PARTNER ORGANISATION:
MONACO HYDROGEN ALLIANCE

ARP4_7 FINAL REPORT

Moving with Green Hydrogen: *Recommendations to Decarbonise the Maritime Mobility Value Chain*

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EXECUTIVE SUMMARY

Shipping contributed to nearly 2.89% of the global emissions as of 2018, estimated to reach 5–8% by 2050. Against the backdrop of the shipping industry committing to reduce its total annual GHG emissions by at least 50% by 2050 from 2008 levels, there is a growing interest in decarbonising the maritime sector, one that is known to be a pragmatic industry, yet notoriously slow in adopting regulatory development.

This report studies the adoption of green hydrogen and hydrogen-based fuels in decarbonising shipping and port infrastructure in the maritime sector. In particular, green hydrogen and green ammonia are seen as targeted solutions. However, fleets today are mostly reliant on heavy oils, and development of these solutions faces the challenges of lack of strong ambition and regulations, absence of technological readiness of crucial infrastructure, lack of safety standards, inadequate financing for the scaling of these solutions.

Through literature review and interviews with experts, this report analyses the regulatory, technological, and financial barriers and opportunities for shipping and port infrastructure to adopt green hydrogen and green ammonia. The main barriers are associated with the mismatch in timeline between stakeholders in developing technology and infrastructure, establishment of safety standards and regulatory framework, and a "chicken-and-egg" situation in financing market off-take structures. Opportunities are thus related to harmonising national, regional, and international ambitions and policy planning, as well as sector coupling, and establishment of green corridors to foster more centralised, and localised infrastructure development. This report recommends eight action points for relevant stakeholders involved to accelerate the transition process.

LIST OF ABBREVIATIONS

ARCHES	Alliance for Renewable Clean Hydrogen Energy Systems
CAAP	Clean Air Action Plan
CCC	Sub-Committee on Carriage of Cargoes and Containers
CCfDs	Carbon Contracts for Differences
CII	Carbon Intensity Indicator
COP26	26th Conference of Parties to the United Nations Framework Convention for Climate Change
COP27	27th Conference of Parties to the United Nations Framework Convention for Climate Change
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EU ETS	European Union Emissions Trading System
FCEV	Fuel Cell Electric Vehicles
GHG	Greenhouse Gas
IEA	International Energy Agency
IIJA	Federal Infrastructure Investment and Jobs Act
IMO	International Maritime Organization
IPCEI	EU Important Projects of Common European Interest
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LOHC	Liquid Organic Hydrogen Carriers
MARPOL	The International Convention for the Prevention of Pollution from Ships
METI	Ministry of Economy, Trade, and Industry of Japan
MGO	Marine Gas Oil

pLAn	Los Angeles Green New Deal
RH2INE	Rhine Hydrogen Integration Network of Excellence
SDC	Ship Design and Construction
SEEMP	Ship Energy Efficiency Management Plan
SSE	Ship Systems and Equipment

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GLOSSARY OF KEY TERMS

(Green) Ammonia	A compound of (green) hydrogen and nitrogen (NH_3). Widely used as a fertiliser. At -33°C and 1 bar, it has a 50% higher volumetric energy density than liquid hydrogen (IEA 2019, 56).
Blue Hydrogen	Hydrogen derived from fossil fuels, when most of the emitted CO_2 is captured and stored or utilised (IEA 2019, 34).
Compressed Hydrogen	Hydrogen can also be stored compressed at 700 bar and 20°C with similar volumetric energy density to liquid hydrogen (IRENA 2021a, 42).
Gaseous Hydrogen	Hydrogen at 20°C and atmospheric pressure. Very low specific weight at 0.9 kg/m^3.
Green E-Methanol	Green e-methanol is obtained by using green hydrogen and CO_2 captured from renewable sources (bioenergy or direct air capture) (IRENA and Methanol Institute 2021, 4).
Green Hydrogen	Hydrogen produced through electrolysis of water using renewable energy (IEA 2019, 34).
Grey Hydrogen	Hydrogen derived from fossil fuel using steam methane reforming. This produces CO_2 (IEA 2019, 34).
Liquified Hydrogen	Hydrogen at -253°C and atmospheric pressure. Higher specific weight than gaseous hydrogen at 71 kg/m^3.
Liquid Organic Hydrogen Carriers (LOHCs)	A liquid or high-melting solid that can be reversibly hydrogenated and dehydrogenated and used as a carrier to transport hydrogen (KBR 2020, 25).
Maritime Mobility	Sea Transport, or any movement of goods and/or passengers using seagoing vessels on voyages wholly or partly at sea (OECD 2003). Expanded to include port activities.
Shipping	The instrumentation of transportation by water of goods, cargo etc. (International Maritime Dictionary 1961, 2nd edition), a subset of maritime activities at large.
Synthetic Methanol	A synthetic compound of hydrogen, carbon, and oxygen (CH_3OH). It has almost double the volumetric energy density of liquid hydrogen at 20°C and 1 bar (IRENA 2021a, 42).

INTRODUCTION

Background

Climate change is one of the greatest challenges of our times, caused by record concentrations of greenhouse gases ("**GHGs**") in the atmosphere. The transport sector was responsible for approximately 23% of the total GHG emissions in 2021 (IEA 2022), with shipping contributing to nearly 2.89% of the global emissions as of 2018, going up to an estimated 5–8% by 2050 (IMO 2021a, 112, 236).

Against this background, there is growing interest from diverse stakeholders, including policymakers, governments, shipping operators, port authorities, and the international community to cut shipping emissions, traditionally considered a hard-to-decarbonise sector (IRENA 2021b, 6). Sustainable fuels such as green hydrogen and green ammonia are one solution. However, fleets today mostly rely on heavy oils, with only 1% of the trading fleet of 60,000 vessels using alternative fuels as of 2019 (IMOHQ 2021).

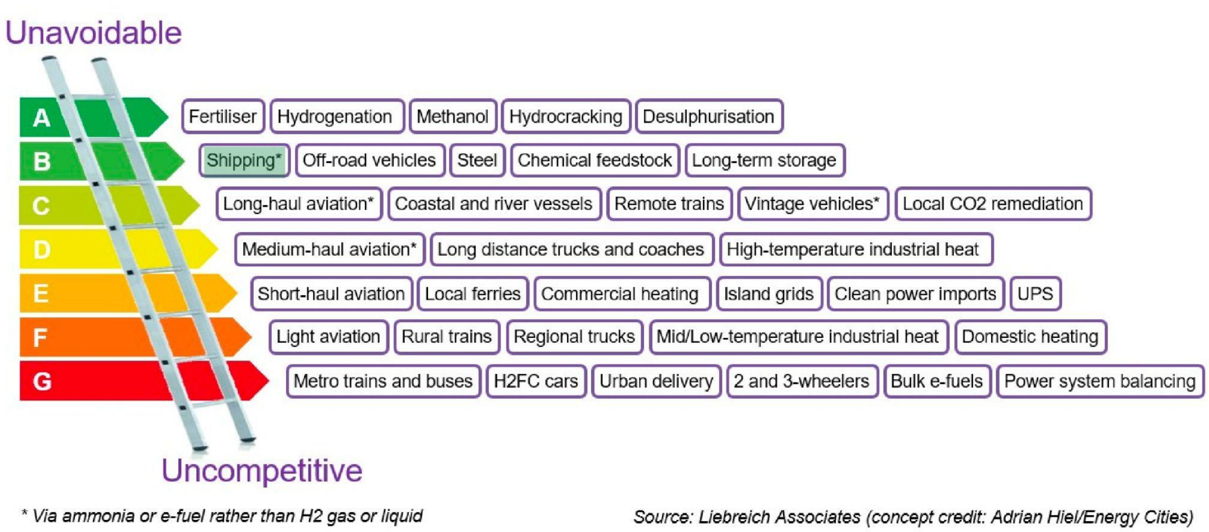


Figure 1: *"The Hydrogen Ladder":*

A merit order of hydrogen uses for decarbonisation (© Michael Liebreich)

Ships that will be in operation in 2050 will be built in the next few years. Thus, any new ships being designed and built to operate on traditional fuels lock in several thousand tonnes of GHG emissions (IRENA 2022a, 95). Therefore, there is a need for all stakeholders in the shipping industry to act swiftly and prevent stranding of assets.

Research Questions

Against this background, this research project explores the adoption of carbon-free fuels such as green hydrogen and ammonia in shipping and port infrastructure to decarbonise the maritime mobility value chain. Our inquiry will be guided by the following overarching questions:

1. Which factors are opportunities or barriers (*inter alia* regulatory, technical, financial) to the adoption of green hydrogen in the maritime mobility industry?
2. How can these factors be addressed?
3. In particular, which policy and regulatory frameworks are needed to implement a green hydrogen transformation in the maritime mobility industry? How can issues around scalability be addressed?

Methodology and Case Study Selection

This report adopts a case study approach. To acquire a holistic understanding of the regulatory landscape, the technical specifications, and the financial incentives pertaining to both port infrastructure and shipping, the researchers have chosen four case studies. They are the Port of Rotterdam (the Netherlands), the Port of Los Angeles (USA), Germany, and Japan. They each can offer insights into different aspects and contexts of hydrogen adoption along the maritime mobility value chain.

The selection of case studies is based on the maturity of hydrogen policies of the countries and ports, their ambition to scale technologies, and the importance of certain countries in the maritime sector either as a port or maritime player. Countries such as Singapore, South Korea, and the city of Neom in Saudi Arabia were considered (cf. **Box 5**). Broad regional representation was aimed for. Yet, the dearth of concrete policies or projects—many of which were in the development stage—coupled with a lack of publicly available information—meant that countries and ports with relatively more mature policies for hydrogen and maritime decarbonisation were selected.

The report relies on in-depth secondary research. Given the rapidly evolving policy landscape and changing geopolitics of green hydrogen and the small amount of academic literature on policy aspects of green hydrogen adoption, the research relies heavily on reports from industry bodies, experts, and international organisations working in the field of maritime decarbonisation, hydrogen, or energy in general. Meanwhile, the academic literature reviewed is focused on technical aspects, including price determination and technical aspects of hydrogen production and storage.

The secondary research is supplemented by interviews with *inter alia* professors, port operators, policymakers, and industry experts, providing valuable insights into the case studies and research questions. The interviewees were predominantly introduced to the team by the partner organisation (MHA). They were conducted in a semi-structured manner, and the questions were shared with the interviewees in advance. The interviews were conducted mostly online, through videoconferencing. Most interviews were recorded in agreement with the interviewees.

Structure

The report is divided into seven chapters. The first chapter sets the scene of the report by providing key information pertaining to the types of hydrogen and projections regarding the future share of hydrogen in the maritime energy mix. The second, third, and fourth chapters provide detailed insights into the regulatory, technical, and financial aspects of the adoption and scaling of green hydrogen and the respective barriers and opportunities. The fifth chapter delves into the case studies and analyses existing regulatory, financial, and technical barriers and best practices found in each case, providing further insights into the findings from the previous chapters. The sixth chapter comprises the analysis, answering the research questions and, lastly, the seventh chapter concludes the report by giving concrete policy recommendations regarding the adoption of hydrogen in the maritime sector.

Limitations

The research is constrained by the following limitations.

Research on hydrogen and its derivatives is rapidly evolving, including but not limited to the maritime sector. This research analyses relevant information and developments till 22 November 2022 due to the timeline of the project.

Although countries across continents are developing strong hydrogen policies and ambition, policy options at the disposal of developed/mature economies are more abundant. Therefore, the geographical focus of the case studies lies on developed countries. To mitigate this constraint, the report will give short insights into other potential case studies (cf. **Box 5**) with the potential for the production of hydrogen or the adoption of hydrogen policies in the long term.

There is a strong gender imbalance in the group of people interviewed for this report, stemming from the general imbalance in the sector. As an all-women team, we hope to help break down this imbalance.

CHAPTER 1. SETTING THE LANDSCAPE

This chapter provides an overview of the different types of hydrogen and discusses projections of the share of hydrogen in the energy matrix and in maritime decarbonisation.

1.1. 'Colours' of Hydrogen

Hydrogen is often classified into different 'colours', depending on the production process. This classification is not standardised. Derivatives of hydrogen, such as methanol[1] or ammonia, are usually given the colour classification of their source hydrogen. Currently, approximately 95% of hydrogen is produced from fossil fuels and is thus predominantly 'grey' (IRENA 2022a, 26). The colour of hydrogen does not matter for the end use. Green hydrogen is the only fully sustainable option but currently also the most expensive to produce. As such, cheaper types of hydrogen such as grey and blue could play an important role in the upscaling of hydrogen infrastructure. This report will, however, exclusively focus on green hydrogen and green ammonia.

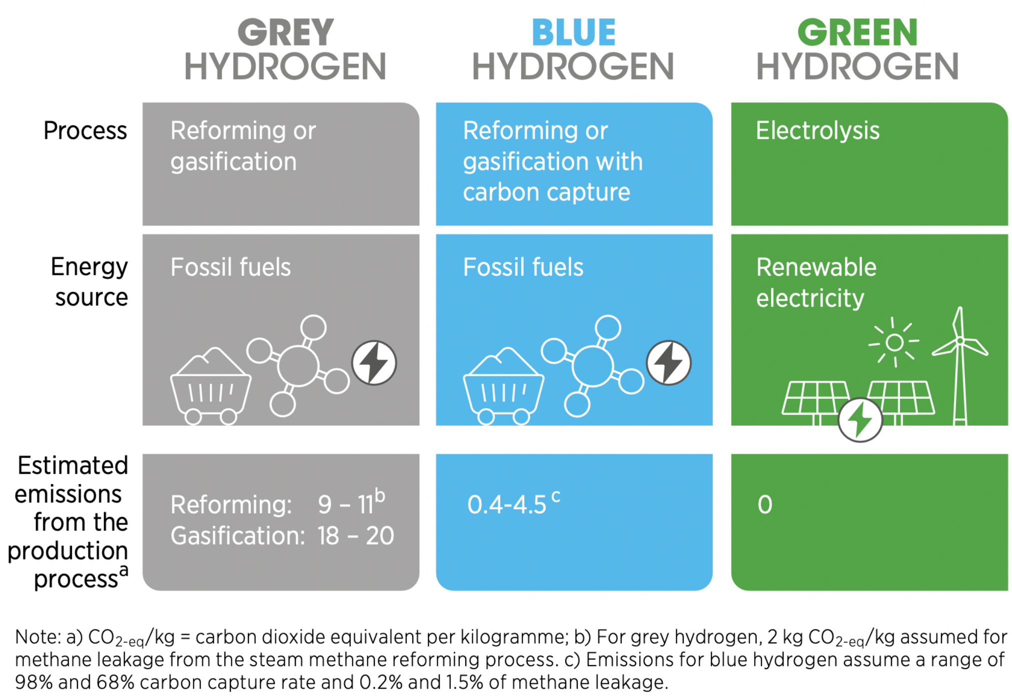


Figure 2: *A typology of grey, blue, and green hydrogen* (IRENA 2022a, 26).

[1] Despite a relatively high technological readiness level, methanol has been excluded from the ambit of this report, as the focus is on carbon-free fuels.

1.2. Scenarios and Projections

The momentum for the production of hydrogen and its application is growing. Projections depict an increasing share of green and blue hydrogen in the energy matrix until 2050. **Figure 3** below captures multiple projections of the share of hydrogen in the energy demand by 2050, according to which the share of green hydrogen will likely grow significantly and the percentage of hydrogen's share in final energy demand is estimated to be between 12–22% (IRENA 2022a, 20). **Figure 4** captures IRENA's energy pathway from the 2018–50 forecast of the energy mix of maritime fuel in a scenario intending to limit warming to 1.5 degrees.

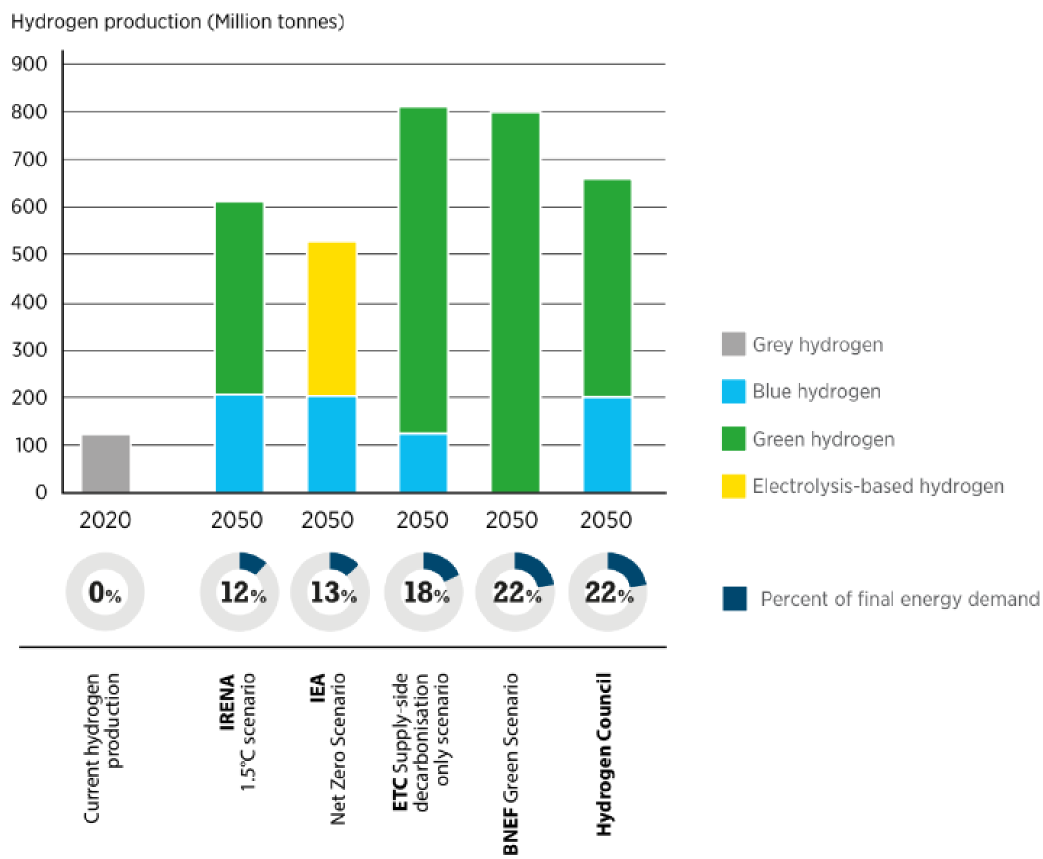


Figure 3: *The estimated share of hydrogen in global energy demands by 2050 (IRENA 2022a, 20)*

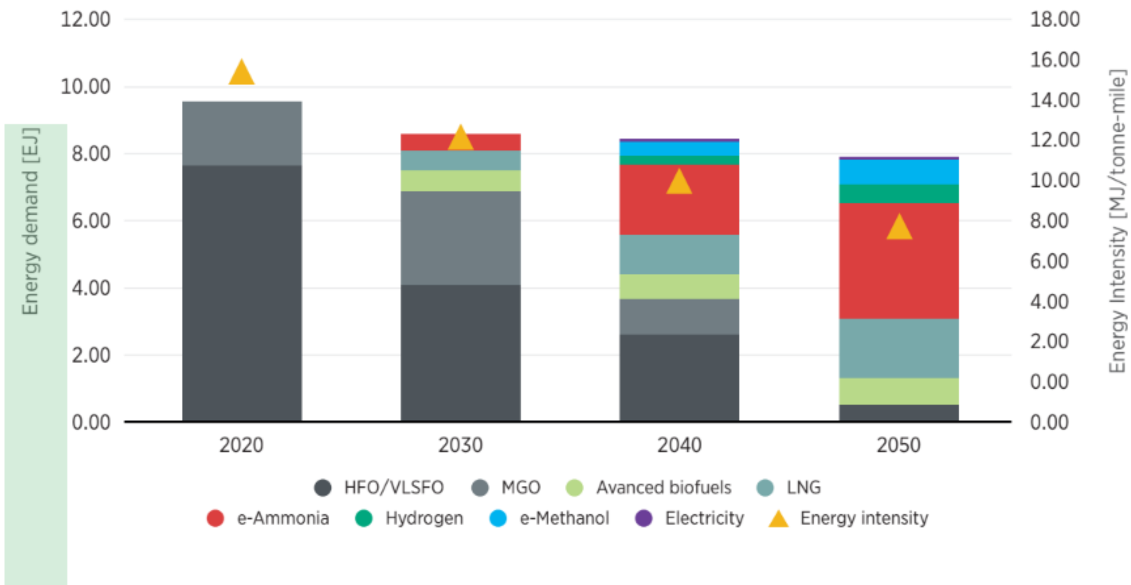


Figure 4: *IRENA's 1.5°C Scenario energy pathway, 2018–50 (IRENA 2021, 80)*

According to IRENA, hydrogen would feature on a standalone basis in the energy mix for short sailings in domestic navigations only. The fuels most suited to international shipping would be methanol and ammonia, but ammonia is considered more attractive than methanol as it is carbon-free. Renewable ammonia may become the backbone for decarbonising the maritime economy, with a purported share of close to 43% in the energy mix in 2050, with blue ammonia playing a transitional role. Ammonia may have a participation rate of more than 4.5 times over renewable methanol due to higher costs linked to emissions-free CO2 feedstock for methanol (IRENA 2021c, 14–15, 80).

DNV has also simulated 24 scenarios to explore shipping's fuels transition based on two decarbonisation pathways, one in which shipping achieves a 50% reduction in GHG emissions by 2050 consistent with the IMO GHG strategy, and another in which the fleet is decarbonised by 2050. In the second pathway, e-ammonia[2] (occupies a prominent place in the energy mix especially with low to very low costs of electrolysis and higher prices of sustainable carbon (DNV 2022, 14). The scenario is explored in detail in **Annex I**.

These scenarios show the immense potential of hydrogen-based fuels and particularly ammonia in decarbonising the maritime sector.

[2] Electrolytic ammonia, synthesised from hydrogen produced through electrolysis

CHAPTER 2. REGULATORY ASPECTS

This chapter covers the international political landscape and regulatory aspects of the adoption of hydrogen, with an analysis of existing barriers and opportunities. Regulation can be made on multiple levels: from sub-national to national, regional, and international. This chapter will focus on developments at the international level by looking at developments at the United Nations Climate Change Conference of Parties and regulations of the International Maritime Organization ("**IMO**").

Several countries have adopted hydrogen policies (cf. **Figure 5**) with varying levels of maturity and focus on the maritime sector, and a broad overview of these policies would not capture the depth and breadth of measures. Therefore, national and sub-national policies will be covered through the case studies in Chapter 5.

Figure 5*: Countries with announced policies, funding, or targets*

(Green Hydrogen Organisation 2022)

2.1. Developments at COP: Looking Back and Forward

2.1.1. COP26

The 26th Convention of the Parties to the United Nations Framework Convention for Climate Change (**"COP26"**), held in Glasgow in 2021 witnessed the launch of several maritime-related initiatives.[3] Among them is the *Clydebank Declaration*, which aims to support the establishment of green shipping corridors (see **Box 1**) between two or more ports. It currently has 24 signatories, with the intention to have six corridors by the middle of the decade (United Kingdom Department for Transport 2022a; Saul and Piper 2021). The *Just Transition Maritime Task Force* was launched to support the development of green skills of workers in the shipping industry (Christensen and Palmer 2021; DNV 2021b). Additionally, a group of companies *Cargo Owners for Zero Emission Vessels* (Koole and Blank 2021) is committed to purchasing only ocean freight services using scalable zero-carbon fuels from 2040 onwards (CoZEV 2022b; 2022a, 3). Discussions on Article 6 of the Paris Agreement on the creation of a global carbon market may also indirectly affect shipping if the IMO opts for market-based measures (DNV 2021b).

Hydrogen also received attention at COP26. The *Breakthrough Agenda* was launched by 45 countries to work towards accelerating the development and the deployment of clean technologies (Smith et al. 2021), with a specific agenda on affordable and accessible renewable and low-carbon hydrogen by 2030 (UN Climate Change Conference UK 2021). A progress report on the agenda noted the need for greater collaboration between companies and countries to achieve the outlined goals (IEA, IRENA, and UN Climate Change High Level Champions 2022). Commitments were also made by the private sector to develop a substantial electrolyser capacity of 45 GW in the short-term, potentially driving down prices to a competitive level of USD 2/kg (Koole and Blank 2021).

[3] Given that these commitments are recent, little information is available on their progress. It has been discussed wherever applicable.

BOX 1: Green Corridors

Likened to special economic zones at sea (Christensen 2022), green corridors have been defined in different ways, including as a "specific trade route between major port hubs where zero-emission solutions have been demonstrated and are supported" (Getting to Zero Coalition et al. 2021, 11; Fahnestock and Pandey 2022).

Critical building blocks for green corridors include cross-value chain collaboration, viable fuel pathways with bunkering infrastructure, market forces demanding green shipping at scale to indicate sufficient customer demand, and policy incentives accompanied by regulations (Getting to Zero Coalition et al. 2021, 11).

Green corridors can provide a strong incentive for the transition to hydrogen in the maritime sector for multiple reasons: 1) They can provide scale and volume for impact as they include essential players across the value chain; 2) They can provide offtake certainty to fuel producers facilitating the scaling of fuel production; 3) They can signal demand to vessel operators and engine manufacturers to catalyse investments; 4) They can spur the energy transition of the shipping sector with targeted regulatory and safety measures, coupled with financial incentives while promoting cross-sectoral partnerships (McKinsey and Company 2021; Getting to Zero Coalition et al. 2021, 16).

2.1.2. COP27

The 27th Convention of the Parties to the United Nations Climate Change (**"COP27"**) was held in Egypt in November 2022. It was the last COP before the IMO revises its initial GHG strategy, with potentially significant effects on the process (Climate Champions 2022). Up until COP27, more than 20 green corridor projects had been announced, more than initially envisaged by the Clydebank Declaration (Christensen and Palmer 2022). Green corridors received a further boost with Norway, the Netherlands, the United Kingdom and the United States making pledges to develop green corridors among themselves (United Kingdom Department for Transport 2022b; Messenger 2022).

Moreover, the *Joint Statement on Green Hydrogen and Green Shipping* was developed by leading organisations and initiatives across the shipping chain and by hydrogen producers. It is a pledge to decarbonise shipping by 2050 and to produce 5.5 million tonnes of green hydrogen for the shipping sector by 2030—an important step towards meeting the estimated shipping needs of 46 million tonnes by 2050 (IRENA Decarb report, p. 15). Ship owners and operators committed to investing in zero emission vessels and green shipping corridors while calling upon the IMO to match their ambition (Climate Champions 2022; MAN Energy Solutions 2022).

2.2. Regulation at the International Level: The IMO Strategy

The International Maritime Organization (**"IMO"**) is the United Nations agency responsible for regulating shipping and thus for maritime safety and international regulation on shipping emissions. In 2018, the IMO adopted an *Initial Strategy on the Reduction of GHG Emissions from Ships*, which aims to reduce GHG emissions from international shipping by 40% before 2030, and 70% by 2050, compared to the levels in 2008 (IMO 2018, 5). The strategy also contains a list of candidate short- (2018–23), mid- (2023–30) and long-term measures (2030–50). The mid-term measures include the uptake of alternative low-carbon and zero-carbon fuels (IMO 2018, 6, 8). The strategy is set to be revised in 2023 (IMO 2018, 4). The IMO also periodically conducts an assessment of GHGs and released its fourth study providing an overview of emissions between 2012-18 (IMO 2021a)**.**

The IMO has created regulations for certain indices and indicators to aid the decarbonisation of shipping, including indices tracking ship energy efficiency which promotes the decarbonisation of shipping through progressively increasing efficiency. Tracking and data collection pursuant to these indices could provide a clear picture of the operation of ships, their fuel use and the need to meet the end goal of decarbonisation. For more information on the individual indices, see **Annex II.**

The *Intersessional Working Group on the Reduction of GHG Emissions from Ships* of the IMO is working towards developing a basket of candidate mid term measures which integrate technical standards (e.g., GHG fuel standard, enhanced carbon intensity measures) with market-based measures (e.g., carbon pricing) (IMO 2022e). The Working Group is also working on GHG life cycle assessment guidelines for all relevant fuel types from well to wake, providing an overview of the environmental footprint from fuel production to its end-use on the ship (IMO 2022c).

The *Sub-Committee on Carriage of Cargoes and Containers* ("**CCC**") is working to include renewable fuels such as hydrogen and ammonia in the *International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels* which came into force in 2017 and has a focus on LNG. The CCC has also initiated the development of draft interim guidelines for ships using hydrogen and ammonia as fuels which will be further developed and finalised in 2023/24 (IMO 2022d)). Furthermore, the CCC approved *Draft Interim Guidelines for Ships Using Fuel Cells* in September 2021, which aims to ensure the safe and reliable delivery of energy through fuel cell technology (which can also use hydrogen) (IMO 2021b; 2021d).

The upcoming review of the initial GHG strategy of the IMO in 2023 will provide a clearer picture of IMO's ambitions and measures to decarbonise the maritime sector with the potential to affect the uptake of fuels like hydrogen and ammonia.

2.3. Regulatory Barriers and Opportunities

Commitments and pledges at the COPs indicate momentum from different actors in the maritime sector to decarbonise. However, some of these declarations are only being signed by a select few countries. For instance, while half of the world's shipping fleet is owned by Asian companies (UNCTAD 2021), only 2 of the 24 signatories of the Clydebank Declaration are from Asia (c.f **Figure 6**). Even though many big maritime players have joined the Declaration, the noticeable absence of China may undermine the Declaration's effects.

With the IMO set to revise its GHG strategy in 2023, political fault lines on decarbonisation goals and measures could appear during the negotiations on the level of ambition and measures (DNV 2021b). A revision of the decarbonisation goals of the IMO and the adoption of a net zero target by 2050 could signal a strong political will to decarbonise. However, as Prof. Douglas notes, even if the IMO sets ambitious targets, the actions to achieve these targets would have to be undertaken by ship owners and operators who are merely observers to IMO processes. Bodies like the *International Chamber of Shipping and the World Shipping Council*, that consist of some of the biggest shipping companies, would thus need to be involved in the process (Interview with Zachary Douglas).

Moreover, there is a significant opportunity for the IMO to update the IGF code for safely using ammonia and hydrogen, and further regulating the usage of alternative fuels on board. Market mechanisms and ambitious targets could spur the switch to alternative fuels. However, in the past, the pace of adoption of various regulations at the IMO has been very slow. Therefore, the IMO will have to act with urgency, or else shipping companies will have to take the baton—outside of the influence of the IMO.

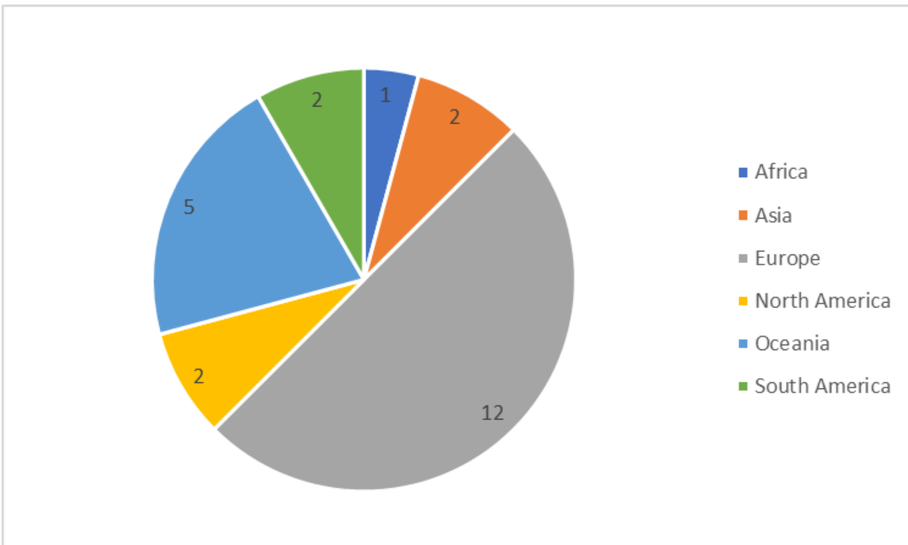


Figure 6: *Geographical distribution of Signatories to the Clydebank Declaration*

CHAPTER 3. TECHNOLOGICAL ASPECTS

This chapter covers technological aspects of hydrogen application, storage, transport, as well as safety considerations in handling hydrogen and its derivatives. These aspects are not specific to shipping or port infrastructure but are nonetheless crucial in our discussion. Hydrogen will have to be transported from production to end-use sites and stored at ports to be able to be used in shipping, and safety should be considered along the entire value chain, including during transport, storage, and onboard use. The chapter will close with a summary of the technological barriers and opportunities for adoption identified in our research.

3.1. Hydrogen Application and Safety

Hydrogen-based fuels such as ammonia, and hydrogen itself can be used in shipping in internal combustion engines, gas turbines, and fuel cells. Fuel cells are preferred over the other two applications, as intermediate steps of producing heat and mechanical work of most conventional power generation methods are avoided (Ammar and Alshammari 2018).

Hydrogen has a high flame speed and low ignition energy, and ammonia is toxic (Depken et al. 2022). Safety standards and regulations in the handling of these hazardous substances are thus necessary. However, currently, there are no IMO regulations published on the use of hydrogen and ammonia in fuel cells (cf. **2.2.**). IMO regulation only states that “alternative design approaches” are allowed to enable the adoption of innovation without corresponding rules in place (‘Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments’ 2013), which gives room to the approval of hydrogen systems.

Safety distancing of bunkering is under development. The main challenge is providing an approach that allows the standardisation of installation requirements that facilitate the deployment of fuelling infrastructure while having non-standardised designs and adapting to technological progress (Engebø et al. 2010). The current application of hydrogen at port infrastructure is limited to storage and usage in cargo handling equipment.

3.2. Hydrogen Storage

For small-scale operations, hydrogen is usually stored compressed or liquified in special tanks, which have high-discharge rates and optimal efficiency—the most commonly utilised method to store hydrogen today. However, hydrogen can also be stored in pure form in underground caverns. Such geological storage is most appropriate for large-scale and long term operations (IEA 2019, 69-70; Robinius et al. 2022).

Current hydrogen storage technology faces some important limitations. Compressed hydrogen has only 15% of the energy density of gasoline, thus requiring seven times the space to store an equivalent amount of energy (IEA 2019, 69-70). Liquified hydrogen has better energy density but needs to be liquified and maintained at -253°C, and the process of liquefaction can cause energy loss of up to 40%, while compressed hydrogen faces a loss of around 10% (Moradi and Groth 2019; Barthelemy, Weber, and Barbier 2017). Geological storage is highly dependent on local geography and infeasible in many areas (IEA 2019, 69-70; Robinius et al. 2022). Hydrogen can also be stored as ammonia or synthetic fuels. The latter has the advantage of allowing the use of fossil fuels infrastructure but face high costs in the conversion process and in sourcing of captured CO2 (Robinius et al. 2022; IRENA and AEA 2022).

Smooth operation of potential future large-scale and worldwide operations of hydrogen value chains will require a broader variety of storage options, and improvement to current technology (IEA 2019, 69-70).

3.3. Import and Transport Infrastructure

As of now, about 85% of hydrogen gas is produced and consumed on-site within a facility. However, the growing demand for green hydrogen in countries with little potential for renewable energy production will increase the demand for importing hydrogen and thus hydrogen infrastructure. However, currently, only about 5000 kilometres of hydrogen transmission pipelines exist worldwide—compared to 3 million kilometres for natural gas (IRENA 2021a, 24). According to IRENA, the distribution of transport through pipelines and on ships will be about fifty-fifty in the future (IRENA 2022a, 33, 37). The first ammonia-powered ships will, in fact, be those transporting it (Interview with Jeroen van der Veer). The best possible method of transporting hydrogen depends mainly on the location of the destination and the distance from production sites (IEA 2019, 67). Reaching large-scale transport and thus trade and end use of hydrogen will, in the short- to medium-term, be primarily restrained by a low technological readiness level and the lack of pipelines and import infrastructure at ports (KBR 2020, 16–28; Interview with Stefan Kaufmann).

3.4. Technological Timeline Mismatches

Swift development of technological capability is needed as ships that are built now will be in use for the next 25–30 years, until 2050, leading to a timeline mismatch in the maturity of the development of technology, safety standards, policy-making, and the industrial value chain.

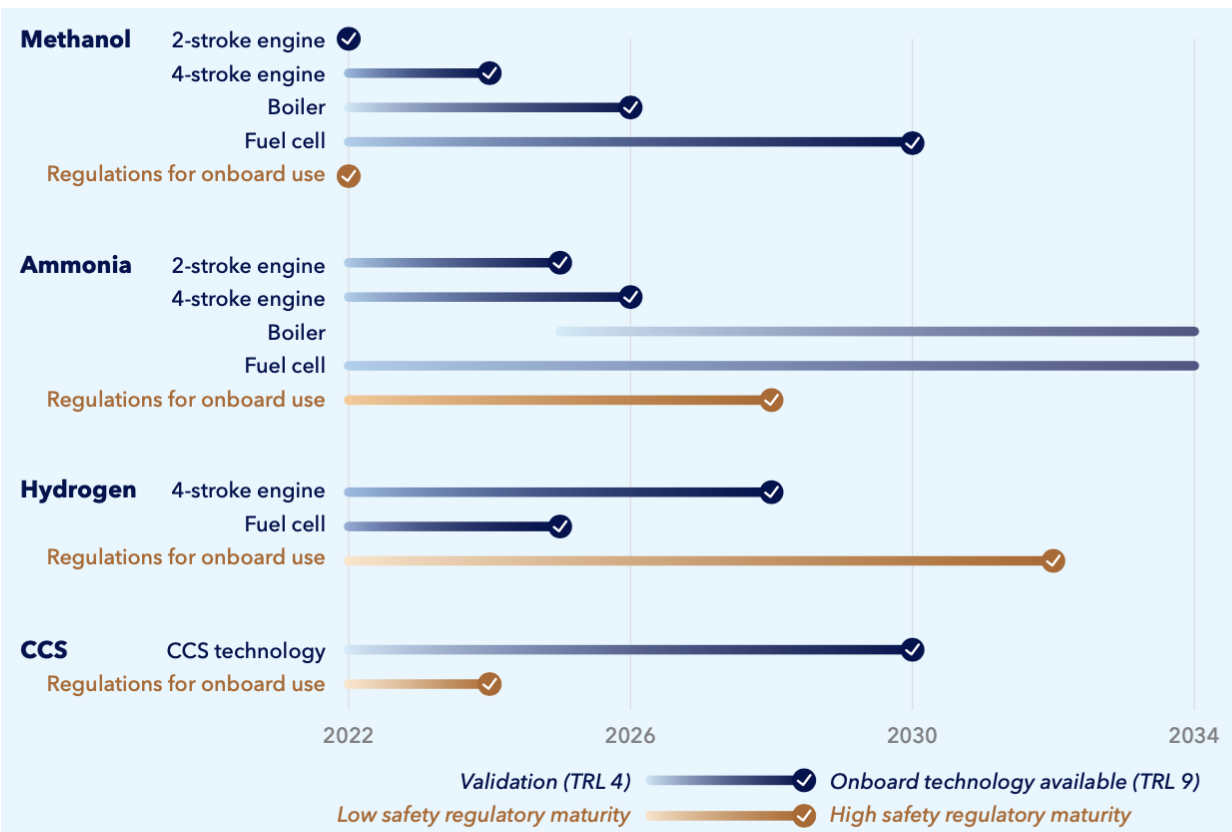


***Figure** 7: DNV estimation of maturation timelines for energy converters, onboard CCS technologies, and corresponding safety regulations for onboard use in shipping (DNV 2022, 37)*

The adoption of hydrogen-based fuels in shipping is based on the technological readiness of engines, boilers, fuel cells, and regulations for onboard use. Due to differences in maturity level, methanol is expected to be in usage much earlier than ammonia and hydrogen, with ships already in operation (DNV 2022, 34). Hydrogen-based fuel-powered ships are not ready to be used at the moment, but are likely to be in use closer to 2028. In particular, the storage problem (cf. **3.2.**) will first have to be solved (Interview with Jeroen Van der Veer).

3.5. Technological Barriers and Opportunities

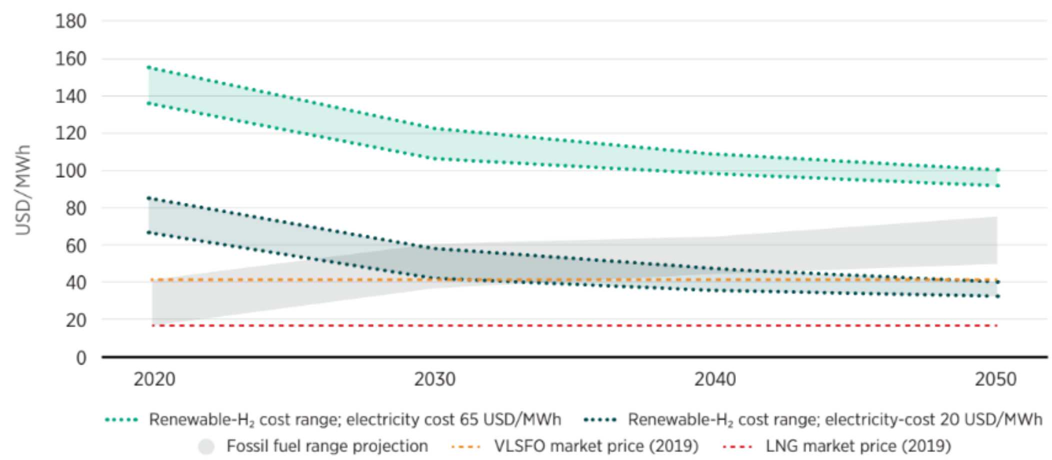
The readiness of fuel cells and corresponding safety regulations for usage is low. For example, the application of ammonia and hydrogen concerns risk in safety usage (cf. **3.1.**) which also challenges the safety designs of the equipment, i.e. fuel cells and tanks needed (DNV 2022, 37). Similarly, there is a lack of technical capacity at ports to store hydrogen, due to the costly design of storage facilities and the conversion process. There is also a decisive lack of hydrogen distribution and import infrastructure, hindering market uptake. However, the usage of existing natural gas pipelines presents opportunities for more flexible transport and import options. Rigorous research and development through demonstration projects could also fast-track standardising international regulations in design, storage, operation, and onboard use, which are needed with great urgency to enable wider use of hydrogen in shipping. Increasing renewable energy production and electrolysis capacity also presents opportunities for scaling up the production of green hydrogen.

CHAPTER 4. FINANCIAL ASPECTS: HYDROGEN ECONOMICS

Chapter 4 focuses on the financial and economic aspects of hydrogen adoption in the maritime shipping industry. In particular, it will look at projected trends in pricing and challenges, along with trade issues, and contrast market- and state-based approaches to making the price of hydrogen competitive. The chapter closes with a summary of financial barriers and opportunities to the adoption of hydrogen identified in our research—concluding the initial literature review, which will be supplemented and substantiated by the case studies in Chapter 5.

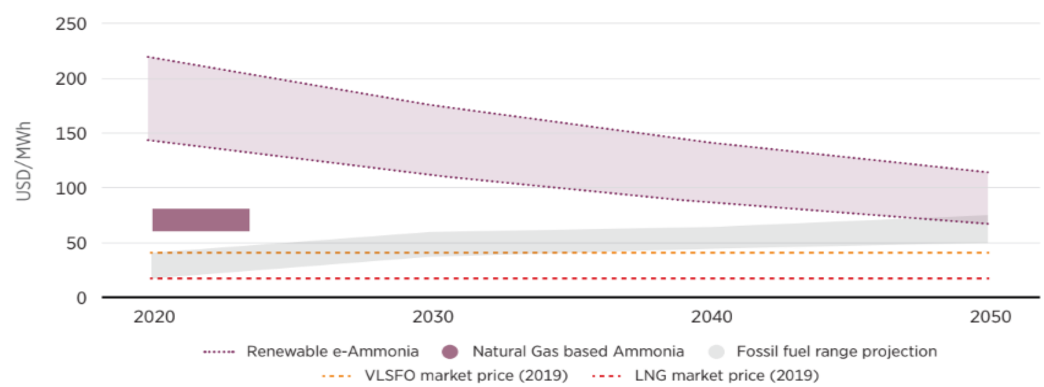
4.1. Pricing Projections and Challenges

Hydrogen has to become price competitive in order to be widely used, in the maritime sector and beyond. There are a variety of estimates on the development of green hydrogen prices. Goldman Sachs estimates that green hydrogen may achieve cost parity with grey hydrogen in advantageous regions by 2025 (at USD 1.5/kg) (Clarke and Vigna 2022, 8), compared to the current prices of USD 4-6/kg (IRENA 2021a, 7). Some predictions indicate that blue and green hydrogen or even blue and grey hydrogen prices will converge by 2030 (Delft, Nuon, and Gasunie 2018; Mackenzie 2019; Port of Rotterdam 2020, 8). IRENA expects that this competitiveness could be achieved in 3–5 years in advantageous locations (IRENA 2019). BloombergNEF concludes that the cost of green hydrogen may even be as low as USD 1.48/kg in 2030 and USD 0.84/kg in 2050 (BloombergNEF 2020, 5). **Figures 8 and 9** capture IRENA's projections for the costs of green hydrogen and ammonia respectively. It should be noted that green hydrogen would also have to be competitive with fossil fuels to ensure their replacement (Interview with Ankie Janssen). However, price sensitivity is different between sectors. While green hydrogen is expensive at an early stage, first users will be able to pay a premium of USD 2.50 or USD 3.50 per kilogram, which could be affordable to the maritime sector (Interview with Mani Sarathay).



Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.
Source: H_2: IRENA (2020a); fossil fuel cost projections: Lloyd's Register (2019)

Figure 8: *Green hydrogen cost projections (IRENA, Decarb report, p. 56)*



Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.
Source: Ammonia: IRENA (forthcoming), IRENA & AEA (forthcoming); fossil fuel cost projections: Lloyd's Register (2019)

Figure 9: *Ammonia cost projections (IRENA Decarb report, p. 68)*

Electrolyser capex may present the greatest scope for cost reduction, decreasing by 50–65% by 2030. Price reductions of renewable energy can further drive down costs of green hydrogen (Clarke and Vigna 2022, 37–38; Hydrogen Council 2020). With economies of scale looking attainable for electrolysers at 1GW/year level, other factors that could lower prices include the predictability of a pipeline of electrolysis projects and the government support in setting manufacturing capacity targets and tax benefits, grants and loans (IRENA 2022b, 73). Price transparency would also strongly support the evolution of hydrogen (IRENA 2022a, 16). This leads to a complex situation in pricing. If the state sets a requirement for green electrolytic hydrogen, subsidies may not be sufficient to lower pricing to a competitive cost (Interview with David Libatique).

4.2. Investment Needs

There are several challenges to driving up investment in the hydrogen sector. Firstly, the average lifespan of ships is about 25 years (Agnolucci, Smith, and Rehmatulla 2014, 176). However, hydrogen-based fuels and propulsion technologies will not be market-ready before 2030 (DNV 2022, 37). As shipping orders are based on shorter-term perspectives, it is unclear for the industry what ships to invest in without compromising the commercial value of ships that are in operation. The lack of long term perspective has impacted investor confidence, as indicated by the decrease in corporate maritime investments in zero-emission technologies from USD 2.7 billion in 2017 to USD 1.6 billion in 2019 (International Chamber of Shipping and Ulreich 2022, 12). Thus, there is a mismatch between the short time span of changing policies and visions in fuels and the long time span of building ships and their operation times. Secondly, there is a lack of sufficient commercial market capital at the moment, and there is a call for cohesive policy along the supply chain to assure investment confidence and for government intervention to facilitate favourable conditions and outlook for investors (IRENA 2021a, 15).

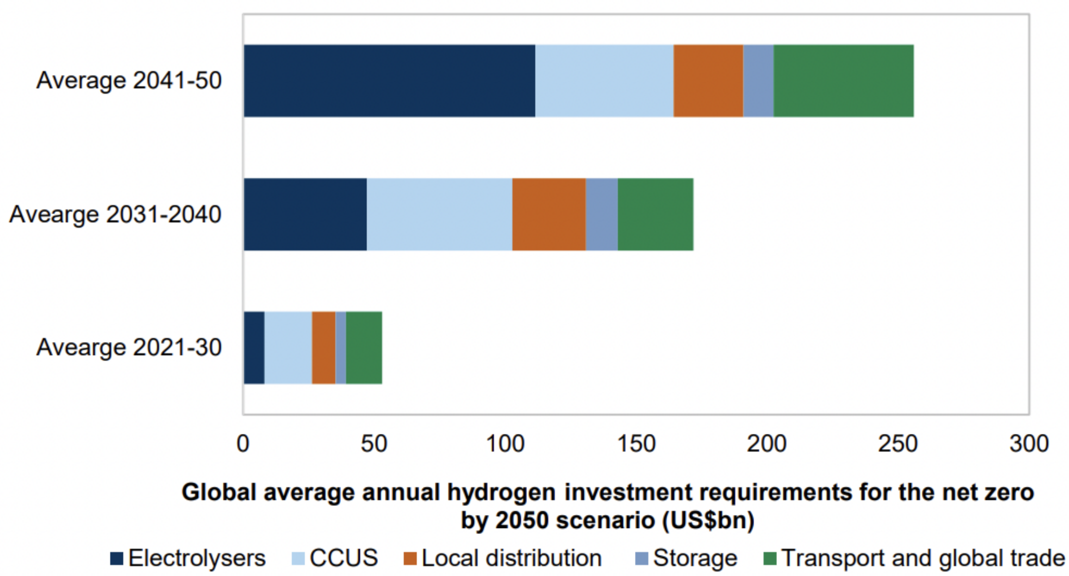


Figure 10: *Investment needs in the clean hydrogen supply chain (Clarke and Vigna 2022, 34)*

Goldman Sachs estimates that USD 5 trillion of investments will be required in the hydrogen supply chain by 2050, with an average annual investment need of about USD 60 billion in the next decade (cf. **Figure 10**) (Clarke and Vigna 2022, 7, 34). The Energy Transitions Commission even estimates a total investment need of USD 15 trillion by 2050 along the entire hydrogen value chain, 85% of which will be needed for the upscaling of the electricity production (Energy Transitions Commission 2021, 72). Thus, investments in hydrogen cannot be decoupled from simultaneous investments in scaling renewable energy. In fact, to achieve net zero carbon, up to 3000 TWh of electricity from renewable sources would be required just for shipping. This is equivalent to all of the world's current renewable energy production (International Chamber of Shipping and Ulreich 2022, 6).

4.3. Trade

Trade of hydrogen will play an important role in shaping the future of hydrogen in the maritime sector and beyond. One-third of hydrogen will be traded transnationally by 2050[4] (IRENA 2022a, 37; Clarke and Vigna 2022, 61). Many early adopters of hydrogen in shipping, such as the featured case studies of the Ports of Rotterdam and Los Angeles, Japan, and Germany, will primarily be importers of hydrogen due to a lack of opportunities for green hydrogen. Meanwhile, countries such as Chile and Namibia have positioned themselves to be large-scale hydrogen producers and exporters. Large-scale trade of hydrogen produced in low-cost production sites can have a strong effect on international hydrogen prices and incentivise change in end-use sectors.

In an age of energy insecurity, hydrogen is not only relevant to decarbonisation efforts but also to national security, and hydrogen partnerships are forming globally. The map below gives an overview of existing bilateral trade agreements. Germany and Japan have been at the forefront of forging such agreements as importers (cf. the respective case studies) (IRENA 2022a, 12). As depicted in the section on infrastructure (cf. **2.3.**), the trade of hydrogen will be limited by the availability of transport and import infrastructure such as pipelines, port storage facilities, and transport ships.

[4] This is more than the current share of natural gas traded transnationally at 24% (IRENA 2022a, 37).

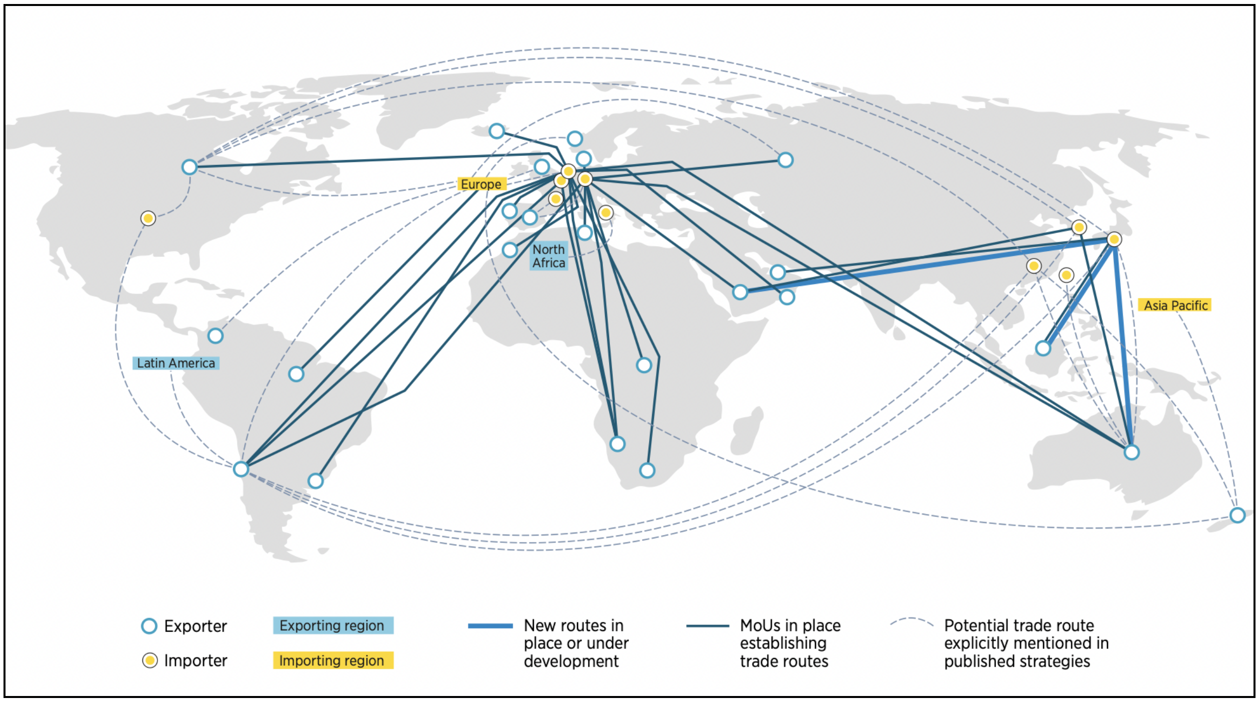


Figure 11: *Bilateral hydrogen agreements (IRENA 2022a, 37).*

4.4. Market- vs State-Based Approaches

There are two main approaches to making the necessary market off-take structures bankable and thus ensuring sufficient demand and supply for green hydrogen in the maritime sector.

The first approach is market-based, using carbon pricing to drive up the costs of fossil fuels and fossil fuel-based hydrogen, negating market risk for green hydrogen. This is noted in the case of Germany (Interview with Stefan Kaufmann). Carbon pricing may take different forms, including specific taxes on fuel use, explicit carbon taxes with tax rates for energy use based on carbon content, and emission allowances traded in emission trading systems ('Energy Taxation, Carbon Pricing and Energy Subsidies' 2022, 11). Such measures may incentivise relevant stakeholders in shipping and port infrastructure to reduce emissions (Interview with Giacomo Luciani). Redistribution of revenue from carbon levy to subsidise shipping and port industry stakeholders would also contribute to narrowing the price gap.

Recent publications suggest that carbon pricing alone is insufficient and further policy instruments will be needed ('Making Renewable Hydrogen Cost-Competitive: Policy Instruments for Supporting Green H_2' 2021, 16). Even if European carbon prices reach EUR 200 per tonne, natural gas would still be the cheapest option out of all forms of hydrogen production. A minimum of EUR 300 per tonne is needed to reach the break-even threshold for hydrogen technologies and green hydrogen would need a carbon price of EUR 100 per tonne to break even with fossil fuel based hydrogen in 2030 (cf. **Figure 12**) ('Making Renewable Hydrogen Cost-Competitive: Policy Instruments for Supporting Green H_2' 2021, 15–16). Estimations are carried out under the assumption of a natural gas price at EUR 20 per tonne and carbon capture rate for fossil-based hydrogen at 75%.

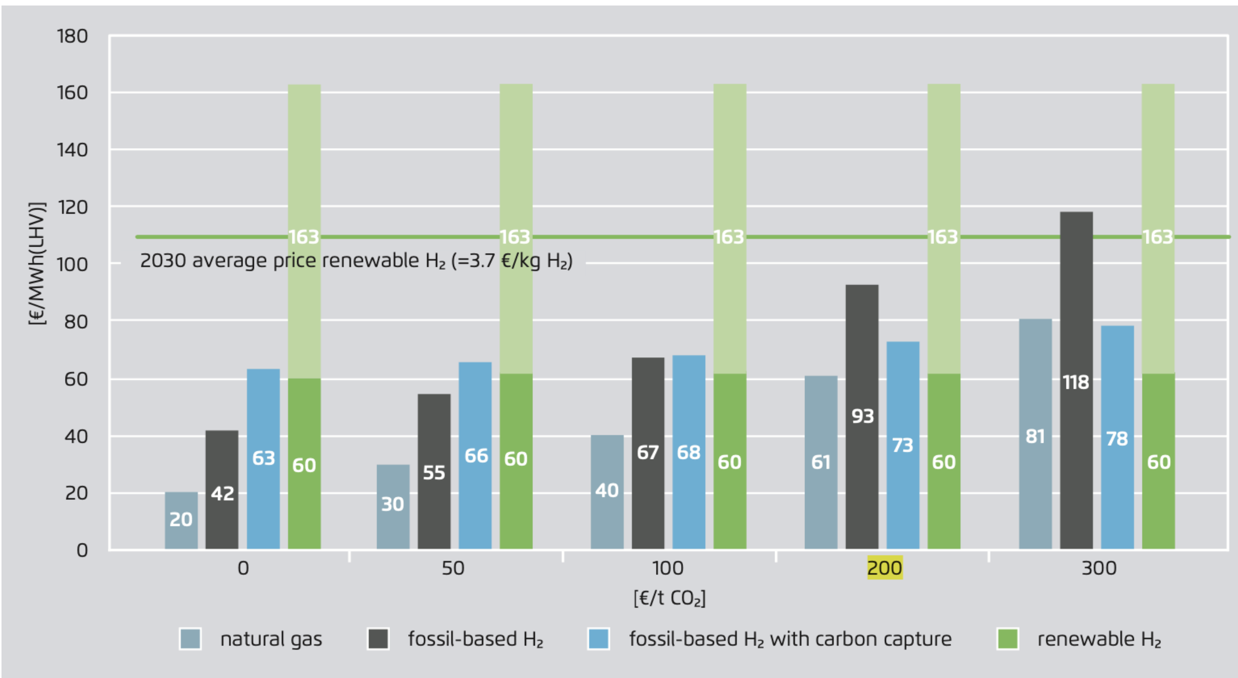


***Figure 12**: Impact of carbon pricing on hydrogen production costs in 2030*[5] *('Making Renewable Hydrogen Cost-Competitive: Policy Instruments for Supporting Green H_2' 2021, 15)*

The second approach is state-based. It emphasises the significance of overriding policy objectives and the role of governments in bridging investment gaps through subsidies, removing early-adoption barriers through private-sector risk management, and sending out a strong policy signal to align actors along the supply chain, to quickly scale up green hydrogen deployment ('Making Renewable Hydrogen Cost-Competitive: Policy Instruments for Supporting Green H_2'

[5] Estimations are carried out under the assumption of a natural gas price at EUR 20 per tonne and carbon capture rate for fossil-based hydrogen at 75%.

2021, 63). Levelised cost of hydrogen through government funding could also help finance early movers (Interview with Stefan Kaufmann).

However, it has also been shown that state regulations such as the excise tax on natural gas proposed by the European Commission are not sufficient alone to achieve a market uptake of green hydrogen and would have to be significantly higher to do so. Similarly, an exemption from levies on renewable electricity cannot alone make green hydrogen cost-competitive (George et al. 2022, 8). Loopholes in regulations, for example not counting shipping emissions in national climate policies in the case of the EU, excludes the sector from receiving government funding for adopting alternative fuels (Interview with Ankie Janssen).

Therefore, innovative measures to account for emissions, minimise price uncertainty and address investment risk are needed.

4.5. Financial Barriers and Opportunities

The financial barriers to making market off-take structures essentially boil down to the classic chicken-and-egg question. However, adopting Carbon Contracts for Differences (**"CCfDs"**) presents an opportunity to break the vicious cycle.

A carbon contract is a contract by which a government or institution agrees with an agent on a fixed carbon price over a given time period, where the agent can sell any carbon emission reductions at that given price (Gerres and Linares 2020, 2). The contract pays out the difference between the carbon price and the agreed strike price, which becomes the CCfDs, thus effectively ensuring a guaranteed carbon price (Joern Constantin Richstein 2017, 4).

Existing literature finds that on top of stringent carbon pricing, exercising CCfDs would have complementary benefits and break the chicken-and-egg situation. Auctions for CCfDs using the European Union Emissions Trading System (**"EU ETS"**) would allow selected, hard-to-abate industries under the scheme to secure a stable income for an agreed period, provided they use green hydrogen. Stakeholders will then bid for a strike price, and receive the difference between that and the market price of the emission allowances from the government. This would cover the costs of green hydrogen investments, attract financing, and reduce the risks associated with the upscaling of technology of early movers (Jörn C. Richstein and Neuhoff 2022, 8; Bianco and Hawila 2021).

BOX 2: Chicken-and-Egg Question in Hydrogen Pricing

Both pricing and the financing of market off-take structures face the chicken-and-egg question. Suppliers are waiting for the production infrastructure for green hydrogen to materialise, while high cost inhibits demand. However, without securing a pool of demand and a clear outlook of a market that has yet to exist, investment on large-scale infrastructure is considered to be too risky. This leads to uncertainty about the availability and price of future volumes of green hydrogen.

Private investments face the challenges of: 1) Costs for off-take structures; 2) Higher operation and investment costs than conventional carbon-intensive processes; and 3) Insufficient and uncertain carbon prices owing to incomplete risk markets (Greenwald and Stiglitz 1986; Jörn C. Richstein and Neuhoff 2022). Market risk thus prevents potential off-takers from committing to contracts that might lock them into paying fuel at higher-than-market rates.

Demand usually follows when the price of green hydrogen breaks even with fossil fuel based hydrogen. However, how to allow early-movers to overcome investment risks and materialise the necessary infrastructure to lower the production cost without sufficient investment becomes a classic chicken-and-egg question.

CHAPTER 5. CASE STUDIES

This chapter will delve into four case studies: Germany, Japan, the Port of Rotterdam (the Netherlands), and the Port of Los Angeles (USA).

5.1. Germany

In 2019, the German Government announced its *Climate Action Programme 2030* ("*Klimaschutzprogramm 2030*"), setting the goal of reducing greenhouse gas emissions by 55% compared to 1990 by 2030 in an economically and socially sustainable way ("Just Transition")—for which hydrogen will play an important role (German Federal Government 2019). To that end, the German Government released a *National Hydrogen Strategy* ("*Nationale Wasserstoffstrategie*") in 2020 (German Federal Ministry for Economic Affairs and Energy 2020). It includes an action plan of 38 measures, covering the entire hydrogen value chain[6].

Germany has been chosen as a case study as it has relatively mature hydrogen policies and a strong economy with incentives and the financial ability for change. Although the Strategy does not place a major focus on the maritime sector, many policies and lessons learned from other sectors could be applied there as well. The literature review is supplemented by an interview with Dr Stefan Kaufmann, who currently works for ThyssenKrupp, and is the former Innovation Commissioner for Green Hydrogen (2020–2022) for the German Federal Ministry of Education and Research, supporting the implementation of the National Hydrogen Strategy.

5.1.1. Pricing

The Strategy identifies a fast international market ramp-up as essential in making green hydrogen competitive. To that end, a national market needs to be established first. Of 90 and 110 TWh of green hydrogen necessary by 2030,[7] roughly 14 TWh will be produced domestically, with the rest being imported (German Federal Ministry for Economic Affairs and Energy 2020, 5). The price of hydrogen imports will have a significant impact on the uptake and structure of a

[6] The Strategy focuses on green hydrogen. However, it acknowledges that a purely green hydrogen market within Europe is unlikely in the next decade and that carbon-free hydrogen such as blue hydrogen will play an intermittent role also in Germany (German Federal Ministry for Economic Affairs and Energy 2020, 3).

[7] Current use is about 55 TWh, mostly grey hydrogen produced as by-products (and thus not easily replaced by green hydrogen). Only 7% of hydrogen (3.85 TWh) is currently produced via electrolysis and is thus green (German Federal Ministry for Economic Affairs and Energy 2020, 10).

hydrogen economy in Germany (Peterssen et al. 2022). With this in mind, Germany has made hydrogen a thematic focus in 18 of its over 20 energy partnerships—including Canada, Chile, Norway, and Qatar (German Federal Ministry for Economic Affairs and Climate Action 2022c, 53; 2022d; German Federal Ministry for Economic Affairs and Energy 2021).[8]

The German government aims to support domestic production and lower hydrogen prices through multiple measures including: 1) Raising the CO_2 price for fossil fuels in transport (primarily in road transport but not yet in shipping) to de-incentivise their use and production. 2) Funding electrolysers; 3) Designating additional areas that can be used to generate offshore electricity for hydrogen production; and 4) An exemption from taxes, levies and surcharges for electricity used to produce green hydrogen. To that end, renewable energy for hydrogen production was exempted from the EEG surcharge[9] in 2021. (German Federal Ministry for Economic Affairs and Energy 2020, 16–17; German Federal Ministry for Economic Affairs and Climate Action 2022c, 27–30).

The Government acknowledges that these measures will not suffice in the short- to medium-term and will have to be supplemented by subsidies to close the price gap. There are no concrete measures for this yet (German Federal Ministry for Economic Affairs and Climate Action 2022c, 37).

According to Dr Kaufmann, the demand for green hydrogen within Germany will be driven mainly by heavy industry such as steel production in the short-term. However, the maritime mobility sector will also be able to benefit from the bigger market.

5.1.2. Use in Maritime Mobility

The Strategy only contains one short paragraph on maritime shipping specifically. The nine transport-related measures focus mostly on air and road transport. However, some measures may be applied directly to maritime shipping: 1) Harmonising standards for hydrogen and fuel cell use in mobility (including ship certification), 2) Funding for projects related to the use of green

[8] The *German Federal Ministry for Economic Affairs and Energy* was renamed *German Federal Ministry for Economic Affairs and Climate Action* in December 2021. They represent the same institution.

[9] The EEG surcharge is a measure of the German government to finance the expansion of renewable energy production. Power plant operators receive a fixed remuneration rate for renewable energy that they feed into the grid. The difference to the market price is then paid for by customers through the EEG surcharge (German Federal Ministry for Economic Affairs and Climate Action 2022b).

hydrogen. Such projects have started running.[10] While furthering technological development, hydrogen-related pilot projects can also inspire market confidence (German Federal Ministry for Economic Affairs and Energy 2020, 19–25).

The lack of focus of the German Government on maritime shipping could be due to the low level of maritime infrastructure and ports in Germany relative to roads. However, the Government has recognised the potential of hydrogen in maritime transport (Interview with Stefan Kaufmann; Elise Zoli at the Monaco Hydrogen Forum).

The maritime sector will also play a role in the import of hydrogen and ammonia by ship, on which Germany will depend (see **Figure 11**). However, Dr Kaufmann noted the risks associated with the storage of ammonia in ports which are closely integrated into cities. As 80% of hydrogen imported to Germany will likely be in the form of ammonia, ports with little surrounding residential area will be most suitable (Interview with Stefan Kaufmann; Karalis 2022).

5.1.3. Import and Transport Infrastructure

Within Germany, hydrogen will mainly be transported through the existing and well-developed natural gas pipeline network and storage facilities that are no longer in use, and infrastructure developed and built especially for hydrogen (German Federal Ministry for Economic Affairs and Energy 2020, 7, 13). A first step to ensure such development has been the reform of the *German Energy Act* ("*Energiewirtschaftsgesetz*") (German Federal Ministry for Economic Affairs and Climate Action 2022c, 28). Dr Kaufmann stressed the need for government financing of such hydrogen infrastructure possibly including harbouring and port infrastructure—as this cannot be covered by the private sector. According to his estimates, about EUR 20–30 billion are needed for this.

5.1.4. Funding of the Strategic Goals

The National Hydrogen Strategy provides significant funding for research and development along the entire green hydrogen value chain. Over EUR 3 billion is going to be provided over the coming decade for green hydrogen production, research, and investment in hydrogen use in the

[10] Examples include: The world's first emission-free push boat, called ELEKTRA-II. It is hybrid-powered by battery and hydrogen and is currently running in its test phase in Berlin (NOW GmbH 2022; Küper 2022).

industry. EUR 7 billion are earmarked for a market ramp-up of hydrogen technologies and EUR 2 billion for international hydrogen partnerships. Moreover, the Strategy sets the frame for private investment. (German Federal Ministry for Economic Affairs and Energy 2020, 2–3). This funding constitutes an important contribution to the multi-trillion funding gap found in the hydrogen economy until 2050—although much more will be needed in the long term.

5.1.5. The Regional and International Level: EU and beyond

Fundamental regulatory issues, including standard setting, certifications, and changes to the EU Emissions Trading System, will have to be tackled at the EU level. Moreover, a harmonisation across the EU and an "interlocking" (Westphal, Dröge, and Geden 2020, 3) of the national hydrogen economies will be necessary.

BOX 3: The EU Hydrogen Strategy

The EU published a *Hydrogen Strategy* (COM/2020/301) in July 2020, followed up by a *Sustainable and Smart Mobility Strategy* (COM/2020/789) in December of the same year and the *Fit for 55* package in July 2021, which is comprised of concrete legislative proposals for the implementation of the action points of the strategies. These will play an important part in reaching the EU's goal of reducing GHG emissions by 55% by 2030 by spurring the uptake and competitiveness of sustainable fuel production and creating a level playing field within the EU (European Commission 2020a; 2020b; European Council and Council of the European Union 2022a).

Concrete proposals of Fit for 55 include but are not limited to: 1) A reduction of GHG emissions of vessels over 5,000 gross tonnes by 6% by 2030, going up to 75% by 2050 (the *FuelEU maritime initiative*) (European Council and Council of the European Union 2022b); 2) The inclusion of emissions from maritime transport in the EU Emissions Trading System (European Council and Council of the European Union 2022a).

On the EU level, a new *Important Project of Common European Interest* (IPCEI) for hydrogen technology and systems was launched in December 2020, with over 18 registered countries (German Federal Ministry for Economic Affairs and Climate Action 2022a), an important step for the development of a hydrogen economy in the region. However, Dr Kaufmann noted that the German National Hydrogen Strategy and the EU Hydrogen Strategy were launched around the same time and thus had little direct influence on each other—showing that possible synergies are not yet used to their full potential.

5.2. Japan

5.2.1. Background

Energy security and historical context characterise the rapid development of hydrogen in the context of Japan (Interview with Katsuhiko Hirose). Due to the poor availability of natural resources and the closure of many nuclear plants after the earthquake of 2011, Japan has relied heavily on the import of fossil fuels ('Japan 2021 Energy Policy Review' 2021, 13). In order to meet the goals of the Paris Agreement and to avoid similar structural vulnerability to the previous two oil crises, the "3E+S" hydrogen strategy was developed—encompassing energy security, economic efficiency, environment, and safety ('Basic Hydrogen Strategy' 2017).

Japan aims to become a net hydrogen importer, to establish a full-scale international hydrogen supply chain to cut the cost of hydrogen by 2030 through economies of scale ('Focus on Hydrogen: Japan's Energy Strategy for Hydrogen and Ammonia' 2022). One of the main goals highlighted is to upgrade existing networks of ports with the technical capacity to receive hydrogen tankers, reducing the cost of hydrogen use in the long term.

The vast network of infrastructure established is enabled through a consolidated effort led by the government, establishing road maps, financing mechanisms, and rigorous R&D funding. This brought in stakeholders along the value chain.

5.2.2. Progressive Government Leadership

In December 2017, the Ministry of Economy, Trade, and Industry (**"METI"**) of Japan issued the world's first national hydrogen strategy, the *Basic Hydrogen Strategy*. It documents the vision that both public and private sectors should share in realising a hydrogen-based society in 2050. The Basic Hydrogen Strategy originated from The fourth Strategic Energy Plan adopted in 2014 that aimed to establish a road map toward the realisation of a "hydrogen society". The *Council for a Strategy for Hydrogen,* comprising representatives of industry, academia, and government officials, then compiled a Strategic Roadmap for Hydrogen and Fuel Cells (the **"Strategic Roadmap"**). It aims to harmonise action plans to be adopted by the public and private sectors and establish a policy framework for an integrated international supply chain by 2030 encompassing production, transportation and storage, and consumption, and sourcing both blue and green hydrogen for industrial consumption in Japan ('The Strategic Road Map for Hydrogen and Fuel Cells' 2019, 3). It includes cost breakdown targets for the fundamental technologies required in research and development, technical demonstration needed to realise a hydrogen supply chain, and technical development targets needed to meet the commercialisation phase in the future ('The Strategic Road Map for Hydrogen and Fuel Cells' 2019).

In 2020, the METI issued the *Green Growth Strategy through Achieving Carbon Neutrality in 2050* (the "Green Growth Strategy") which was subsequently updated in June 2021. It positions hydrogen and ammonia at the core of the strategy as "new resources" to reduce dependency on fossil fuels. For hydrogen, it aims to increase annual consumption to 3 million tonnes per year by 2030 and 20 million tonnes per year by 2050 ('Green Growth Strategy Through Achieving Carbon Neutrality in 2050' 2021, 53). For ammonia, it aims to increase annual consumption to reach 3 million tonnes per year (equivalent to 500,000 tonnes of hydrogen) in 2030 and 30 million tonnes per year by 2050 (equivalent to 5 million tonnes of hydrogen) ('Green Growth Strategy Through Achieving Carbon Neutrality in 2050' 2021, 63).

In addition, the *Environment Innovation Strategy* was published in 2020, aiming to incentivise private enterprises to invest JPY 240 trillion (USD 1.77 trillion) needed for the ambitious targets set in the Green Growth Strategy and important for closing the hydrogen funding gap. This is expected to generate economic benefits of about JPY 140 trillion in 2030 and about JPY 290 trillion in 2050 ('Green Growth Strategy Through Achieving Carbon Neutrality in 2050' 2021, 4). In 2021, the Government also established policies for the Green Innovation Fund, to allocate JPY 2 trillion to provide continuous support to companies aligned with the policy objectives, from R&D through demonstration to social implementation ('Green Growth Strategy Through Achieving Carbon Neutrality in 2050' 2021, 9).

5.2.3. Shipping and Port Infrastructure

Japan aims to realise the commercial operation of zero-emission ships before 2028, by using hydrogen fuel cell ships and full battery-powered ships, and convert to using hydrogen and ammonia as fuel for ships from 2028 to 2050. Demonstration of hydrogen fuel cell ships will take place from 2021–25, while hydrogen and ammonia-fuelled cell engines are still undergoing technological development ('Summary of Japan's Hydrogen Strategy' 2021).

The Port of Kobe is leading the efforts in adopting green hydrogen. It has already accommodated Japan's first hydrogen import terminal on the airport island for the Japanese venture Hystra. The terminal is designed with a 2,500m^3 storage tank that can hold 150 tonnes of liquefied hydrogen, and a loading facility. The Port of Kobe also accommodated the world's first liquefied hydrogen carrier, *Suiso Frontier*, which travelled from Australia to Japan in 2022. The ship was completed in 2020 as part of the Hydrogen Energy Supply Chain pilot project.

Currently, the Port of Kobe is looking into building hydrogen import, storage, and supply infrastructure for a targeted 2030 start-up as part of efforts to assist the proposed fuel shift inside the port and adjacent areas through receiving hydrogen tankers (Matthé, Jain, and Pierre 2021, 4). The long term goal of the Japanese Government is to upgrade the network of ports to receive tankers with hydrogen and reduce the cost of the resource through economies of scale. Targeted financing in creating a vast network of infrastructure is needed in the absence of a merchant market and market off-take structures (Interview with David Morant). In terms of adopting green hydrogen in port operation, Japanese shipping firm Mitsui OSK Lines and engineering firm Mitsui E&S Machinery Co., Ltd. have agreed to jointly study the adoption of hydrogen-fuelled port cargo handling machines at the Port of Kobe (Mitsui O.S.K. Lines 2021).

5.2.4. Technical standards

Given the robust R&D funding, and well-orchestrated set of policies, Japan is already promoting the standardisation of hydrogen station-related products by actively submitting proposals to the International Organization for Standardization (**"ISO"**), and will be at the forefront of regulatory development of technical standards ('Green Growth Strategy Through Achieving Carbon Neutrality in 2050' 2021, 58).

5.3. Port of Rotterdam

5.3.1. Background

The Port of Rotterdam is the largest port in Europe (Port of Rotterdam 2022b). It also accounts for 6% of international bunkering and is a significant container port globally. The Port could thus play a critical role in decarbonisation (IRENA 2021c, 36–38) and could also act as a pioneering model for other ports (David Morant at the Monaco Hydrogen Forum). The port is moreover a gateway for imports of energy to Germany and other customers (Port of Rotterdam 2020, 5). With these reasons in mind, and the relatively mature hydrogen policies of the Netherlands, the Port of Rotterdam was selected as a case study. An interview with Ankie Janssen, Program Manager Alternative Fuels at the Port of Rotterdam, supplements the insights from the literature review.

5.3.2 Dutch Hydrogen Policies

The Netherlands has the ambitious goal of reducing 49% of its GHG emissions by 2030 and 95% by 2050, compared to 1990 levels, contained in the Climate Act of 2019 (Government of the Netherlands 2019a). To this end, the Dutch Government adopted a range of measures, which are discussed below, in addition to a specific hydrogen strategy.

The National Climate Agreement

The Dutch Climate Agreement is an agreement between organisations and companies to combat climate change. With a dedicated section on (primarily green) hydrogen, it envisages hydrogen as a critical part of the economy, including for shipping in the long term (Government of the Netherlands 2019b, 180). The Agreement envisions a programme which will scale electrolyser capacity to 3–4 GW by 2030 (Port of Rotterdam 2020, 6). The first phase of the programme includes research and development for hydrogen, monitoring the development of the business case for electrolysis, a review of hydrogen demand development, and a certification system. The government will contribute EUR 30–40 million per year for demonstrations and pilot projects from the Climate Budget funds, and include it in the SDE++ scheme (cf. below) when hydrogen is able to compete with other fuels in the scheme (Government of the Netherlands 2019b, 181–83).

The Dutch Hydrogen Strategy

The Dutch Hydrogen Strategy was published in April 2020. The strategy is built on 4 pillars: 1) Legislation and regulation, with a focus on market regulation to ensure security of supply, guarantees of origin, and certification for zero-carbon hydrogen; 2) Cost reduction and scaling up, covering support schemes for research and allocation of EUR 35 million for hydrogen pilot projects to achieve price reductions of 50–60%; 3) Sustainability of final consumption focusing on *inter alia* the ambition of Dutch ports to prepare for hydrogen's role in its operations and the EU Green Deal's role in stimulating hydrogen's use in shipping and ports; and 4) Supporting and flanking international policy by the European Commission, and bilateral cooperation with neighbouring states on hydrogen (The Government of the Netherlands 2020, 5–8, 10–13).

5.3.3. Financial Schemes

Carbon Pricing and Carbon Levy

The EU Emissions Trading System ("**EU ETS**") currently does not include emissions from shipping companies but there are plans to do so (cf. **Box 3**). This would affect both EU and non-EU ship operators and companies due to the extra-territorial effects of the ETS scheme (Norton Rose Fulbright 2021). Additionally, the Netherlands has imposed a CO_2-levy on industry emissions, to complement the EU ETS and hasten the adoption of green fuels like hydrogen through incentivising R&D investments. However, it is noted that the carbon levy alone will not be sufficient to tip the breakeven point in the industrial sector (OECD 2021).

The SDE++ Subsidy Scheme

The SDE++ subsidy scheme of the Dutch Government is intended to spur the production of renewable energy and the application of CO_2 reduction techniques, including in the mobility sector of EUR 3 billion distributed through this subsidy (OECD 2021), which will be awarded over a period of 12–15 years and covers hydrogen by electrolysis among other technologies (Netherlands Enterprise Agency 2022). The current application round is now closed and only a negligible share of applications concerned green hydrogen. Moreover, the scheme alone is not sufficient to incentivise investment in green hydrogen because of the large initial investment. Supplementary funding from other sources such as the Dutch National Growth Fund or the EU Important Projects of Common European Interest (**“IPCEI”**) could offer a solution (OECD 2021).

Effects of pricing policies and current developments

According to Ankie Janssen, the EU Fit for 55 programme (cf. **Box 3**) gave a big push to hydrogen, but shipping emissions should be integrated into climate policies of national governments, on which funding for alternative fuels could depend. However, funding would not be automatic because of the high costs associated with building new vessels or refitting old vessels. The current funding gap is almost 100% and even reductions of 20–30% of the extra costs would not be a sufficient incentive for shipping companies. Additionally, infrastructure development in the port area appears to be more popular than shipping from a funding perspective (Interview with Ankie Janssen).

The extremely high current prices of LNG are compelling a reassessment of its use as a transition fuel. Cargo owners would transition towards using alternative fuels if high fuel and carbon prices drive up commodity prices. Opex would also have to be reduced for hydrogen-based fuels and capex and opex would have to match fossil fuels for hydrogen to take off (Interview with Ankie Janssen).

5.3.4. Vision and Programmes at Port of Rotterdam

Dubbed ‘the energy port of Northwest Europe’ (Port of Rotterdam 2021b), the Port of Rotterdam can supply Europe with 4.6 megatonnes of hydrogen by 2030 (Port of Rotterdam 2022c; 2022e, 2). The Port’s vision for hydrogen encompasses both industry and mobility. The Port is planning a 2 gigawatt conversion park for green hydrogen with market parties and estimates that the demand for hydrogen via Rotterdam for maritime shipping could be 3.2 metric tonnes per year in 2050. For clean transport, the vision of the Port is to support the development of hydrogen bunker stations for inland vessels as part of the RH2INE project discussed below (cf. **Box 4**) (Port of Rotterdam 2020, 1-2,5).

The Port of Rotterdam is involved in the creation of a *Port Readiness Level for Alternative Fuels for Ships*. The tool will assist ship operators in assessing the availability of alternative fuels to plan bunkering calls. It has nine levels of readiness in three categories (International Chamber of Shipping 2022; World Ports Sustainability Program 2022). At levels 1–3, a port is in the preliminary stage of developing capacity for alternative fuels; levels 4–6 signify the development stage, design of safety frameworks, and demonstrations; at levels 7–9, a port is ready to bunker safely. At the port of Rotterdam, ammonia is currently at levels 3–4, with expected demonstrations in 2024–25. However, green hydrogen is behind ammonia and will take 2–3 years more to become viable (Interview with Ankie Janssen).

5.3.5 Import and Partnerships

The Port has a joint venture with Pecém Industrial Port Complex in Brazil to create a green hydrogen hub to supply 2.2 million tonnes of green hydrogen over the next decade and is developing additional import terminals for green hydrogen (Port of Rotterdam 2022a). There are also plans to triple the capacity for ammonia imports and will invest in port-side ammonia to hydrogen cracking facilities and additional ammonia infrastructure and import terminals (Jones et al. 2022, 34, 53). It has also signed agreements with Chile (Port of Rotterdam 2021a), Namibia (Hydrogen Central 2021), and Tasmania (Barnett 2021), among others.

A study pertaining to the Port of Rotterdam found that the import of ammonia could be cost-effective compared to local production but the import of LOHC and gaseous hydrogen would be more expensive than local production. However, if the Port cannot meet the demand for hydrogen, imports could supplement local production. It would also need significant amounts of renewable electricity to produce hydrogen (van Kranenberg and Schipper 2022, 12,15,17).

The Port has also created green corridor synergies with other ports. It has joined hands with CEPSA in Algeciras, Spain to create the first hydrogen green corridor between North and South Europe (CEPSA 2022) and with Singapore to create the world's longest green corridor for zero-carbon shipping (Port of Rotterdam 2022d). Despite the push towards green methanol, there is an inadequate supply of the fuel, prompting a switch to the green corridor strategy at the Port to monitor the demand and supply of fuels and incentivise stakeholders on particular maritime routes (Interview with Ankie Janssen).

BOX 4: RH2INE Project

The Rhine Hydrogen Integration Network of Excellence (**"RH2INE"**) is an initiative of the Dutch Province of Zuid-Holland and the German State of North Rhine-Westphalia. It is a comprehensive corridor approach focused on synergies between energy, transport, and telecommunications by realising market-ready applications of hydrogen. The initiative will promote infrastructure development and conditions for using hydrogen for the inland transport chain, including inland shipping, freight transportation, and last-mile transportation by rail and road (RH2INE 2022c). Even though the corridor is for inland transportation, some findings are still relevant for the maritime value chain.

A RH2INE Kickstart Study found that bunkering of hydrogen on inland waterways in Germany and the Netherlands was not allowed and that specific rules and regulations for hydrogen liquid tankers and bunker vessels, hydrogen-fueled vessels, and hydrogen bunkering activities are absent from the port by-laws of EU ports and harbours (DNV 2021a, 62), while they exist for LNG at the Port of Rotterdam (DNV 2021a, 38). As such, needs for standardisation, closing regulatory gaps, and organising logistical processes as the main topics for the near future are identified (RH2INE 2022a; DNV 2021a). The plan recommends a corridor-focused approach, market initiatives to implement hydrogen bunkering and retrofit vessels, cooperation along the value chain, and policy measures such as subsidies and taxes to improve the business case of hydrogen usage in shipping which is still more expensive than its fossil fuel counterparts (RH2INE 2022b).

5.4. Port of Los Angeles

5.4.1. Background

The Port of Los Angeles is the busiest container port in North America, and operates as a landlord port with more than 200 tenants, generating its revenues from leases and shipping fees (Port of Los Angeles 2022). The Port of Los Angeles is an interesting case study to explore the uptake of hydrogen solutions in the context of port infrastructure and port-connected activities, due to the presence of developed decarbonisation policies, and hydrogen demonstration projects already being underway.

In addition to the literature review, the team separately interviewed David Libatique, the Deputy Executive Director of Stakeholder Engagement for the Port of Los Angeles, and Michael J. Galvin, the Director of Waterfront and Commercial Real Estate at the Port of Los Angeles.

5.4.2. Port Decarbonisation policies and legislation

The Port of Los Angeles (together with the Port of Long Beach) has a Clean Air Action Plan (**"CAAP"**) as part of its sustainability objectives, which include emission reduction aims. The first version of CAAP was born in 2006 from the need to protect public health by improving air quality. Its latest update, released in 2017, stems from a thorough understanding of the need for decarbonisation (San Pedro Ports Bay 2017) and is the result of extensive outreach to local communities, environmental justice groups, elected officials, and other regulatory agencies (San Pedro Ports Bay 2017; Interview with Michael Galvin). In its latest version, the CAAP aims for zero emissions for cargo handling equipment by 2030, and for on-road drayage trucks serving the ports by 2035 (San Pedro Ports Bay 2017).

According to David Libatique, the CAAP is not a regulation, but a voluntary action with tenants and partners of the ports (Interview with David Libatique). While the policy is not enforceable by law, it can still be implemented through leases (Interview with Michael Galvin). However, David Libatique remarked that there is interaction between regulations and policy actions, and even discussions on potential state regulations can boost the CAAP and drive tenants in their decarbonisation efforts (Interview with David Libatique). For example, at the state level, the port stated it will be engaged in the rulemaking process with the California Air Resources Board (San Pedro Ports Bay 2017), while, at the local level, the decarbonisation plans at the Port of LA interact with and are encouraged by the Los Angeles Green New Deal (**"pLAn"**) (Garcetti 2019; Interview with David Libatique).

5.4.3. Hydrogen for Port Infrastructure

While all cargo handling equipment has to produce zero emissions by 2030, the Port is agnostic to the technology used by tenants. At the moment, hydrogen is one of the solutions being explored in such projects to pursue the CAAP goals. Hydrogen has the potential of mimicking well current cargo equipment operations and refuelling characteristics. It is being explored together with electrification measures, and there is competition and complementarity between the different measures depending on the operations. Hydrogen is viewed as a better solution than electrification when the time to refuel and recharge could be cumbersome and necessitate the purchase of more equipment to accommodate current operational practices. Hydrogen provision is being handled directly by the tenants carrying out hydrogen projects, who need to understand if there is going to be a consistent supply of hydrogen at a reasonable rate and price (Interview with David Libatique; Interview with Michael Galvin).

Drayage trucks also have to produce zero emissions by 2035. Here, the port can supervise their decarbonisation by controlling emission requirements of trucks coming into their facilities, as it concerns port operations (Interview with Michael Galvin). A demonstration project for drayage trucks powered by hydrogen fuel cells was started in 2021 (Port of Los Angeles 2021). The USD 82.5 million project began its rollout with five hydrogen-powered fuel cell electric vehicles (**"FCEV"**) and two hydrogen fueling stations and is seen as a model for developing and commercialising such equipment. The project is equally financed by the public and private sectors (Port of Los Angeles 2021).

5.4.4. Hydrogen for Shipping

At the moment, hydrogen-based solutions to decarbonise maritime transport in Los Angeles pertain mostly to port infrastructure and operations. However, CAAP includes incentives to promote decarbonisation for ships operating at the port, including improving efficiency in energy consumption and installing emission reduction technologies. The plan proposes to start charging rates for ships that reach the port based on environmental characteristics, although not earlier than 2025 (San Pedro Ports Bay 2017).

Currently, the Port of Los Angeles is developing a green corridor partnership with the port of Shanghai, which is a collaboration between port authorities, host cities, shipping lines, cargo owners, and terminal operators. It aims to introduce a zero-carbon vessel by 2030. However, which fuel will be used to achieve this is still to be decided, with methanol and ammonia being considered. Additionally, the Port of Los Angeles has no plans regarding the handling of hydrogen bunkering operations at the moment (Interview with Michael Galvin; Interview with David Libatique).

5.4.5. Financial Issues and Cooperation

Despite a high degree of interest in hydrogen for port infrastructure, market confidence remains an issue. Together with its tenants, the Port of Los Angeles is working towards creating market confidence through hydrogen demonstration projects by demonstrating equipment viability and directing more state and federal funding into testing equipment to allow its commercialisation (Interview with Michael Galvin; Interview with David Libatique).

It is estimated that prices will have to reach USD 2/kg for hydrogen to become competitive at the Port of Los Angeles. Hydrogen has the potential to break the "chicken-and-egg" cycle if 1) There are sufficient investments in hydrogen equipment; and 2) The demand side shows sufficient market confidence in technology. Then, the supply side will chase the demand, provided that there are sufficient tax breaks. The government (on a state or federal level) thus needs to make an initial investment on the demand side through grants, and allow tax incentives for the supply side (Interview with Michael Galvin; Interview with David Libatique).

The Port of Los Angeles is cooperating with multiple stakeholders on a state-level board to build a Californian hydrogen ecosystem. Stakeholders are working to gain an understanding of necessary state-wide infrastructure and the potential hydrogen supply-demand equilibrium within the hub, and most importantly how to direct funding correctly (Interview with Michael Galvin).

According to Michael Galvin, over USD 20 billion will be needed to build the hydrogen system in California. Recently, California hydrogen stakeholders convened under the Alliance for Renewable Clean Hydrogen Energy Systems (**"ARCHES"**) with the objective of channelling part of the USD 8 billion funding package dedicated to hydrogen hubs from the federal Infrastructure Investment and Jobs Act (**"IIJA"**). While such effort is positive, they remain aware that they cannot get overly focused on only one source (Arches H2 2022; Interview with Michael Galvin).

5.4.6. Social Acceptance of Hydrogen

David Libatique flagged the consideration of social and political acceptance of hydrogen at the Port of LA in addition to regulatory, technological, and financial aspects. For example, environmental justice groups that are active in the port complex are much more supportive of batteries as they are already very familiar with existing state regulation and city policies on electrification. Ammonia operations would also face political opposition as the areas around the Port of LA are densely populated, and safety issues would raise concerns. On the other hand, labour unions of port workers are more likely to support hydrogen infrastructure compared to electrification, which they view as a pathway to automatisation.

BOX 5: Additional Case Studies of Interest

The following will give a brief overview of other countries and ports which would constitute interesting case studies because of their policies or potential for hydrogen development.

1) As the second busiest ports in the world (World Shipping Council 2022), **Singapore's ports** are important for developing a hydrogen refuelling infrastructure and its use in shipping. The ports are looking into becoming a hydrogen hub, but policies and their implementation are not mature yet (KBR 2020; World Maritime News 2020).
2) Some countries such as **Chile** and **Namibia** have plans to become green hydrogen production hubs and are relevant across the maritime value chain. For example, Chile has a national strategy with maritime decarbonisation as a medium term goal of hydrogen application (Government of Chile 2020). These countries are interesting from the production perspective but not yet from the maritime perspective.
3) The planned Saudi Arabian **city of Neom** launched the construction of the world's largest green ammonia project this year, to operate from 2026 and produce 1.2 million tonnes of ammonia per year (NEOM 2022; ACWA POWER 2022). Additionally, Neom's strategic position on the Red Sea and plans to develop a port would make it a favourable case study on production and maritime mobility once policies and projects are in place.
4) Given the significant role of the private sector in the transition to green hydrogen in the maritime sector, a closer look at companies such as the world's biggest container shipping company **Maersk** and **DNV**, one of the leading classification societies for shipping, could be informative.

CHAPTER 6. ANALYSIS

This chapter will provide considerations on opportunities and barriers to the adoption of green hydrogen and green hydrogen-based fuels in shipping and ports, as emerged from the case studies.

6.1. Regulatory Opportunities and Barriers

The role of the state differs significantly between the case studies. The Japanese Government overall takes a strong role in orchestrating policies that align public and private sector interests. On pricing issues, the German and Dutch governments on the other hand favour market-based measures such as carbon pricing, while acknowledging the need for some state intervention to close the price gap in the short-term.

The optimal combination of measures will thereby largely depend on the governance structure and culture of the respective country. Moreover, differing policy priorities of certain countries such as a focus on energy security (Germany) or a strong decarbonisation culture (Los Angeles/California) will strongly influence policy-making.

It was observed that hydrogen policies to date are relatively vague, and even where clear or relatively mature policies exist, they are focused on infrastructure development in general with sparse mention of maritime decarbonisation. Hydrogen use in ports and shipping is currently not a priority in many national hydrogen strategies and, in particular, safety guidelines are lacking. Early movers would be needed in this sector as well. In the case studies, significant amounts of hydrogen will be needed in the next five years and time is of the essence. Concrete policies are needed to scale-up domestic hydrogen production and create governance structures for policy implementation. The increase in bilateral hydrogen partnerships, however, can be seen as an important first step. National policies can also create opportunities for sector coupling. As such, creating national hydrogen policies with a broad outlook on hydrogen production and application within a country is beneficial.

Lastly, regional and international frameworks to facilitate trade and create a level playing field for counties play a crucial role in the future of the hydrogen market. There is an opportunity to interweave national hydrogen economies and align national policies with these frameworks to harness synergy effects. Moreover, opportunities for the harnessing of signalling effects and strengthening market confidence can be observed in the case studies, such as carrying out pilot projects and signing agreements and memoranda of understanding with hydrogen suppliers.

6.2. Technological Opportunities and Barriers

The case studies confirmed the technological barriers identified in Chapter 3. Concerns about a lack of hydrogen infrastructure are reflected in the cases of the Port of Los Angeles, the Port of Rotterdam, and Germany, where there is a need for bunkering infrastructure at ports, and large-scale storage facilities for hydrogen and ammonia. Only Japan has the capacity to install import terminals for hydrogen and receive hydrogen tankers so far.

A lack of technical capacity can, however, be countered by demonstration projects, which presents opportunities to boost investor confidence. Examples can be seen with cargo handling equipment using green hydrogen in the case studies of the Port of Los Angeles and Japan. The pioneering of a toolkit to assess port readiness level for alternative fuels also presents an opportunity to move forward with the adoption from a technological standpoint, as illustrated in the case of Port of Rotterdam.

Ports have immense potential in accelerating the use of green hydrogen through coupling offshore wind farms as a production facility and become suppliers of hydrogen ('Energy Transition Outlook 2022. A Global and Regional Forecast to 2050.' 2022, 237), and to power green mobility in port logistics as in the case of Japan and the Port of Los Angeles. However, there is still a lack of port infrastructure that is required (Interview with David Morant), as well as compatible wind farm technologies at the scale forecasted ('Port Energy Supply for Green Shipping Corridors' 2020, 26–27).

6.3. Financial Opportunities and Barriers

Across case studies on Japan, Germany, and the Port of Rotterdam, it was found that there is a clear focus on financing infrastructure development through the creation of necessary offtake infrastructure such as refuelling and bunkering stations and electrolyser capacity, which could significantly drive down costs. This financing is often in collaboration with the market or startups and SMEs, which can be an opportunity to integrate stakeholders into hydrogen development and leverage market dynamics.

Market mechanisms were recognised as critical in reducing prices of hydrogen, even if the prices cannot be tipped over to reach breakeven prices. Even with the EU ETS system not including maritime emissions in its current scope, carbon pricing could make conventional fuels relatively more expensive and divert investments towards clean fuels like green hydrogen or offshore electricity production in general.

Government subsidies have been identified as another important factor in driving down the prices of hydrogen and ammonia. However, even in developed countries such as The Netherlands, subsidies alone would be insufficient for the technology to break even on investments In Germany and the Port of Rotterdam, the effects of a combination of market measures and subsidies, although necessary, would be either inadequate to drive down costs to desired levels or uncertain, thus affecting investment decision-making. More funding from governments and the mobilisation of private investments could bring the necessary breakthrough.

The chicken-and-egg situation in pricing was also a thread in case studies, showing the importance of ramping up demand through inspiring investor confidence in the technology and that the supply-side economics of hydrogen would then follow to bring down prices. However, the demand and supply of hydrogen are uncertain even with pledges and ambitions being announced.

Lastly, it is clear that renewable electricity is insufficient to meet maritime demand for hydrogen. However, there is recognition of the need to invest in renewable energy, the lack of which will be a critical barrier to scaling green hydrogen.

6.4. Other Opportunities and Barriers

Some of the other opportunities and barriers identified are cross-cutting in nature or do not directly fit into any of the above categories. When questioning how to upscale hydrogen in shipping and port infrastructure, the need for stakeholder cooperation along the value chain is an element that emerged in all case studies. For instance, the German Government consulted with the private sector when drafting the National Hydrogen Strategy—however, the maritime sector was left out of this consultation. Moreover, in the cases where hydrogen development has been moving the fastest, cooperation has been a key element. This can be seen in Japan's *Council for a Strategy for Hydrogen*, comprising representatives from industry, academia, and government officials, and in the Port of Los Angeles' collaboration with many different stakeholders in establishing a hydrogen hub in California.

Maritime green corridors are another example. They are a form of cooperation with the potential to greatly upscale the adoption of green hydrogen and green hydrogen-based fuels in shipping. Green corridors combine regulatory, financial, and technical aspects—helping to understand the readiness and feasibility of different fuels and technical options, how to interweave international and local regulation, and how to establish market confidence in greening shipping. Moreover, the establishment of green corridors promotes cooperation between port authorities, ship owners and operators, and can set examples for the implementation of decarbonisation practices in the whole sector.

Lastly, the dimension of social and political acceptance of hydrogen has to be considered. In the case of the Port of Los Angeles, labour unions' positive perception of hydrogen could constitute a political opportunity, while doubts from local environmental groups and the local population could hinder adoption. Generally, human security concerns are expected to play an important role, especially in the case of ammonia-related operations, which would be perceived as dangerous. As noted also in the case of Germany, ports closely surrendered by residential areas will be less suitable to host operations such as ammonia import.

CHAPTER 7. RECOMMENDATIONS AND CONCLUSIONS

Noting the existing barriers and opportunities in regulatory frameworks, technological development, and financial incentives presented in this report through conducting a literature review, case studies, and interviews with experts, we have identified eight action points for relevant stakeholders involved in the transition process.

We *recommend* the following policy measures to:

1. *Harmonise* the use of vocabulary, standards and classifications of relevant terminologies in the hydrogen market used in regulatory frameworks;
2. *Establish* and *advance* industry and localised hubs for fostering academic and pragmatic exchange on hydrogen regulatory, technical and financial development between academia, stakeholders along the value chain and government representatives;
3. *Utilise* and *develop* synergies that arise between the national, regional, and international level by:
   (a) *Strengthening* cooperation, *fostering* multilateral exchange, and *aligning* policy objectives on the three levels through:
   (i) Investigating and mapping transformative sectors that will participate in the international hydrogen market, which allows cross-sector coupling to benefit from the development of a consistent and broader network of hydrogen infrastructure,
   (ii) Harmonising and consolidating national hydrogen strategy action plan across sectors and visions of development, including the revision of national by-port laws to facilitate bunkering and storage of alternative fuels,
   (iii) Prioritising the development of short-distance and regional networks of infrastructure through green corridor agreements and export-import agreements,
   (b) *Developing* inclusive climate ambition and targets at the international level which can be co-opted by all maritime states and stakeholders along the mobility value chain;
4. *Develop* a robust regulatory framework and cohesive standards with regard to the use of alternative fuels in maritime shipping and ports within the instruments of IMO, by:

(a) *Adopting* new technical standards in the use of fuel cells, engines, tankers, fueling stations, and necessary infrastructure through:

(i) Encouraging innovation through R&D funding and demonstration projects to realise technological breakthroughs,

(ii) Encouraging countries to submit regulatory guideline proposals to ISO,

(iii) Fostering timely revision of ISO technical standards, and facilitate IMO to adopt applicable standards rapidly, to signal and guide stakeholders within the maritime sector in the transition process,

(b) *Adopting* certification systems and safety standards and guidelines for bunkering and onboard use of hydrogen and ammonia through:

(i) Consulting independent experts and entities in assurance and risk management, and industry trade associations,

(ii) Revising guidelines and standards overseen by the Sub-Committees of the Maritime Safety Committee, including Carriage of Cargoes and Containers (**"CCC"**), Ship Design and Construction (**"SDC"**), Ship Systems and Equipment (**"SSE"**),

(c) *Incorporating* decarbonisation targets and the use of alternative fuels into the work plan at the bi-annual IMO General Assembly;

5. *Urge* governments to adopt a progressive revision of pricing strategy to make the price of green hydrogen economically competitive with fossil fuels based hydrogen, and fossil fuels by:

(a) *Introducing* suitable strategies under context through measures including but not limited to:

(i) Applying stringent carbon pricing measures i.e. ETS, with policies to prevent carbon leakage,

(ii) Redistribution of revenue from carbon levy to subsidise stakeholders in the industry,

(iii) Adopting CCfDs to grant guaranteed carbon prices to industry stakeholders,

(b) *Focusing* on both the capex and opex expenses of hydrogen and ammonia to make it match with fossil fuels;

6. *Facilitate* the financing of market-off take structures and a vast network of infrastructure needed in the hydrogen market by:
    (a) *Adopting* risk-sharing management practices in public-private partnerships,
    (b) *Applying* auctions for CCfDs using an emissions trading system to cover the costs of green hydrogen investments, and reduce the risks associated with the upscaling of technology of early movers,
    (c) *Formulating* a communication strategy to strengthen social acceptance and address investment risks;
7. *Scale up* renewable energy and hydrogen production, storing and transportation infrastructure to meet the demand for green fuels in the maritime sector by:
    (a) *Investing* in renewable energy infrastructure and production that aligns with national energy policy and action plan,
    (b) *Incentivising* electrolyser capacity,
    (c) *Scaling up* dedicated transportation channels and repurposing existing gas infrastructure to allow hydrogen distribution to end-use sectors;
8. *Upskilling* and *retraining* of seafarers and workers in the sector to achieve a just transition and overcome labour reluctance to the adoption of green hydrogen, making the process more inclusive.

ANNEXES

Annex I: List of scenarios from DNV Maritime Forecast to 2050

The DNV scenarios are based on two decarbonisation pathways, namely one in which shipping achieves a 50% reduction in GHG emissions by 2050 consistent with the IMO GHG strategy, and another in which the fleet is decarbonised by 2050 (DNV 2022, 60). The scenarios simulate the following fuel family variations:

1) Availability of sustainable biomass to produce biofuels;
2) Availability of renewable electricity to produce e-fuels; and
3) Fossil fuels with CCS to produce blue fuels.

In each variation, DNV ascribes a high or very high fuel price to one fuel family over others to account for the uncertainty in pricing of these fuels. Three cost variations for each fuel type explore the differences in relative costs between fuels within each family. For producing carbon-based electrofuels, the sustainable carbon feedstock price is used which is higher than the lower-cost CO2 from biogenic sources. To reflect potentially higher production costs, a higher price for bio Marine Gas Oil ("**MGO**") and bio-LNG is used relative to methanol. Lastly, a higher LNG price is used to reflect higher costs compared to other fossil fuels (DNV 2022, 60).

DNV's findings from the scenarios contain several pertinent observations. First, the report finds that regulatory policies and primary energy prices would be key for the uptake of carbon-neutral fuels which needs to pick up in the mid 2030s. Secondly, given the uncertainties in prices and availability of different types of fuels, it is hard to decide a clear winner from among the various carbon neutral fuels but the report outlines the enabling conditions for each fuel type. While sufficient availability of biomass would determine the competitiveness of bio-methanol, bio-LNG or bio-MGO, low availability would make these fuels lose out to blue and electro fuels (DNV 2022, 13–14).

For electrofuels (including e-ammonia), the report identifies the prerequisite of sufficient renewable energy to produce hydrogen by electrolysis. This would require phasing out of fossil fuels in power generation as even electricity partly reliant on fossil fuels would be less energy efficient and lead to higher emissions. In the absence of sustainable carbon which can be combined with green hydrogen to produce e-MGO, e-methanol or e-LNG (which are more energy dense), e-ammonia or green ammonia would become the preferred fuel (DNV 2022, 13–14).

Decarbonization Pathway	Fuel family variation	Specific fuel cost variation	Scenario No.
IMO ambitions	Very Low bio		1
	Very Low bio	+ 20% bio-MGO and bio-LNG	2
	Low bio		3
	Low bio	+20% bio-MGO and bio-LNG	4
	Very Low electro		5
	Very Low electro	+150% to 200% e-MGO, e-LNG, e-methanol	6
	Low electro		7
	Low electro	+150% to 200% e-MGO, e-LNG, e-methanol	8
	Very Low fossil and blue		9
	Very Low fossil and blue	+20% LNG	10
	Low fossil and blue		11
	Low fossil and blue	+20% LNG	12
Decarbonization by 2050	Very Low bio		13
	Very Low bio	+20 % bio-MGO and bio-LNG	14
	Low bio		15
	Low bio	+ 20 % bio-MGO and bio-LNG	16
	Very Low electro		17
	Very Low electro	+150% to 200% e-MGO, e-LNG, e-methanol	18
	Low electro		19
	Low electro	+150% to 200% e-MGO, e-LNG, e-methanol	20
	Very Low fossil and blue		21
	Very Low fossil and blue	+20% LNG	22
	Low fossil and blue		23
	Low fossil and blue	+20% LNG	24

Figure 13*: DNV scenarios for maritime energy mix in 2050, share of energy use per fuel type (DNV 2022, 60)*

For the purpose of this project, it can be seen from Figure 10 that e-ammonia occupies a prominent place in the energy mix in scenarios 17-20 alongside e-MGO (produced with sustainable carbon and electrolytic hydrogen) and bio-LNG and bio-methanol (produced with biomass). These feature in the envisaged decarbonisation scenario of net zero emissions by 2050. These are all scenarios with low to very low costs of electrolysis and e-MGO, e-LNG and e-methanol having higher costs by 150-200% due to higher prices of sustainable carbon from biogenic sources or air capture (DNV 2022, 13–14). Interestingly, hydrogen does not feature as a standalone fuel but is a necessary component for e-fuels.

Annex II: IMO Indicators

The IMO has adopted some indicators and indices to monitor and increase ship efficiency and achieve reduction of GHG emissions. These include the Energy Efficiency Design Index ("**EEDI**") and the Ship Energy Efficiency Management Plan ("**SEEMP**"), adopted for all ships in July 2011 under Annex VI of The International Convention for the Prevention of Pollution from Ships ("**MARPOL**")(IMO 2022b). Further amendments to Annex VI were adopted in June 2021, putting in place measures to calculate the Energy Efficiency Existing Ship Index ("**EEXI**") and establish an operational carbon intensity indicator ("**CII**"), which will come into effect from 01 January 2023 (IMO 2021c). These are discussed below.

EEDI: The Energy Efficiency Design Index (EEDI) promotes the use of more energy efficient equipment and engines for new ships. New ship designs are required to meet the reference level for their ship type, which will be progressively tightened every five years. The C02 reduction level of 10% in the first phase started in 2015, followed by a reduction level of 20% in 2020. The third phase with a 30% reduction level was to commence in 2025, but was brought forward to 2022 for certain kinds of ships. This is against a baseline representing the average efficiency of ships built between 2000 and 2010 (IMO 2019; 2022b).

SEEMP: The Ship Efficiency Management Plan (SEEMP) is an operational measure with a mechanism to improve a ship's energy efficiency with cost efficiency. Ships can voluntarily use the Energy Efficiency Operational Indicator (EEOI) as a monitoring tool to manage ship and fleet efficiency over time (IMO 2022a; 2022b).

EEXI: The Energy Efficiency Existing Ship Index (EEXI) indicates the energy efficiency of a ship compared to a baseline for ships of 400 gross tonnage or above, in accordance with different values for ship types and categories. The EEXI attained will be compared to a required EEXI based on an applicable reduction factor relative to the EEDI baseline, and the attained EEXI should be below the required EEXI (IMO 2022f; 2021c).

CII: The Carbon Intensity Indicator Rating (CII) will determine the annual reduction factor to ensure continuous improvement of the operation carbon intensity of a ship within a rating level, The intensity will be rated from A (superior performance) to E (inferior performance). A ship rated D for three years or E for a year will have to submit a corrective plan to align with level C. Administrations and port authorities are encouraged to provide incentives to ships rated A or B. A range of measures are available for ships to get a higher rating, including but not limited to running on low-carbon fuel. The effectiveness of the CII and the EEXI will be reviewed in 2026, both of which are supported by numerous guidelines (IMO 2022f; 2021c).

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Interviews and Panel Discussion

Interviews conducted, sorted by date (dd/mm/yyyy):

DATE	NAME	AFFILIATION	FORMAT
12/05/2022	Prof. Giacomo Luciani	IHEID	In person, Geneva
27/05/2022	Jonas Moberg	Green Hydrogen Organisation	In person, Geneva
31/08/2022	Mani Sarathy	ENOWA	Videoconferencing
21/09/2022	Ankie Janssen	Port of Rotterdam	Videoconferencing
26/09/2022	David Morant	Belfast Maritime Consortium	Videoconferencing
27/09/2022	Herman Sondhi	FOWE Eco Solutions	Videoconferencing
17/10/2022	David Libatique	Port of Los Angeles	Videoconferencing
21/10/2022	Jeroen van der Veer	DNV	Videoconferencing
28/10/2022	Prof. Zachary Douglas	IHEID	In person, Geneva
14/11/2022	Michael J. Galvin	Port of Los Angeles	Videoconferencing
14/11/2022	Dr Stefan Kaufmann	ThyssenKrupp	Videoconferencing
17/11/2022	Prof. Katsuhiko Hirose	HyWealth	Videoconferencing

Presentation and panel discussion conducted at the Monaco Hydrogen Forum:

22/11/2022	Dr Stefan Kaufmann	ThyssenKrupp	In person, Monaco
	Dr Gokce Mete	South Pole	
	David Morant	Belfast Maritime Consortium	
	Dr Yasmeen Najm	ENOWA	
	John Rossant	Monaco Hydrogen Alliance	
	Hermant Sondhi	FOWE Eco Solutions	
	Elise Zoli	Wilson Sonsini	