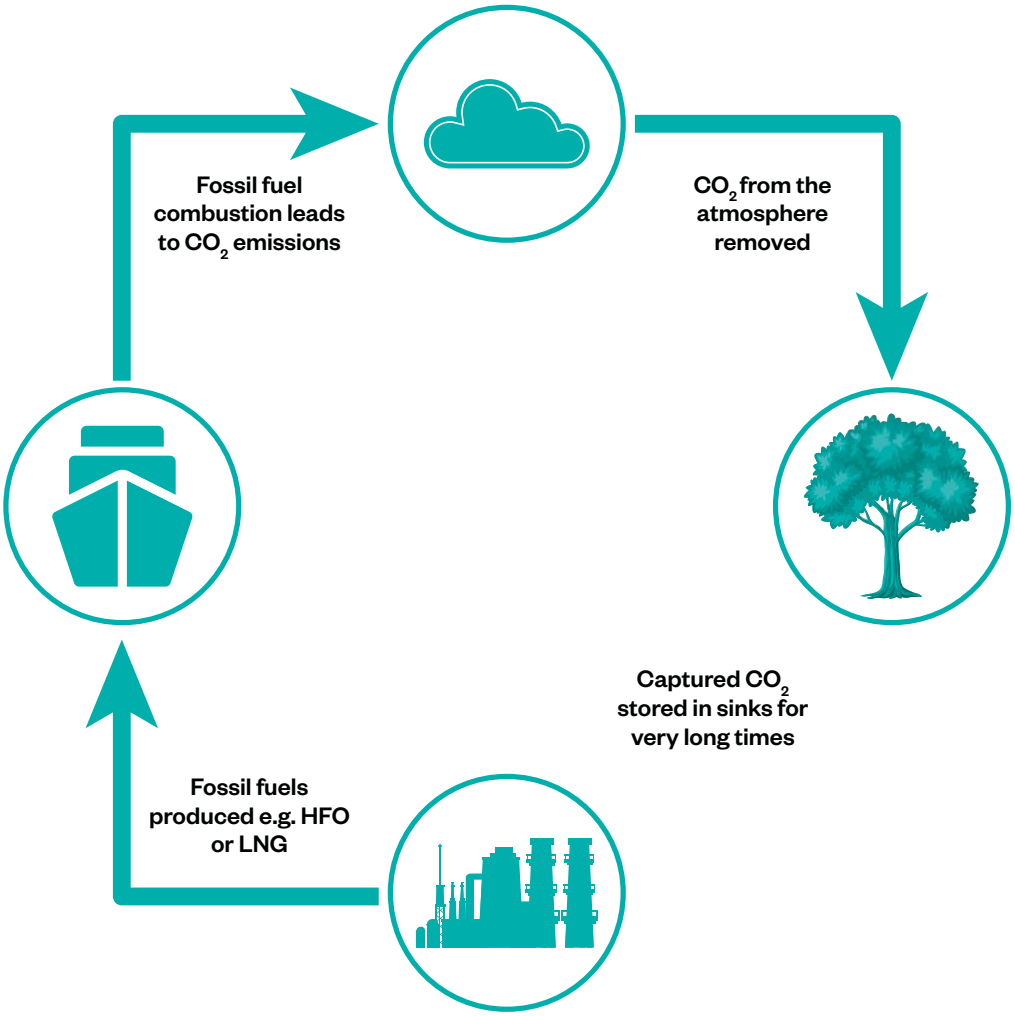


Figure 7.4: Climate neutral cycle: fossil fuels with carbon dioxide removal. The CO_2 emissions of the conventional fuel use are compensated by carbon offsets

KEY POINT:
Capturing and storing CO_2 from the atmosphere compensates for the GHG emissions due to the combustion of fossil fuels.

The cost of using these fuels is defined by fuel costs (and respective investment costs for adjustments to the engine, storage, etc.). In the case of conventional fuels, the ship operator actively has to take care of the carbon market price unless the refinery sells this as a combined product.

7.2 The Ideal Hedge for a Vessel Investment

The good news is that there are different ways to achieve the emissions reduction goal, in the sense that there are choices among (net) zero carbon fuels. However, this is only good news if an engine is capable of running on two or more fuels. A multi-fuel engine is best equipped to allow optimal economic decisions for fuel purchasing over the 30-year lifetime of a vessel. This also means that an early decision on a vessel investment will not cause much harm. Conversely, an early investment in a vessel with a single-fuel engine can result in massive harm: if the underlying fuel does not succeed in the market – with the consequence of high market prices due to limited production facilities and a slow learning curve – the operational costs for this vessel will become high and uncompetitive. Unless a retrofit is possible and not significantly expensive, there is a high risk potential in the vessel investment.

The ideal engine – regardless of whether it will be an ICE or a fuel cell – would be able to run on all fuels, i.e. conventional fossil fuel, biofuels and synthetic fuels (hydrogen, methanol, synthetic diesel). Additionally, the fuel storage on the vessel should also be able to work with these fuels. The vessel is therefore not only in need of an ideal engine, but also ideal fuel storage.

This ideal vessel would not only work as a perfect hedge against all market movements during its lifetime, but would also enable a gradual shift from the existing circumstances to a long-term situation with net zero emission requirements. However, this also means that the multi-fuel vessel should be able to run on conventional fuels. This approach allows the operator to define a maximum price for alternative fuels that is competitive with conventional fuels combined with CDR. This approach assumes that the most economical solution for climate-neutral transport would consist of this combination – knowing that the large-scale roll-out of CDR would lead to public criticism should the maritime industry not also be looking intensively for other solutions.

Another characteristic of the ideal vessel would be its ability to run on a fuel blend, e.g. biofuels blended with conventional fuels.

	Carbon price	0	10	20	30	40	50	60	70	80	90	100
HFO	SSD	360	393	427	460	494	527	560	594	627	660	694
HFO	MSD	360	396	432	468	504	540	576	612	648	684	721
VLSFO	SSD	430	464	498	532	567	601	635	669	703	737	772
VLSFO	MSD	430	467	504	540	577	614	651	688	725	761	798
MGO	SSD	530	563	596	629	662	695	728	761	794	827	860
MGO	MSD	530	565	600	635	670	705	740	775	809	844	879
LNG	LNG-Diesel	550	579	608	636	665	694	723	752	780	809	838
LNG	Steam turbine	550	578	606	634	662	690	718	746	774	801	829

Table 7.1: Adjusted conventional fuel prices – due to the different carbon content of conventional fuels, a higher carbon price (or tax or levy) will make these fuels economically less attractive

KEY POINT:

With the carbon price in the first row ($/t) the total fuel costs including carbon compensation can be calculated. This allows a comparison with alternative fuel prices.

However, in reality the choices are not always ideal. Consequently, the ideal vessel is a challenge to realise. If a modular design is possible, an easy exchange between engines and fuel storage of various types might be possible at a cost. The most critical point is the fuel storage system. This is closely connected with the density of the energy carrier and with the potential chemical reactions of the fuel with the material used for storage and local distribution of the fuels on board the vessel. Consequently, the storage system is a decisive element of the ship design and cannot easily be changed or replaced.

RD&D and deployment will help shipbuilders come close to the properties of an ideal vessel, but it is unrealistic to assume that the perfect solution will be reached. Any steps that make the vessel closer to this ideal picture will help investors reduce the risk of a stranded asset.

> Multi-fuel engines and multi-fuel storage systems will help to reduce the risk of stranded assets, provided they are technically feasible.

The choice of the fuel – and consequently the choice of the ship design – has a long-term impact, since the typical vessel lifetime is roughly 30 years. This means that not only will the carbon price trigger the investment, but also considerations like the CAPEX for the ship and its engine, the availability of the fuels along the main shipping routes, maintenance costs and many other aspects.

The forecast for fuel prices over such a long period of time is a major challenge, as well as predicting carbon prices. Investments are difficult to assess on the current carbon price on the market: this price will mainly influence short-term optimisation, e.g. from fuel switching or efficiency investments with short payback times. This is a challenge well known to the power sector, where the lifetime of power plants is easily 40 years. Investors in these assets used scenarios to find out how robust the investment decisions are in response to market price movements. They also often used a carbon budget approach, i.e. made a forecast of the remaining GHG emissions in their generation portfolio to find out how much "space" is left in the coming decades. Budget constraints are heavily influencing the investment decisions, especially when enough climate-neutral technologies are available to invest in and enough operational experience was gained from demonstration and pilot projects. Consequently, RD&D will be essential to equip a sector with a set of technical answers that can be used.

> The market price for carbon will mainly impact short-term decisions, whereas investment decisions are mainly based on expectations with regard to the carbon budget and depend strongly on the available set of technology solutions.

The supply industry – especially with regard to ship engines – has intensified its R&D pipeline in the recent months in order to deliver sound technological answers to meet the demands of the maritime industry. Companies like Wärtsilä or MAN Energy Solutions are currently testing a blend of conventional fuels with hydrogen or ammonia (up to 70%). With regard to ammonia as a fuel, the supply industry is optimistic of delivering solutions very soon; for pure hydrogen solutions the year 2025 is envisaged. Parallel to engine and fuel systems, storage and supply systems are also being developed.

Apart from technical and economic challenges, also regulatory and legal challenges need to be addressed: The material properties of the various (net) zero carbon fuels play a decisive role in the possible uses on board and in the risk assessment of the bunker[96]. A detailed technological evaluation of these fuels, including a description of the global bunker options is the natural foundation of bunker regulation – which is needed to give guidance to the investments in the needed port infrastructure.

7.3 Beyond Shipping

Similar to maritime shipping, the aviation sector has a major challenge in meeting climate neutrality by 2050. Aviation is actively pursuing to increase the use of sustainable aviation fuels (SAF). SAF covers bio kerosene as well as synthetic fuels. Kearney[97] estimates the production costs for SAF as roughly 2.50 €/l in Germany and 1.00 €/l in Saudi Arabia by 2030, in comparison to 0.50 €/l for current SAF based on cooking fat. Current SAF pilot plants produce 1 tonne of SAF per day – which translates into 12 minutes flying an Airbus A350.

The recent oil price increases, however, increased interest in synthetic SAF. Biofuel is also considered as an important part of the solution in aviation, however scalability is expected from hydrogen-based SAF. INERATEC, a German company, has planned a production facility near Frankfurt airport to produce 3,500 tonnes of SAF per year using 10,000 tonnes of CO_2 and renewable energy. Operations are expected to start in 2023.

96 Deutsche Maritime Zentrum (DMZ), Bunker Guidance für alternative Kraftstoffe in deutschen Seehäfen (March 2021)

97 https://www.kearney.at/article/?/a/nachhaltiges-kerosin-f-c3-bcr-die-luftfahrt

Ammonia – which is considered a very likely candidate for maritime shipping fuel – is currently one main ingredient to produce fertilizers. Production of ammonia is based on using natural gas – however, similar to the just mentioned SAF vs. kerosene case – the price hike of natural gas made green ammonia produced by hydrogen from renewable electricity competitive.

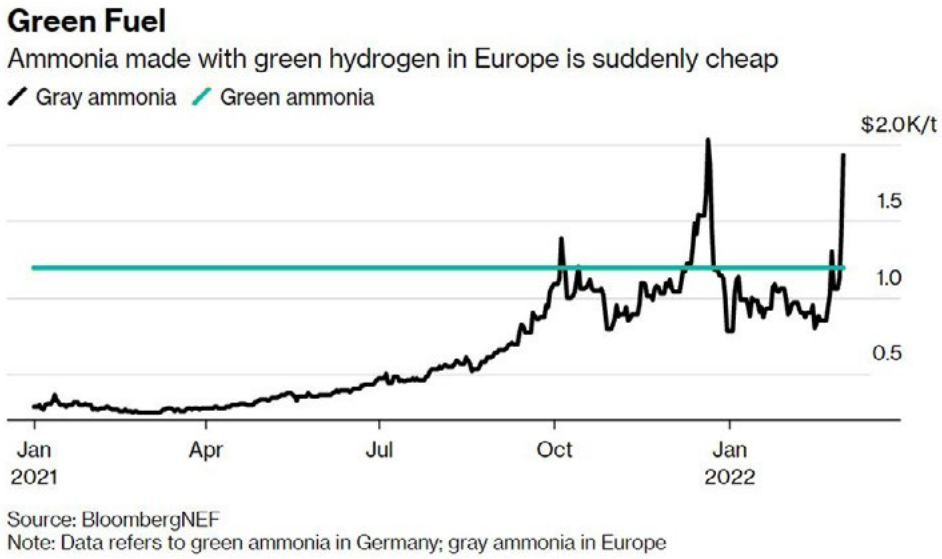


Figure 7.5: Due to the price increase of natural gas, grey ammonia is suddenly more expensive in comparison with green ammonia

Source: BloombergNEF, April 2022

Both examples indicate that the strong price movements of conventional fuels might help to trigger research and pilot projects and consequently help the faster deployment of (net) zero carbon fuels.

7.4 Conclusions and Recommendations

Decarbonising maritime transport is technically possible; however, the use of (net) zero carbon fuels is economically much more attractive for industrial use cases. Consequently, these sectors are likely to dominate the initial application of (net) zero carbon fuels (if economic costs are considered) and the maritime sector will follow provided non-economic factors (e.g. regulation) enables this. This means that, in the short term, the maritime sector should prepare for the future use of (net) zero carbon fuels. It can do this firstly by creating the infrastructure in ports and transport systems for (net) zero carbon fuels. Secondly, it can increase its energy efficiency ambitions to help reduce emissions immediately and reduce energy consumption, which will improve the economics of the future use of synthetic fuel. Thirdly, through RD&D and deployment of new ship engines and especially new fuel storage systems, the sector will enable reliable operations on board the vessel, and consequently a large-scale roll-out of these solutions within the maritime shipping industry.

(Net) zero carbon fuels will play a major role for maritime shipping. The example of SAF and green ammonia shows that price hikes on the conventional fuels market might lead to accelerated investments in the (net) zero technologies.

However, from an investor perspective the risk of a stranded asset is a strong concern: ideally, vessels able to run on various (net) zero carbon fuels help to mitigate this risk most efficiently, provided technical solutions allow so.

8 Conclusions

The future use of (net) zero carbon fuels will depend crucially on the interplay between various players in a new ecosystem. Hence some guidance will help all the actors to find their interfaces for cooperation.

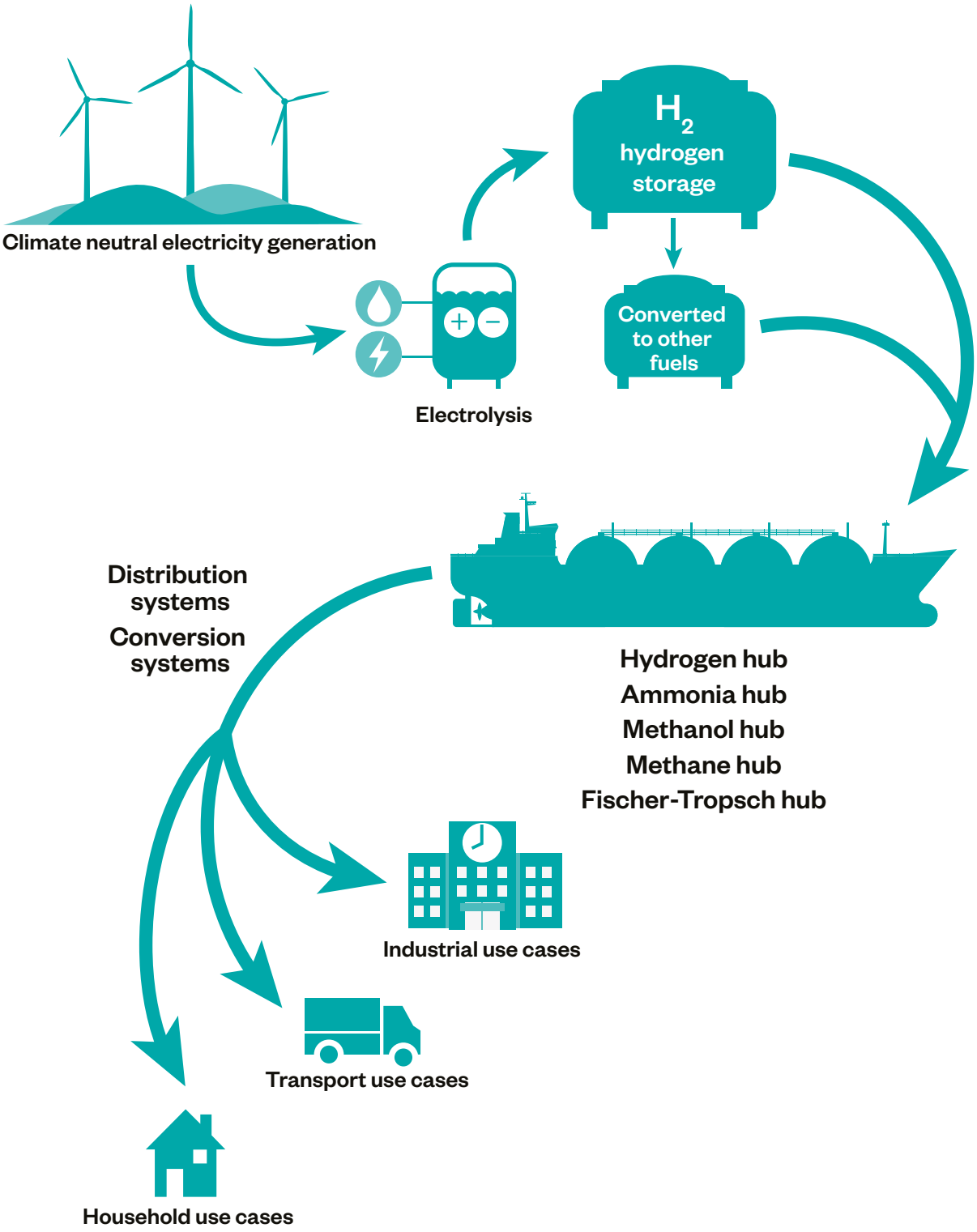


Figure 8.1: Hydrogen ecosystem for maritime

It is clear that the transition to a green fourth propulsion future will be a once-in-a-generation opportunity. Shipping will be a key enabler of the global energy transition, providing cost effective and flexible solutions to transport at least half of (net) zero carbon fuels around the world by 2050. Immediate investment in technology, infrastructure and the establishment of international cooperation projects is needed. As a user and carrier of (net) zero carbon fuels, shipping will underpin and benefit from this transition – and it must be adequately supported.

The speed and scale of change cannot come at the cost of safety. Defined and agreed global safety and sustainability standards for hydrogen-based fuels and strong safety standards for the transport and use of (net) zero fuels must be developed quickly, to keep pace with the transformation. Seafarers and those in the supply chain must be trained and new standards developed to maintain safety and minimise risk.

Key takeaways

1	**Producing (net) zero carbon marine fuels, especially close to ports, will create a significant opportunity for renewable energy producers** It could require the equivalent of all the world's current renewable energy production just to supply shipping's (net) zero carbon fuel needs.
2	**Shipping will have a multi-fuel future** No one fuel can replace current fossil fuels for maritime and decarbonising will require a mix of bio-fuels, e-fuels, natural gas and hydrogen derivatives such as ammonia and methanol.
3	**High demand for (net) zero carbon fuels presents opportunities for the global south** Developing economies are well-placed to become fuel suppliers and exporters of (net) zero carbon fuels but must move quickly to gain early mover advantage and will need support from the international community for capacity building and access to finance.
4	**Renewable energy production of (net) zero carbon fuels provides economic opportunities for all** Investors should be confident in opportunities for (net) zero carbon fuel production as the demand for hydrogen-based solutions is expected to increase strongly in many industrialised countries with strong green policies, that do not have the potential to produce enough renewable hydrogen for their own needs.
5	**Invest in infrastructure and research, development and demonstration now or economic gains will be minimised** Early mover advantage is vital and all stakeholders, including governments, ports, fuel suppliers and industry must invest now to ensure a stable supply of (net) zero carbon fuels.

Annex A: Country Case Studies

Case Study: Chile

Chile aims to be the world's main exporter of hydrogen, leveraging 1,800GW of renewable energy potential — 70 times more than its current installed capacity — to become the most competitive exporter of green hydrogen.[98] Observers expect Chile to reach production costs of $1.30/kg in 2030 and $1.00/kg later. Generally, the anticipated production costs in Chile (and also in Argentina) are very promising.[99]

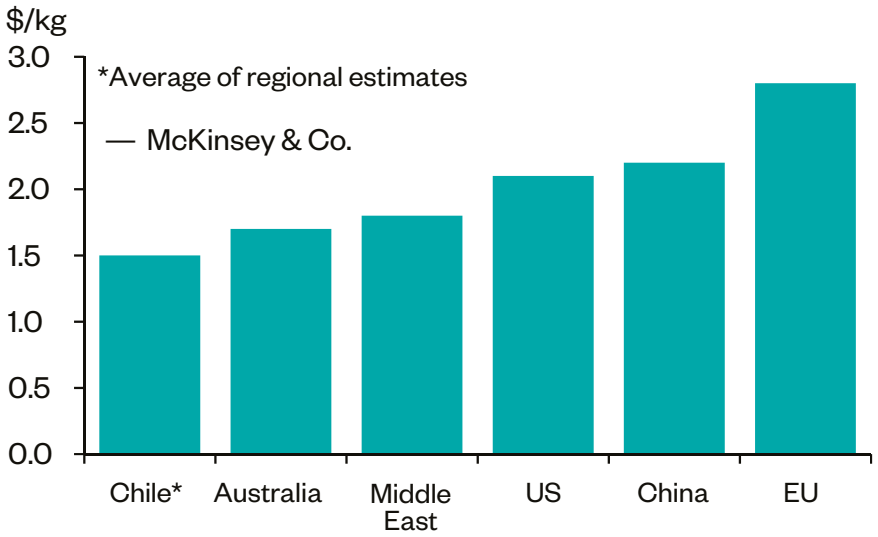


Figure A1: Chile's typical production costs for hydrogen (projected)

Source: Argus, Special Report: Hydrogen – Hope or Hype?, 2021

KEY POINT:

Projections show Chile to have the lowest production costs for green hydrogen, followed by Australia and the Middle East.

Chile's national green hydrogen strategy was launched in November 2020 and has three main objectives: to have 5GW of electrolysis capacity under development by 2025, to produce the most cost-efficient green hydrogen by 2030, and to be among the top three exporters by 2040. The hydrogen strategy is part of the country's 2050 net zero goal. Part of the hydrogen strategy is also to finance the national energy transition using the export revenues. Expectations for 2050 are very ambitious: Chilean policy makers want to see 25Mt of green hydrogen produced annually and expect $30 billion of earnings per year from hydrogen exports, with a 50% market share in Japan and South Korea and a 20% market share in China.

Chile is already active in preparing the necessary regulatory framework and developing funding programmes for 20 pilot projects. In parallel, it is active in promoting international cooperation: in February 2021 a memorandum of understanding (MoU) was signed with Singapore, and in June 2021 a partnership was signed with Germany. Additionally, in March 2021 an MoU was signed with the Port of Rotterdam. Part of the latter MoU is to increase the role of Rotterdam as a European energy hub and to ensure the supply of hydrogen and hydrogen products from Chile.

98 Gobierno de Chile, *National Green Hydrogen Strategy*, Ministry of Energy, Santiago, November 2020

99 Julien Armijo and Cédric Philibert, *Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina*, International Journal of Hydrogen Energy, Vol. 45, pp. 1541–1558, 2020

However, Chile is not only developing an export strategy, but will also use the hydrogen opportunities to decarbonise domestically. To this end, Chile is looking at green hydrogen use in six areas — refining, green ammonia for industry, heavy transport in mining, heavy trucks, long-distance buses and blending into gas networks. Some early projects for domestic use and for export are already underway.

Currently, rather expensive hydrogen imports are used in Chile, e.g. the refiner Enap uses 24,500t/yr at its two main plants. However, the renewable opportunities in Chile are promising. In northern Chile – with many mining operations – the local explosives manufacturer Enaex and the French utility Engie have started a feasibility study on producing green ammonia from solar-generated hydrogen. The pilot plant (18,000t per year) will supply the ammonium nitrate plant, replacing imports from Trinidad and Tobago and the United States. Around 2030, a large-scale plant of 700,000t per year is due to come online, which can also be used as an export plant. However, the overall economics of green hydrogen still depend on financial support.

In southern Chile, the companies Andes Mining and Energy (AME), Enap, Italian generator Enel, German carmaker Porsche, and Siemens are cooperating on an export-focused methanol-to-gasoline project using wind-derived green hydrogen, based on ExxonMobil's methanol-to-gasoline technology. The demonstration plant will produce clean methanol with wind-based green hydrogen and atmospheric CO_2. Porsche will then take the methanol as fuel. With financing from Germany's economy and energy ministry, AME has started building the $45m demonstration plant "Hari Onu". The plant will use atmospheric CO_2 and wind-based green hydrogen to produce clean transport fuel and methanol, with Porsche accepting initial export volumes from the first quarter of 2022.[100] The targeted production in 2022 is 750,000 litres of e-methanol or 130,000 litres of e-gasoline. In two further steps, the site should be scaled up to 55 million litres of synfuel (2024) and then 550 million litres of synfuel (2026)[101]. For comparison, 550 million litres of synfuel correspond to roughly 9,500 barrels per day. The largest refinery operated by ENAP in Chile has a daily output of 113,000 barrels.

In April 2022, the project idea of H2 Magallanes was announced, where the French company Total Eren aims to produce hydrogen and ammonia by electrolysis (capacity 8 GW) based on 10 GW of wind power. This project should also entail a desalination plant, an ammonia production facility and port facilities to transport the green ammonia to national and international markets. The site under consideration is San Gregorio in Southern Chile. Total Eren aims to launch the project in 2025 with the production start by 2027. The project is designed to be fully off-grid, i.e. it will have no connection to the public grid.

Case Study: Australia

Australia is also looking with huge interest at the developing hydrogen market, especially since demand centres like Japan, South Korea and Singapore are within reasonable proximity. A study entitled "GERI Renewable Hydrogen and Ammonia Feasibility Study"[102] has recently been presented, looking in detail at the technical feasibility of large-scale renewable hydrogen and ammonia production for export in Australia. To realise this potential, however, some financial aid is needed, such as from a carbon price.

The situation is especially beneficial in Western Australia due to its vast potential solar and wind resources and its proximity to key importing countries. Nevertheless, additional infrastructural investments are needed in ports and water and electricity networks and distribution.

While the study concludes that a global ammonia market is already in existence, there is still some work needed to create a global hydrogen market.

---

100 https://newsroom.porsche.com/en/2020/company/porsche-siemens-energy-pilot-project-chile-research-development-synthetic-fuels-efuels-23021.html

101 Presentation by Siemens Energy at a webinar on 29 September 2021

102 https://arena.gov.au/knowledge-bank/geri-renewable-hydrogen-and-ammonia-feasibility-study/
This report was commissioned by BP (with support from ARENA) as a key component of Project GERI (Geraldton Export-Scale Renewable Investment).

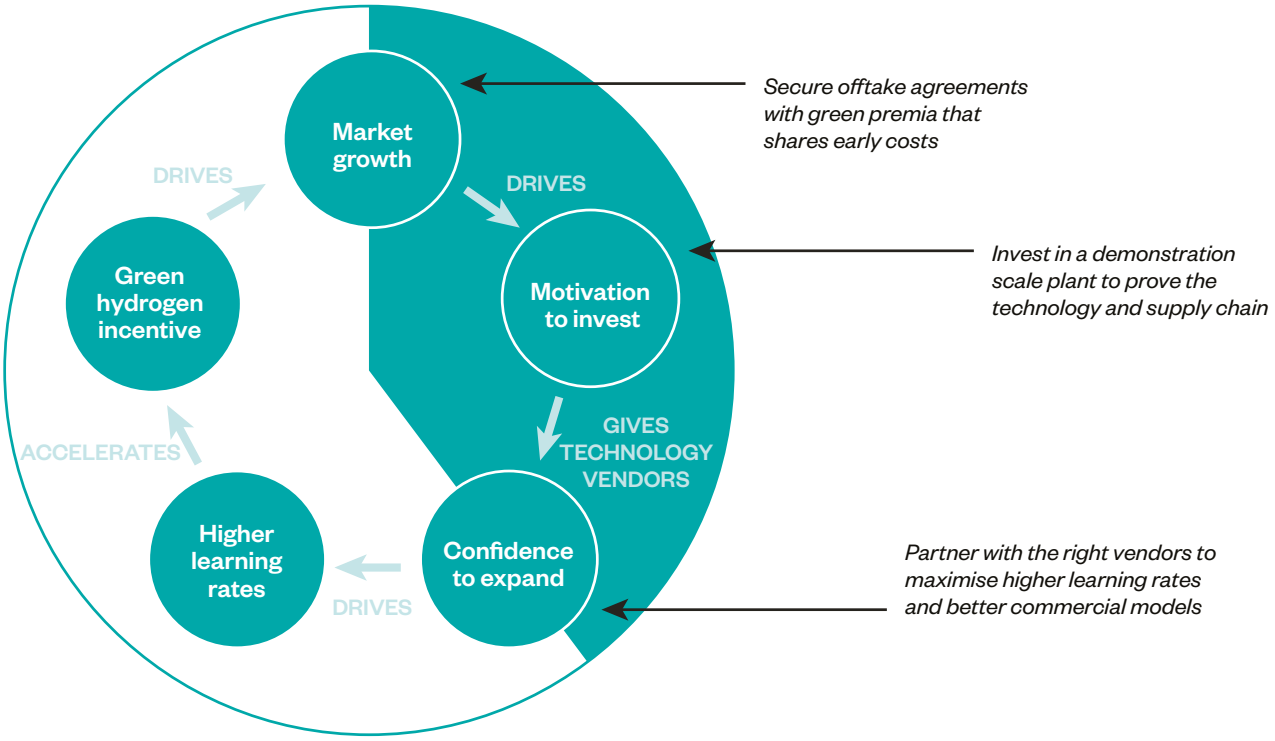


Figure A2: Pathway to a hydrogen economy as BP views it

Source: BP, GERI Renewable Hydrogen and Ammonia Feasibility Study, 2021

The study also confirms the strong interest from potential customers in the hard-to-abate sectors.

Australia has been looking for some time at the country's substantial hydrogen opportunities.[103] Examples are the Victorian Hydrogen Investment Program (2018), the Queensland Hydrogen Industry Strategy (2019) and the Western Australian Renewable Hydrogen Strategy (2019). The Australian federal government announced in September 2021 its plans to extend the prospective national network of clean hydrogen hubs to each of Australia's states. To this end, it pledged additional $150 million to hydrogen projects. The shortlist for the hydrogen hubs now contains seven locations:

- Bell Bay, Tasmania;
- Gladstone, Queensland;
- Latrobe Valley, Victoria;
- Hunter Valley, New South Wales;
- Darwin, Northern Territory;
- Eyre Peninsula, South Australia; and
- Pilbara, Western Australia.

Parallel to these government activities, private companies are actively looking at transport solutions. Australian electricity retailer Origin teamed up with Japanese refinery ENEOS to explore a commercial-scale green hydrogen supply chain between Australia and Japan. Apart from the production of green hydrogen, the companies also want to explore the feasibility of converting hydrogen to methylcyclohexane (MCH), which fixes hydrogen with toluene and remains liquid at normal temperature and pressure for storage and transport. Consequently, a special focus of this cooperation is on the existing infrastructure and transport options.

103 Feitz, A.J., Tenthorey, E. and Coghlan, R., *Prospective hydrogen production regions of Australia*, Record 2019/15, Geoscience Australia, Canberra, 2019

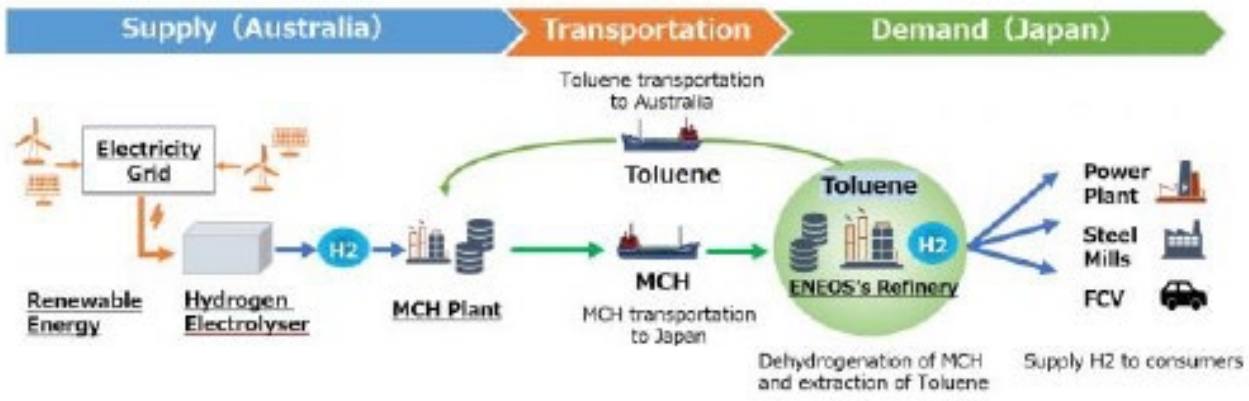


Figure A3: The Origin-ENEOS project for hydrogen supply from Australia to Japan

Source: Shakhar Ali, Eneos, Origin Energy to develop Japan-bound hydrogen supply chain in Australia, H2 Bulletin, 31 August 2021

Origin also signed an MoU with global shipping company Mitsui O.S.K. Lines. The focus of this cooperation is to develop an export-scale supply chain for green ammonia from Australia to Japan. Both have a target to secure green ammonia supply from 2026 onwards.

In April 2022, German utility E.ON and Australian company Fortescue signed a contract about the delivery of 5 Mt of hydrogen from Australia to Germany by 2030. Partly, this is driven by the decarbonization agenda of Germany and the need to replace fossil fuels quickly with (net) zero carbon fuels. However, more recently, this is also driven by the need to replace swiftly natural gas from pipelines to the more flexible import route by maritime shipping.

Case Study: Saudi Arabia

Saudi Arabia sees in the emerging hydrogen economy a great opportunity to replace the current fossil fuel model over the coming decades. This strategic shift will also allow it to use its operational experience in large industrial facilities. Additionally, the CCUS experiences gained by Saudi Arabia could become valuable when synthetic fuels are produced using CO_2. Saudi Arabia could also benefit from the export of blue hydrogen. Observers expect renewable hydrogen to become competitive in 2030. Consequently, Saudi Arabia could create a hydrogen export infrastructure for blue hydrogen first and then switch to green hydrogen. Interestingly, Saudi Arabia sees very high potential for hydrogen exports to China.

One famous project is the futuristic city, NEOM.[104] This is scheduled to be part of the future Saudi hydrogen ecosystem. NEOM aims to become a hydrogen hub in the region and to provide clean hydrogen as a chemical feedstock for fertilisers and other chemical operations. This is to take place in cooperation with SABIC (Saudi Basic Industries Corporation) and Saudi Aramco. Another mega-project is NEOM Helios, which is scheduled to start operations in 2025. This will become the world's largest renewable hydrogen-to-ammonia facility and is a joint venture between Air Products, ACWA Power and NEOM. With electricity produced from wind and PV, the electrolysers are expected to run at a very high load factor. Its estimated ammonia output is 1.2Mt per year by 2050. For comparison, annual ammonia production globally is about 125Mt. Air Products will be the sole off-taker of this ammonia; it plans to export it to other countries and use it there as a climate-neutral solution for various transport modes. For comparison, the amount of green hydrogen would be sufficient to power approximately 700,000 fuel cell cars.

In March 2021, the Japanese company ENEOS signed an MoU with Saudi Aramco regarding cooperation on blue hydrogen and blue ammonia, and before that, in 2019, Hyundai and Aramco signed an MoU for collaboration on hydrogen.

104 Dii Desert Energy, *The Risks and Opportunities of Green Hydrogen Production and Export from the MENA Region to Europe*, November 2020

Saudi Arabia concluded the first blue[105] ammonia shipment to Japan in September 2020, and thus established a successful transnational and multi-industry partnership as part of a circular carbon economy.[106] This cooperation was launched in 2017. Participating entities were the Saudi Arabian government, Saudi Aramco and SABIC on the exporting side, and on the buying side the Japanese Ministry of Economy, Trade and Industry (METI) and the Institute of Electrical Engineers of Japan. This first deal covered 40t of high-grade blue ammonia aimed for use in zero carbon power generation. Technically, the first step was a conversion of hydrocarbons to hydrogen and then to ammonia. The process emissions of CO_2 were captured: 30t CO_2 were used for methanol production at SABIC's Ibn-Sina facility and 20t CO_2 were used for enhanced oil recovery at Saudi Aramco's Uthmaniyah field. The ammonia delivered to Japan was used there in various sites for zero carbon electricity production. The transport logistics were arranged by the Japanese trading house Mitsubishi.

Case Study: Singapore

Singapore is a small but highly industrialised country in Southeast Asia with a very diversified economy, including financial services, electronics and mobility services. Singapore also hosts large oil refineries to deliver fuel to the seaport and the airport. Singapore wants to increase its renewable energy production. However, there is the challenge of limited space in a very densely populated area. Consequently, importing synthetic fuels offers an interesting alternative, since they can be imported from various countries (thus reducing import dependency) and can be stored to avoid short-term disruptions to fuel supply.

Singapore is one of the leading crude oil and LNG trading hubs, several banks based in Singapore finance energy projects, and fuel demand at the seaports and the airport are high. Consequently, the prerequisites for Singapore to become a leading trading place for (net) zero carbon fuels are excellent. Its proximity to Australia as one of the important production centres led to a partnership that was established in June 2021. The initiative will trial the use of clean hydrogen, clean ammonia and other hydrogen derivatives in shipping and port operations and explore the potential for hydrogen demand from the maritime sector.

With an annual marine and aviation fuel demand of 2,000PJ (corresponding to 556TWh, i.e., roughly the total electricity consumption of Germany), the mobility services sector is more than a factor of three larger than the final energy consumption of Singapore, which is around 600PJ. Electricity production in Australia is currently about 265TWh (2020). This shows that Australia needs to ramp up substantially its electricity production to cover demand in Singapore, but also shows the huge opportunity for (net) zero carbon fuel exporters in general.

Assuming that a hydrogen ship delivers 0.300TWh, Singapore would require roughly 1,850 deliveries by hydrogen ship per year to meet the above mentioned 2,000 PJ p.a., i.e., slightly more than five ships per day. This simple calculation assumes, however, that there are no efficiency gains in producing and consuming (net) zero carbon fuels and that there is no major increase of electricity imports to Singapore. Nonetheless, it gives again an example and some magnitude of order, how powerful maritime shipping can be in order to implement the changes needed to sector-wide decarbonisation.

105 Blue hydrogen is hydrogen production combined with CCUS, resulting in zero emissions.

106 https://www.aramco.com/en/news-media/news/2020/first-blue-ammonia-shipment

Annex B: Hydrogen Applications

Application: Oil refineries

In crude oil refineries, some use cases based on hydrogen can be considered as mature and a large amount of hydrogen is already used, e.g. for sulphur removal or heavy crude upgrading. Currently roughly one third of global hydrogen production is used in refineries for hydrotreatment and hydrocracking, about 38Mt annually. The on-site production of hydrogen is slightly more than three quarters of the volume used, either as a refinery by-product, by on-site steam methane reforming (SMR), or to a very limited extent by coal gasification. External supply of hydrogen accounts for 23% of the consumed hydrogen.

Future supplies of carbon-neutral hydrogen can be realised via pipelines or on-site electrolysers. Interesting opportunities exist for refineries close to harbours, since they might also use shipping for hydrogen supply.

In general, however, crude oil refineries have enormous challenges to adopt their business model to a climate-neutral world.

Application: Chemical production (ammonia, methanol)

The chemicals industry consumes about 45Mt of hydrogen per year for ammonia and methanol synthesis. Currently, 80% of the ammonia produced is used in fertiliser production. Methanol can be used for the production of polymers and olefins and also as a fuel for internal combustion engines (ICEs). The hydrogen consumed by the chemicals industry is almost solely produced from fossil fuels such as natural gas, crude oil and coal. Green hydrogen production will become more cost-competitive over time, hence an increasing number of new ammonia and methanol facilities will be based on climate-neutral hydrogen.

Application: Iron and steel production

The steel industry consumes roughly 13Mt of hydrogen per year, of which 4Mt are dedicated to the direct chemical reduction process of ironmaking. The steel industry has for several years been looking closely at hydrogen applications to reduce its use of fossil fuels in the production process.

Currently about 8% of global carbon emissions are due to steel production, according to the World Steel Association. The steel industry feels some pressure to reduce its emissions. This is due to the fact that in some regions carbon prices have led to substantial GHG emission costs. However, there is also increasing demand for carbon-neutral or low-carbon steel products among consumers.

Consequently, the industry needs a drastic decrease in emissions to remain economically competitive (and in operation).

Application: Power generation

Renewable electricity has major benefits in many ways, however, especially wind and solar generation have a challenge with their weather-dependent and hence intermittent generation. Solutions that provide flexibility, e.g. batteries, will help to meet this challenge. Many market observers, however, are convinced that gas-fired power stations are needed to ensure a stable electricity supply. To meet the climate neutrality goals, these power plants need to by hydrogen ready, i.e. able to use hydrogen or ammonia as fuel.

For all the mentioned applications – and there are more e.g. in the food industry and glass manufacturing – hydrogen or (net) zero carbon fuels built on hydrogen will be needed and also in many cases imported. Maritime shipping will hence maintain its role as the backbone for energy logistics.

International
Chamber of Shipping

Shaping the Future of Shipping

International Chamber of Shipping
7th Floor, Walsingham House, 35 Seething Lane,
London EC3N 4AH

Telephone + 44 20 7090 1460
info@ics-shipping.org
www.ics-shipping.org

Stay updated with ICS news,
events and publications:
www.ics-shipping.org/sign-up