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REDUCTION OF GHG EMISSIONS FROM SHIPS

Vol. 1: The potential of zero-carbon bunker fuels in developing countries

Submitted by the World Bank

SUMMARY

Executive summary:	This document presents the World Bank report *Vol. 1: The potential of zero-carbon bunker fuels in developing countries.* The report examines a range of zero-carbon bunker fuel options that are considered to be major contributors to shipping's decarbonized future and concludes that green ammonia and green hydrogen are the most promising options today. Furthermore, the report finds that many countries, including developing countries, are very well positioned to become future suppliers of these zero-carbon bunker fuels. By leveraging their potential, these countries would be able to tap into an estimated USD 1 trillion + future fuel market while decarbonizing and modernizing their own domestic energy and industrial infrastructure. The report highlights the need for strategic policy interventions to unlock these potentials.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 3
Related documents:	MEPC 77/7/19; MEPC 77/INF.22; and MEPC 77/INF.24

Introduction

1 This document presents the World Bank report *Vol 1.: The potential of zero-carbon bunker fuels in developing countries.*

2 The key findings of this report are provided in document MEPC 77/7/19 submitted by the World Bank.

Action requested of the Committee

3 The Committee is invited to note the information contained in this document, in particular the conclusions put forward in the report annexed to this document.

***

ANNEX

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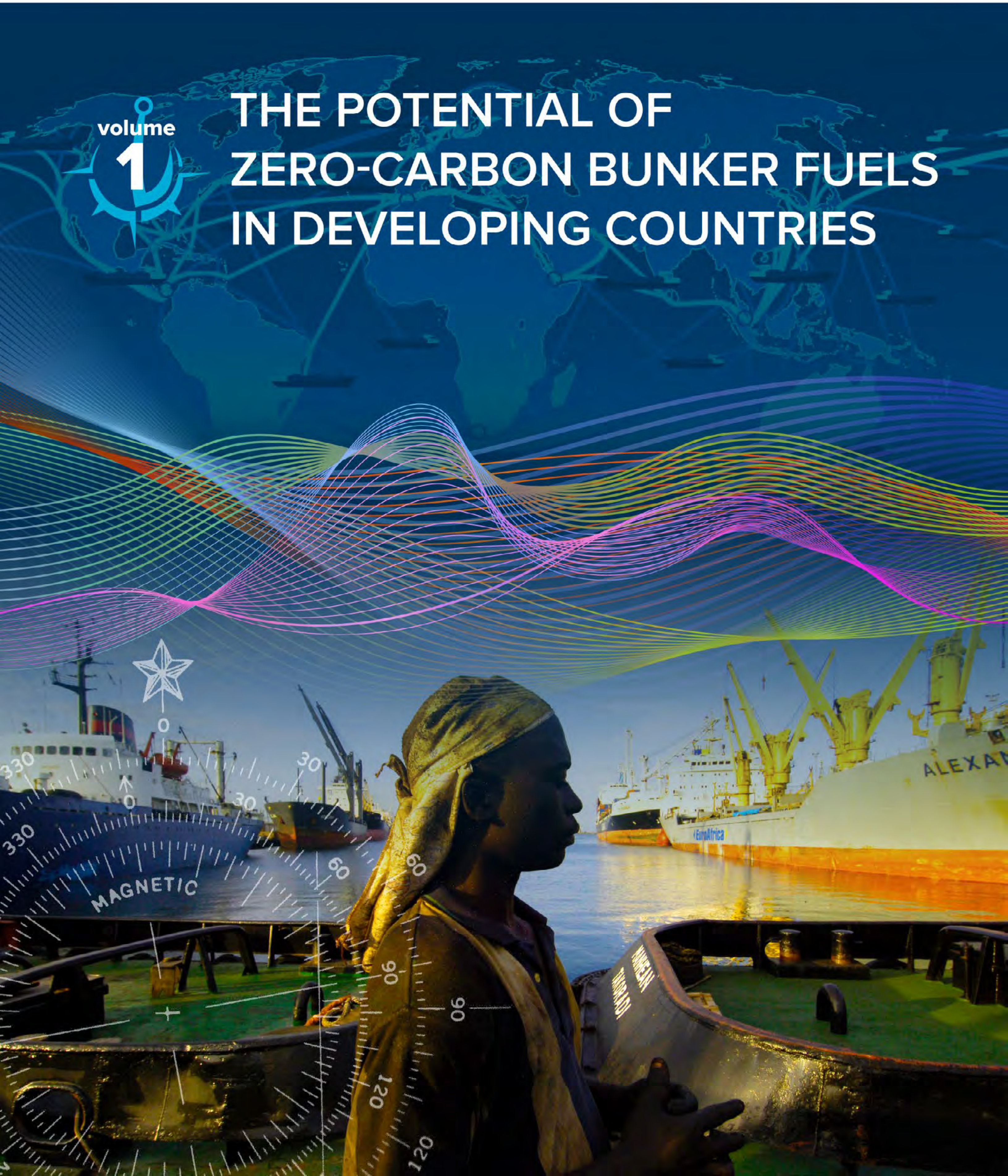
PROBLUE

volume 1

THE POTENTIAL OF ZERO-CARBON BUNKER FUELS IN DEVELOPING COUNTRIES



1818 H Street NW
Washington DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org

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PREAMBLE

The World Bank has undertaken analytical work on the prospects of decarbonizing maritime transport. This report *Volume 1: The Potential of Zero-Carbon Bunker Fuels in Developing Countries* outlines this research, and should be read in accompaniment with *Volume 2: The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping*,[1] and *Summary for Policymakers and Industry: Charting a Course for Decarbonizing Maritime Transport*.[2]

1 Englert, Dominik; Losos, Andrew; Raucci, Carlo; Smith, Tristan. 2021. Volume 2: The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/35437 License: CC BY 3.0 IGO.

2 Englert, Dominik; Losos, Andrew. 2021. Summary for Policymakers and Industry: Charting a Course for Decarbonizing Maritime Transport. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/35436 License: CC BY 3.0 IGO.

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ABBREVIATIONS

ACRONYM	DEFINITION
ABS	American Bureau of Shipping
bcf	Billion cubic feet
BECCS	Bioenergy with carbon capture and storage
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CH_4	Methane
CO_2	Carbon dioxide
DAC	Direct air capture
DNV	Det Norske Veritas
DNV GL	Det Norske Veritas Germanischer Lloyd
EIA	Energy Information Administration
ESMAP	Energy Sector Management Assistance Program
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt hour
H_2	Hydrogen
HFO	Heavy fuel oil
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kWh	Kilowatt hour
kWp	Kilowatt peak
LNG	Liquefied natural gas
NO_X	Nitrogen oxide
N_2O	Nitrous oxide
PV	Photovoltaic
PVOUT	Potential photovoltaic electricity production
RAE	Royal Academy of Engineering
RAG	Red Amber Green
SCC	Shipping in Changing Climates
SCR	Selective catalytic reduction
SMR	Steam methane reforming
SSI	Sustainable Shipping Initiative
tcf	Trillion cubic feet

TEU	Twenty-foot-equivalent unit
TWh	Terawatt hour
UCL	University College London
UMAS	University Maritime Advisory Services
UNCTAD	United Nations Conference on Trade and Development
US	United States
$	All dollar amounts are US dollars unless otherwise indicated

EXECUTIVE SUMMARY

UNDERSTANDING THE NEED FOR ZERO-CARBON BUNKER FUELS

Across the maritime industry, there is general agreement that shipping must undergo a rapid energy transition. This implies a shift from fossil bunker fuels, such as the predominant heavy fuel oil (HFO), to a new generation of alternative bunker fuels. These alternative fuels are known to produce very low, and ultimately zero, greenhouse gas (GHG) emissions during their production, distribution, and use. They are called zero-carbon bunker fuels and encompass fuels which are "effectively zero" (that is, where the fuel is produced from zero-carbon electricity, for instance, hydrogen produced from solar or wind power), or "net-zero" (that is, where the production of the fuel removes a quantity of carbon dioxide from the atmosphere equivalent to that emitted during combustion, such as with biofuels).

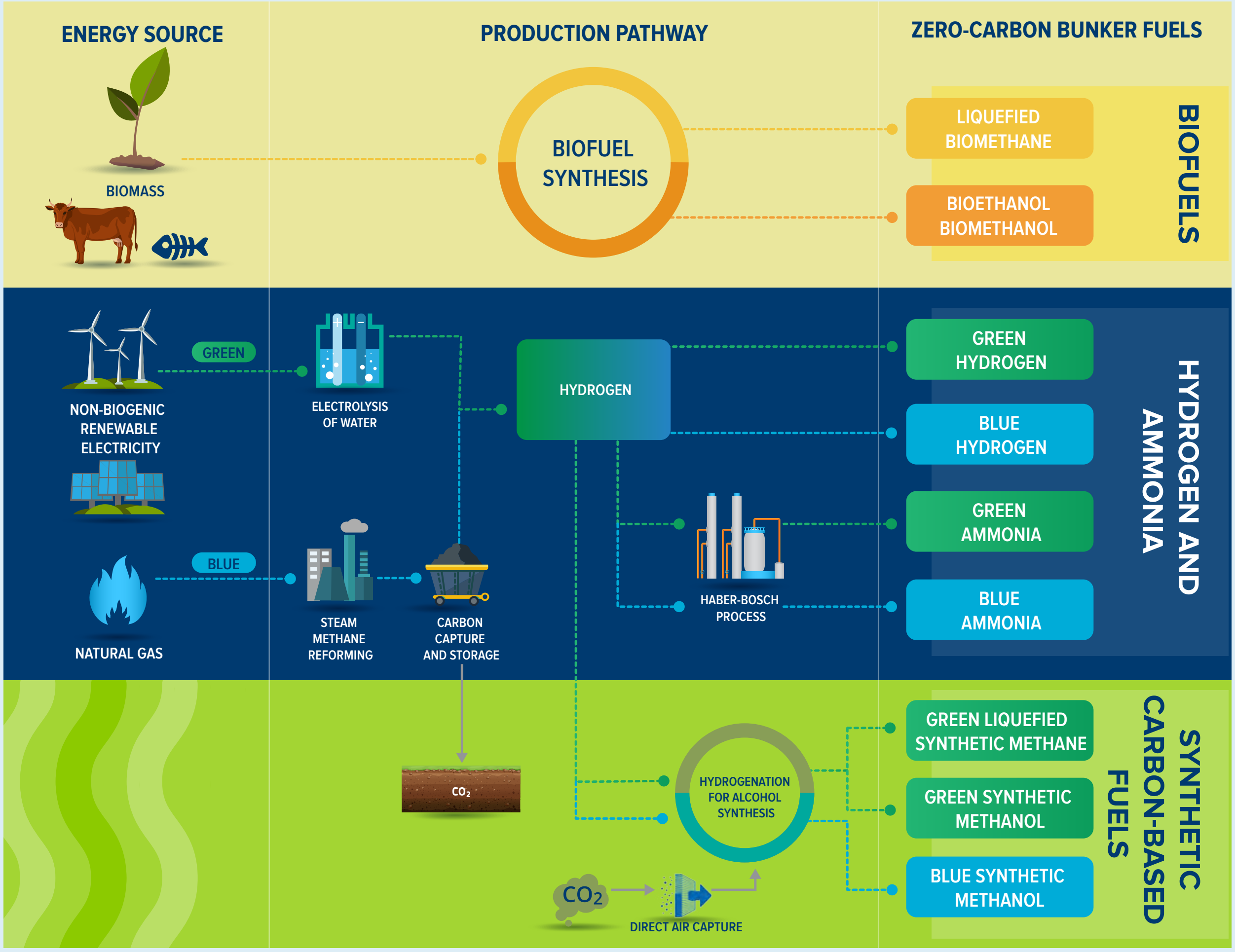
Such zero-carbon bunker fuels have been identified as the primary pathway for the sector to meet the climate targets set by the International Maritime Organization's (IMO) Initial GHG Strategy in 2018. These targets set out to contribute to the Paris Agreement's temperature goals by committing international shipping to reduce GHG emissions from ships by at least 50 percent in absolute terms by 2050 compared to 2008 levels—with the clear ambition to exceed this target, if possible—and to phase out GHG emissions from ships entirely as soon as possible in this century. Given this minimum GHG reduction target for 2050 and the expectation that the scale of maritime trade will grow in that timeframe, the development of zero-carbon bunker fuels represents an imperative for the maritime industry if the climate targets set by the IMO are to be achieved.

IDENTIFYING THE MOST PROMISING ZERO-CARBON BUNKER FUELS

This report combines an extensive literature review with a multi-objective "Red-Amber-Green" analysis to identify the zero-carbon bunker fuels that are most likely to be major contributors to shipping's decarbonized future.[3] The zero-carbon bunker fuels considered are biofuels, hydrogen, ammonia, and synthetic carbon-based fuels. Their primary energy sources and production pathways are illustrated in Figure 1.

3 A "Red-Amber-Green" or "RAG" analysis is a visual way of assessing a number of options against a wide range of criteria and sources of information. Each option is coded red for a poor score against the chosen criteria, amber for a mid-level score, and green for a good score. The information is then visualized as a table to summarize the information. The technique is a common decision-making aid.

FIGURE 1: ZERO-CARBON BUNKER FUEL OPTIONS FOR SHIPPING



WHY AMMONIA AND HYDROGEN?

The analysis concludes that green ammonia, closely followed by green hydrogen, strikes the most advantageous balance of favorable features among a range of different zero-carbon candidate bunker fuels. These crucial features relate to the fuels' lifecycle GHG emissions, broader environmental factors, scalability, economic viability, and the technical and safety implications of using these fuels.

Ammonia or hydrogen fuels also have the advantage of offering multiple production pathways, as they can be produced either from renewable electricity (resulting in "green" ammonia or hydrogen) or from natural gas, with the resulting carbon emissions captured and securely stored underground (resulting in "blue" ammonia or hydrogen; see Box 1). The multiple production pathways provide an important strategic advantage insofar as they help to alleviate some concerns about initial capacity limits and technology issues. Indeed, where possible, it may prove economically beneficial to start the production of zero-carbon bunker fuels with blue ammonia or hydrogen and then progressively transition to their green counterparts as renewable electricity prices decrease. However, this may also present a certain risk of “stranded assets” for blue ammonia or hydrogen infrastructure, which needs to be carefully assessed.[4]

BOX 1: DEFINITIONS OF “GREEN” AND “BLUE” HYDROGEN OR AMMONIA

"Green” hydrogen is hydrogen produced from the electrolysis of water using renewable electricity. “Green” ammonia is produced by combining “green” hydrogen with nitrogen from the atmosphere using an established and scalable process called the Haber-Bosch process.

“Blue” hydrogen is hydrogen produced from the steam methane reforming of natural gas combined with a carbon capture and storage (CCS) plant. This approach captures the carbon emitted from the transformation of natural gas, and stores it indefinitely underground in specific geological features. "Blue" ammonia is, consequently, produced by comining "blue" hydrogen with nitrogen from the atmosphere using the Haber-Bosch process.

Both ammonia and hydrogen can be used in a modified internal combustion engine in much the same way as HFO is currently used. Their use in adapted internal combustion engines has technical and economic benefits. First, existing ships can begin to burn ammonia or hydrogen with minimal modifications and without replacing the main engine. This also allows ammonia or hydrogen to benefit from an existing powertrain supply chain (for both production and subsequent maintenance). At the same time, ammonia and hydrogen will also be compatible with emerging fuel cell solutions. Their use with fuel cells has additional advantages including potential efficiency gains and lower air pollutant emissions relative to internal combustion engines. While these advantages may make fuel cells the preferred option in the long term as their costs decrease and their technology improves, the general findings here do not depend on that specific outcome.

WHY AMMONIA OVER HYDROGEN?

The preference for ammonia over hydrogen is supported by numerous studies. Hydrogen is more expensive to store and handle than ammonia, particularly on board a vessel. To maximize the amount that can be stored in a given volume of space on board, hydrogen is often stored at -235°C in order to keep the fuel in a liquid state. This requires complex, bulky, and energy-consuming refrigeration systems and insulation. Conversely, ammonia is much easier to store and requires less space on board a ship for the same amount of energy content. However, ammonia is toxic to humans and aquatic life. Therefore,

4 "Stranded assets” are those that “have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities” (Caldecott, Tilbury, and Carey 2014).

its toxicity must be managed through design and operational measures before it can become a mainstay of zero-carbon maritime transport. Fortunately, ammonia is already a major commodity which is traded globally in bulk quantities by sea. Therefore, challenges associated with its safe storage and handling on board can be mitigated effectively through the application of appropriate protocols, compliance with technical standards, and the use of safety equipment. Many of these solutions already exist today.

WHY NOT BIOFUELS?

Without a breakthrough in aquatic biomass production, biofuels (for example, biomethanol, bioethanol, or liquefied biomethane) are likely constrained to play a rather minor role in shipping's future energy mix. Limitations are linked to the availability of sustainable feedstock, potential high demand across multiple sectors of the global economy, and the resulting uncertainty surrounding future supply-and-demand price dynamics. Biofuels may well become part of the maritime industry's fuel mix, particularly during the initial transition towards zero-carbon shipping. However, this report concludes that they are highly unlikely to be available at sufficient scale and to be sufficiently cost-competitive to provide most of the zero-carbon energy input needed by 2050.

WHAT ABOUT SYNTHETIC CARBON-BASED FUELS?

Synthetic carbon-based fuels (for example, green liquefied synthetic methane, green synthetic methanol or blue synthetic methanol) are chemically very similar to the conventional fossil bunker fuels in use today. Consequently, these zero-carbon bunker fuels would have significant advantages from the perspective of requiring smaller changes to the existing fleet and fuel supply infrastructure. Nevertheless, this group of fuels is also not expected to become the major source for shipping's future zero-carbon energy needs due to the economic challenges facing their adoption. The production pathway for synthetic carbon-based fuels involves multiple energy-intensive steps which leads to poor energy efficiency overall in terms of fuel output compared to energy input. In turn, this results in very high fuel costs relative to other zero-carbon candidate bunker fuels reviewed.

ASSESSING THE POTENTIAL OF DEVELOPING COUNTRIES TO PRODUCE ZERO-CARBON BUNKER FUELS

To assess the production potential of countries, this report develops and deploys a new methodological approach. The assessment seeks to understand, at a global scale, which countries are likely to be well positioned to produce zero-carbon bunker fuels for the maritime industry in the future.

Using the example of ammonia and hydrogen, the potential of each country to become a potential supplier of zero-carbon bunker fuels is assessed against the following five key criteria:

1. Energy resources required;
2. Shipping volumes;
3. Geographic location;
4. Adequacy of current and projected regulatory framework; and
5. Potential to leverage existing infrastructure.

A score is assigned to each criterion. These scores are then combined to create a weighted composite score, and countries are grouped accordingly into three tiers reflecting their potential to produce zero-carbon bunker fuels: “high”, “promising”, or “limited or insufficient data”. The high-level assessment is repeated for three different scenarios to provide insights into each country’s mid-term and long-term zero-carbon bunker fuel production potential. The scenarios for the shipping sector are as follows:

1. In the first scenario assessment, countries are evaluated to identify those well positioned to produce ammonia or hydrogen from natural gas in conjunction with carbon capture and storage (CCS).
2. The second scenario assessment identifies those countries well positioned to produce ammonia or hydrogen from renewable energy sources.
3. The third scenario assessment identifies those countries well positioned to produce ammonia or hydrogen from natural gas in conjunction with CCS initially, and to move eventually to a production pathway based on renewable energy sources.

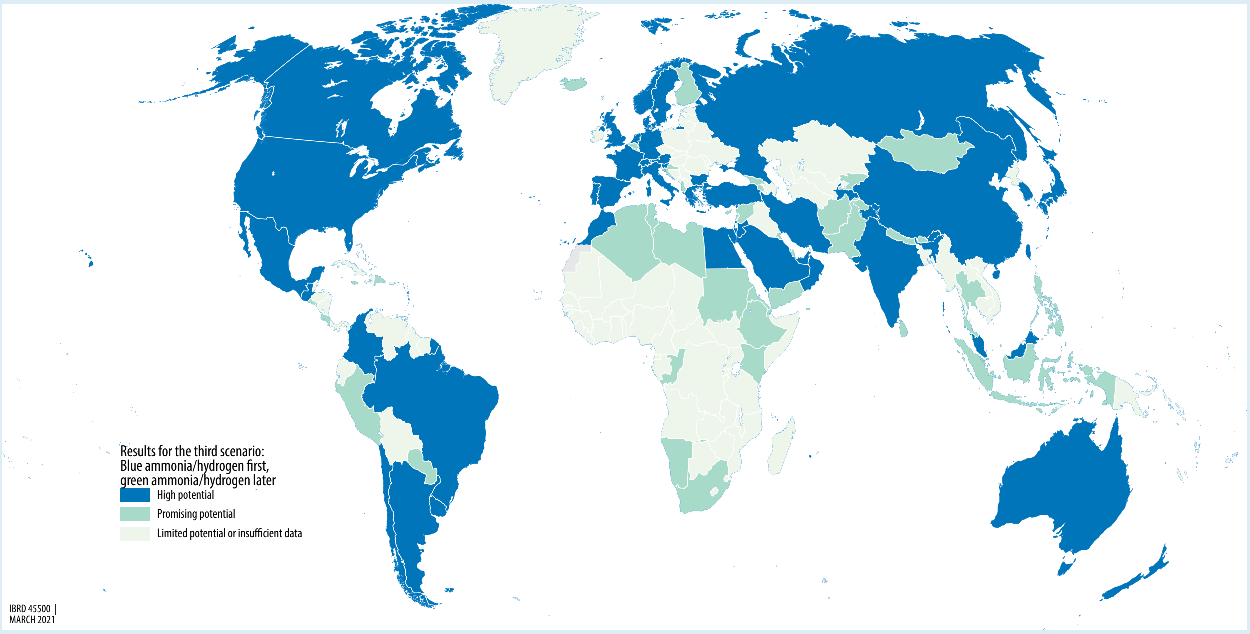
This methodological approach is particularly important as it provides both an indication of the early potential of countries to produce zero-carbon bunker fuels, as well as the analytical foundations for further refinement that can help assess future investment opportunities in developing countries[5] more precisely. These investment opportunities have the potential to foster the economic development of the World Bank’s client countries and support their development priorities.

The report finds that many countries, including developing countries, are very well positioned to become future suppliers of zero-carbon bunker fuels, namely ammonia and hydrogen. These insights are used to produce shortlists of countries for which further and deeper investigation appears useful.

5 The World Bank classifies countries by income groups (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups). In this report, the term “developing countries” refers to the countries classified as low income, lower middle income, and upper middle income economies as of June 2020.

As an example, Figure 2 shows the world heatmap of countries illustrating their potential to produce blue ammonia or hydrogen first before ultimately moving to the production of green ammonia or hydrogen, under the third scenario production pathway outlined above. It should be noted that the validity of this analysis, to a large degree, does not depend on the zero-carbon bunker fuels considered as top candidates in this report. As all of the synthetic zero-carbon bunker fuels are made from hydrogen, the results for ammonia and hydrogen production can also be used proxies for the remainder of other viable zero-carbon bunker fuels.

FIGURE 2: HEATMAP INDICATING THE POTENTIAL FOR COUNTRIES TO PRODUCE BLUE AMMONIA/HYDROGEN INITIALLY, BEFORE SHIFTING TO GREEN AMMONIA/HYDROGEN PRODUCTION FOR SHIPPING EVENTUALLY



Well-positioned countries tend to be those endowed with many of the energy resources required to produce the zero-carbon bunker fuels, combined with favorable access to a large volume of shipping activity. The individual results of the high-level assessment can be found in Appendix B – Production potential of green/ blue ammonia/hydrogen for shipping by country.

ESTIMATING THE SCALE OF INVESTMENTS REQUIRED IN SELECTED DEVELOPING COUNTRIES

Based on these findings, the following four developing countries are selected for high-level case studies:

- Brazil, as a developing country in Latin America well positioned to produce blue ammonia for shipping;
- India, as a developing country in South Asia well positioned to produce green ammonia for shipping;
- Mauritius, as a small island developing state in Africa with explicit interest in developing into a bunkering hub; and
- Malaysia, as a developing country in Southeast Asia well positioned to produce blue ammonia initially, followed by green ammonia for shipping eventually.

These case studies discuss the implications for each country of becoming a potential future producer of zero-carbon bunker fuels in their respective regional markets and globally. The case studies focus on the production of ammonia (either blue ammonia, green ammonia, or "first blue, then green" ammonia). Hydrogen as a fuel is not explicitly taken into consideration. This is because the capital expenditures needed for the supply of liquefied hydrogen to shipping would be very similar to the capital expenditures needed for the supply of ammonia, as can be seen in. Appendix E – Hydrogen and ammonia investment comparison. As a consequence, the ammonia-related results in each country can also be considered representative for liquefied hydrogen.

The key findings of these four high-level case studies are summarized in Table 1.

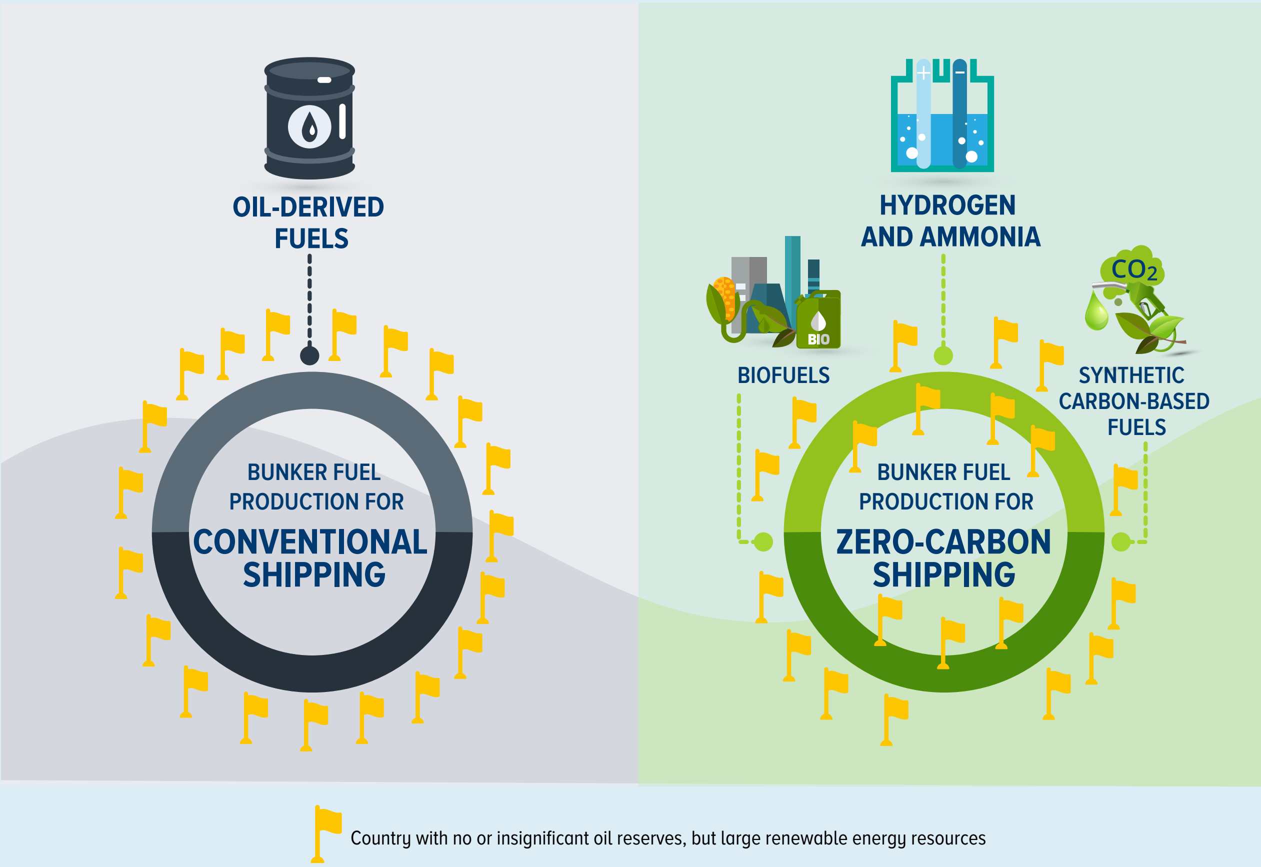
TABLE 1: OVERVIEW OF KEY FINDINGS FROM THE HIGH-LEVEL CASE STUDIES

	PRODUCTION PATHWAY	ENERGY RESOURCES CONSIDERED	POTENTIAL COVERAGE OF GLOBAL SHIPPING DEMAND FOR AMMONIA BY 2050	CAPITAL EXPENDITURE NEEDED
Brazil	Blue ammonia	Natural gas with CCS	2-9 percent	$24-$107 billion
India	Green ammonia	Solar	10-27 percent	$147-$385 billion
Mauritius	Green ammonia	Solar and wind	0.3-0.5 percent	$1.6-$2.7 billion
Malaysia	First blue, then green ammonia	First natural gas with CCS, then solar	1-10 percent	$17-$138 billion

IMPLICATIONS FOR POLICYMAKERS

In the past, the global market for bunker fuels—heavily based on HFO—has been dominated by a limited number of oil-exporting countries. In the future, the emergence of zero-carbon bunker fuels and the decoupling of the energy supply for shipping from crude oil reserves offer a unique opportunity for more countries to enter a more inclusive market—as illustrated by Figure 3. Well-positioned countries include a number of developing countries, characterized by their low-cost renewable energy sources combined with other advantages, such as a strategic geographic proximity to major shipping routes.

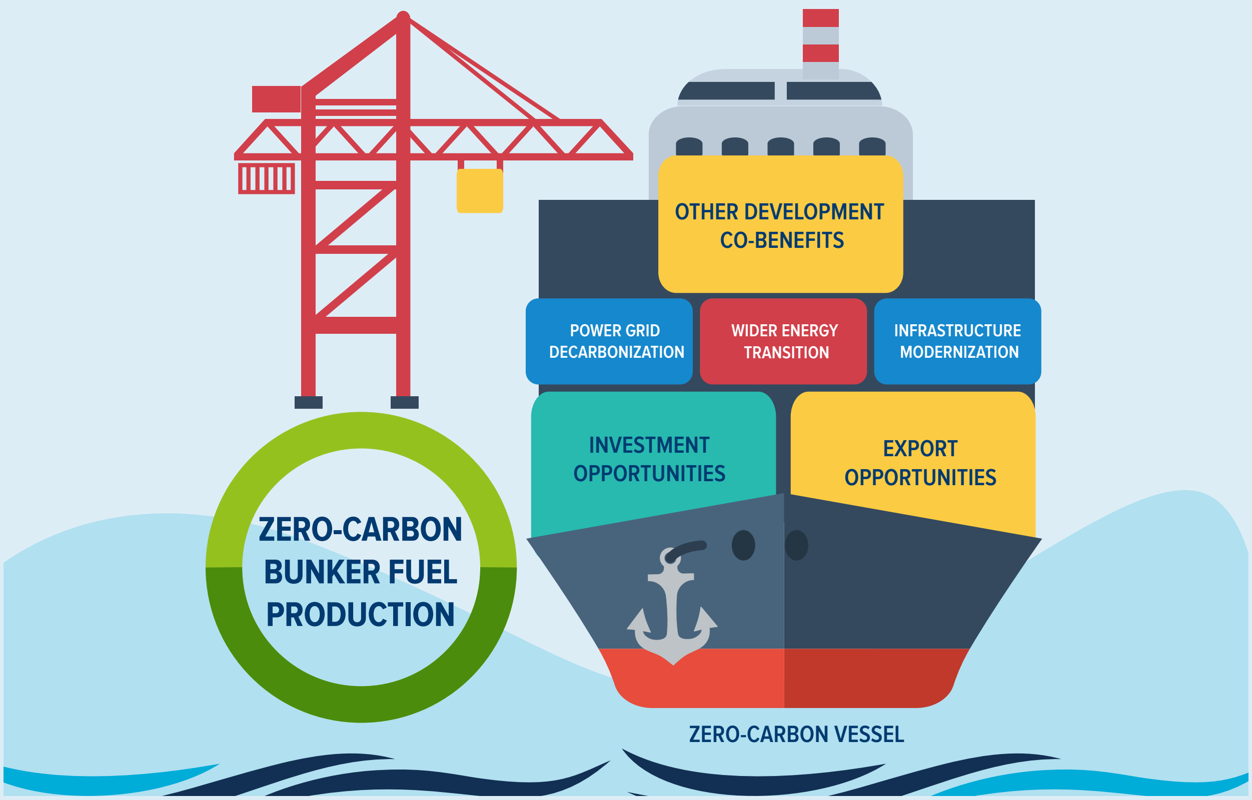
FIGURE 3: POTENTIAL REALIGNMENT OF THE GLOBAL BUNKER FUEL MARKET THROUGH ZERO-CARBON SHIPPING



This realignment of the global bunker fuel market gives policymakers from these developing countries the opportunity to leverage national comparative advantages during the expected period of growing demand for zero-carbon bunker fuels from 2030 onwards. Indeed, policymakers could strategically harness demand for zero-carbon bunker fuels to support investments in the decarbonization of their domestic energy systems. Obvious synergies between both systems could be exploited:

for instance, ammonia/hydrogen could be used as an energy carrier to help compensate for the intermittency of renewable electricity generation; they could be marketed as a commodity for further industrial use within the country, or they could be exported as a low-cost renewable energy resource to other countries where no physical connection through power transmission lines exists. Additionally, these investments are able to create further development opportunities—as shown by Figure 4—like, for instance, maritime and non-maritime infrastructure modernization and contributions to the country's wider energy transition.

FIGURE 4: OPPORTUNITIES FOR DEVELOPMENT CREATED BY ZERO-CARBON BUNKER FUEL PRODUCTION



The potential application of green hydrogen and ammonia in developing countries is broad, thereby offering economies of scale through sector coupling. While sector coupling once referred primarily to electrifying the demand side of sectors like heating and transport based on renewable electricity, the concept has now been broadened to also include the supply side of the power and gas sectors through versatile technologies like power-to-gas. The European Commission, for instance, understands sector coupling as "a strategy to provide greater flexibility to the energy system so that decarbonization can be achieved in a more cost-effective way" (European Parliament 2018).

Besides these policy and industrial strategy considerations for national governments, zero-carbon bunker fuels may also have important implications for the way national governments interact at the IMO to finalize and enhance the Initial IMO GHG Strategy. Carbon pricing represents a prime example of a cost-effective policy option that could be instrumental in creating a level playing field between fossil and zero-carbon bunker fuels. Furthermore, carbon pricing can generate revenues which in turn can be used to help support the creation of a global zero-carbon energy supply infrastructure for shipping and ensure a fair and equitable energy transition away from fossil fuels. If this support included targeted investments toward developing countries which are well positioned to produce zero-carbon bunker fuels, this could help to allay some existing controversies in the policy debate about "Common But Differentiated Responsibilities and Respective Capabilities", a guiding principle of both the Initial IMO GHG Strategy and the United Nations Framework Convention on Climate Change.

These opportunities warrant further and more detailed assessment. This report provides the basis for such work by providing a discussion of the most promising zero-carbon bunker fuel options, a robust new method for identifying those countries well positioned to produce these fuels for shipping in the future, and a number of high-level quantitative estimates of the scale of opportunity and capital expenditures needed in four representative developing country examples.

IMPLICATIONS FOR INDUSTRY

This report also has clear implications for both incumbents as well as potential new market entrants in the maritime industry. The supply of zero-carbon bunker fuels will impact the whole shipping sector including, for example, fuel producers, fuel suppliers, equipment manufacturers, shipyards, ship owners, charterers, and shipping companies.

With regard to infrastructure, the large capital costs and short timescales likely required for the important expansion in production capacity of zero-carbon bunker fuels imply a significant commercial opportunity, but also a certain level of risk. When considering such investment decisions, several factors influence the assessment of risk and reward. These include concerns such as the scale of initial public support that may be necessary to ensure the economic sustainability of any private sector activity and the availability of specialized financial mechanisms, including different types of bonds (including, for example, impact bonds and green bonds), which can be used in addition to equity and other sources of debt finance. Furthermore, the critical scale at which infrastructure becomes competitive is also an important consideration. This is illustrated by the relatively low green ammonia production capacity in the case of Mauritius in contrast to the much larger capacity of India. In addition to scale, given a regional landscape of potential producers there may be other factors which affect the commercial competitiveness of different countries and therefore their investment capacity.

A key investment risk is the creation of stranded assets. For shipping's energy transition, the focus on blue or green hydrogen—either directly or as a feedstock for ammonia—increases the range of technological options which could make use of a given zero-carbon bunker fuel. However, for individual industry stakeholders who may need to choose which of these options to invest in, this also increases investment uncertainty related to either choice's long-term commercial competitiveness. For example, suppliers that have invested in blue hydrogen may be left with stranded assets should green hydrogen quickly become very competitive, and vice versa.

On the vessel and operational side, ship owners also need to manage their investment risks regarding onboard technologies. For example, many shipowners have expressed their unwillingness to invest in a certain type of vessel until there is a broad understanding of what the dominant zero-carbon bunker fuel will be in 10 or even 30 years. This would have cascading implications for the equipment supply chains associated with each of these fuels. Conversely, the increasing shift toward stronger corporate social responsibility considerations in corporate strategies could present an opportunity for progressive shipping companies, owners, and technology providers to capture new market share by actively contributing to shipping's energy transition away from fossil fuels and toward zero-carbon bunker fuels.

RECOMMENDATIONS FOR FURTHER WORK

The key findings and underlying methods of this report provide an important early indication and framing for assessing which countries may be well positioned as future fuel suppliers. Nevertheless, further work will be required, focusing, for instance, on the following aspects:

- **Cost competitiveness**: Considering the individual cost competitiveness of different developing countries in addition to any competition effects between neighboring countries (including both developing and developed countries) has been beyond the scope of this report, but should be a key topic for any further research.

- **Multi-criteria assessment**: The multi-criteria assessments of the most promising zero-carbon bunker fuels (including the current RAG matrix approach) for shipping should be further developed as first pilots and demonstrator projects conclude and provide practical insights. Additionally, further valuable insights in how to build a future supply chain for zero-carbon bunker fuels could be gained by extending the scope of the assessment to consider opportunities for bilateral energy cooperation between neighboring countries.

- **National datasets**: There is an opportunity to increase the coverage and granularity of national datasets on energy resources. This would enable the assessment framework to better classify the nature and scale of the business opportunity in individual countries.

- **Case studies**: Additional country case studies can make important contributions to validate general global findings on a national scale, and to facilitate comparison among countries.

Ultimately, any further analysis which enables constructive policy design, including carbon pricing in particular, can inform effective policymaking and strategically exploit synergies between global GHG emissions reduction, national development opportunities, and multilateral cooperation at the IMO.

1. INTRODUCTION

The global consensus on the need to reduce Greenhouse Gas (GHG) emissions—as embodied in the Paris Agreement (2016)—has seen industries making fundamental changes to their operations. The International Maritime Organization (IMO) is targeting a reduction in GHG emissions from international shipping of at least 50 percent over the next 30 years (2020–50) compared to 2008 levels. This is a period when the industry is expected to see increased demand, driven by further expansion of global trade.

The current conventional fuels used to power ship engines (known as "bunker fuels") are: marine distillates such as marine diesel oil and marine gasoil, and heavy fuel oil (HFO). Other options entering the market include low-sulfur heavy fuel oil and liquefied natural gas, both of which are still fossil fuels. To cut GHG emissions while increasing capacity, shipping will need to rapidly transition away from fossil bunker fuels and toward a new generation of alternative bunker fuels, the so-called zero-carbon bunker fuels. Initial estimates are that these zero-carbon bunker fuels should reach at least five percent of the bunker fuel mix by 2030 to reach a tipping point that allows them to rapidly scale up afterwards and enable the industry to meet the IMO's 2050 target and fully decarbonize (Global Maritime Forum 2021).

BOX 2: DEFINITION OF ZERO-CARBON FUELS

In this report, the proposed alternative fuels are referred to as "zero-carbon bunker fuels". This reflects the use of "carbon" as a common proxy term for CO_2, which accounts for over 90 percent of shipping's total GHG emissions and provides a useful shorthand. It does not mean that the analysis is limited to considering CO_2 emissions only. The general term "carbon" is used to refer to the full range of GHG emissions emitted by various fuels during their production, transportation, and use. Other relevant GHGs include methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Carbon and GHG emissions are used interchangeably in this report unless an explicit distinction is made.

Similarly, "zero" is used in its sense as a common proxy term for "effectively" zero and "net-zero" carbon fuels. An "effectively" zero-carbon fuel is produced from zero-carbon electricity (e.g., green hydrogen), while a "net-zero" fuel is one where its production removes a quantity of CO_2 from the atmosphere equivalent to that emitted during combustion. Both categories may emit very small amounts of GHG in their respective upstream processes (e.g., land use, harvesting, refining, transport, and processing to capture and store the CO_2). The term "zero" therefore represent fuels that have a sufficiently small GHG impact such that they are capable of reaching the IMO's minimum target of a 50 percent absolute GHG emissions reduction, even when considering these lifecycle GHG emissions, and that with further management of upstream (mostly land-side) emissions, can achieve a complete 100 percent reduction.

This report aims to identify developing countries[6] that are well-placed to benefit from this expected future market for zero-carbon fuels, and to estimate the level of capital expenditures needed to build the infrastructure associated with the production of these alternative fuels.

The report is divided into three main sections following these objectives:

1. Identifying the most promising zero-carbon candidate fuels for further consideration within the report. This section assesses the potential of a range of alternative zero-carbon fuels through an extensive literature review, covering GHG emissions, economics, and technical and safety implications. A high-level multi-objective analysis is then used to identify the most promising fuel or fuels.
2. This section sets out the weighted criteria used to score each country against the identified performance metrics. Composite scores are calculated and used to rank countries based upon their ability to supply the identified top zero-carbon fuel(s). Four developing countries among those identified as well-positioned are then selected for further analysis.
3. This section examines the selected countries in greater depth, analyzing available energy sources and assessing the potential size of the bunker fuel market. These factors are then combined to determine a range of fuel-supply scenarios for which the capital expenditures required to build the zero-carbon fuel production and dispensing infrastructure are calculated.

6 The World Bank classifies countries by income groups: (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups). In this report, the term "developing countries" refers to the countries classified as lower-middle income and upper-middle income economies.

2. OVERVIEW OF ZERO-CARBON BUNKER FUEL OPTIONS

An extensive literature discusses zero-carbon fuels that potentially could be used in shipping. Some key papers include recent publications by: American Bureau for Shipping (ABS) (2019), which examines the relative advantages and drawbacks of methanol, ammonia, hydrogen, and biofuels; Det Norske Veritas Germanischer Lloyd (DNV GL) (2019), which provides maritime forecasts for hydrogen, ammonia, methane, and biodiesel; and Sustainable Shipping Initiative (SSI) (2019), which focuses on biofuels as alternative zero-carbon fuels for shipping. Lloyd's Register and University Maritime Advisory Services (UMAS) provide a series of studies containing techno-economic analyses of various zero-carbon fuels for shipping. Full bibliographic details of these publications can be found in the reference list at the end of this report.

This report investigates a range of promising fuels from these references. These fuels are classified based on their chemical composition and energy source, potentially in combination with carbon capture and storage (CCS), in Table 2.

TABLE 2: POTENTIAL ZERO-CARBON FUELS SELECTED FOR FURTHER ASSESSMENT

	BIOFUELS	HYDROGEN AND AMMONIA	SYNTHETIC CARBON-BASED FUELS
Methane	Liquefied biomethane		Green liquefied synthetic methane
Ethanol	Bioethanol		
Methanol	Biomethanol		Green synthetic methanol, Blue synthetic methanol
Hydrogen		Green hydrogen, Blue hydrogen	
Ammonia		Green ammonia, Blue ammonia	

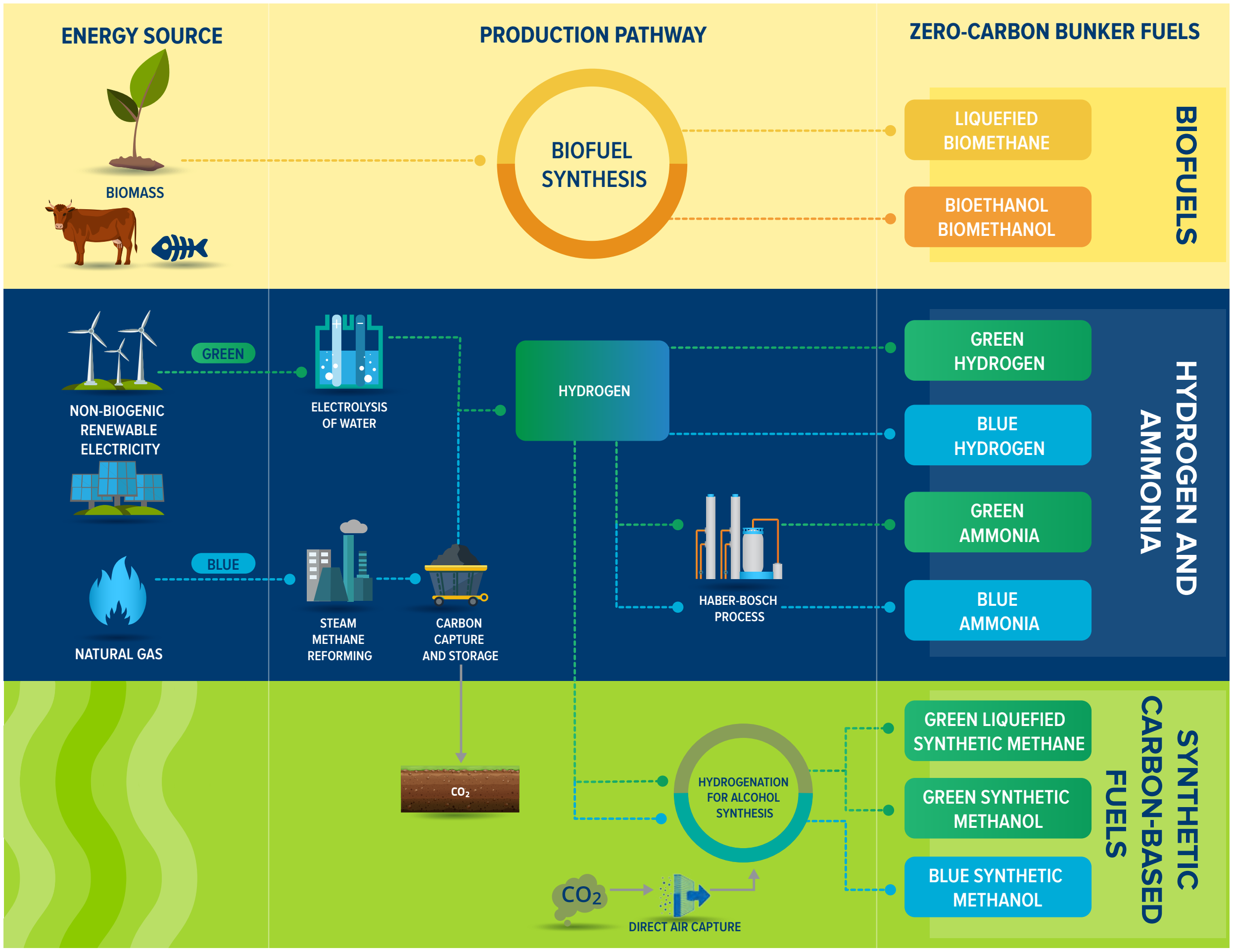
While other zero-carbon bunker fuel options exist—including synthetic diesel, novel biofuels such as those produced from algae, and the use of renewable electricity with batteries on board ships—they are expected be of minor significance for the shipping sector (Lloyd's Register and UMAS 2019c), and therefore are not further considered in this assessment.

To conduct a comprehensive assessment of the fuels listed in Table 2, it is necessary to compare carbon emissions across the entire fuel lifecycle—including emissions from the production and transportation of alternative fuels alongside those from their final use in the propulsion machinery of ships. Only the alternative fuels that have zero or at most very low carbon emissions across their entire lifecycle can be referred to as true "zero-carbon" fuels.

Figure 5 shows the lifecycle steps associated with the production of each of the fuels listed in Table 2, and the major chemical processes needed to convert the original energy source into the desired zero-carbon fuel. Each fuel is created by a particular "production pathway" comprising of a set of production steps. To assess the feasibility of a particular fuel, it is also necessary to understand the key processes used in each fuel's production pathway.

For fuels which involve hydrogen, its production from natural gas in conjunction with 100 percent CCS and its production from 100 percent non-biogenic renewable electricity are color-coded as "blue" and "green", respectively. If strictly applied, these production pathways result in zero or at most very low GHG emissions. There are no universally recognized color codes for hydrogen from natural gas in conjunction with incomplete CCS, biomass, nuclear, or different varieties of electricity and these production pathways are disregarded in this report. In any case, this underlines the importance of considering the full lifecycle GHG emissions of any potential zero-carbon bunker fuels.

FIGURE 5: ZERO-CARBON BUNKER FUEL OPTIONS FOR SHIPPING



In Figure 5, zero-carbon bunker fuels are grouped by broad fuel type and production pathway into the following categories: biofuels, hydrogen and ammonia, and synthetic carbon-based fuels.

Table 3 provides a clearer breakdown of the required energy-intensive process steps in each production pathway.

TABLE 3: ZERO-CARBON FUEL CATEGORIES, FUEL TYPES AND PROCESS STEPS[7]

FUEL CATEGORIES	FUEL	PROCESS STEP					
		BIOFUEL SYNTHESIS	ELECTROLYSIS OF WATER	STEAM METHANE REFORMING (SMR) WITH CCS	HABER-BOSCH PROCESS	DIRECT AIR CAPTURE (DAC)	HYDROGENERATION FOR ALCOHOLS SYNTHESIS
Biofuels	Liquefied biomethane	√					
	Bioethanol	√					
	Biomethanol	√					
Hydrogen and ammonia	Green hydrogen		√				
	Blue hydrogen			√			
	Green ammonia		√		√		
	Blue ammonia			√	√		
Synthetic carbon-based fuels	Green liquefied synthetic methane		√			√	√
	Green synthetic methanol		√			√	√
	Blue synthetic methanol			√		√	√

Several studies look at the benefits and challenges of zero-carbon fuels from an environmental, economic, and technical perspective. The next section describes the relevant studies and provides a review of these benefits and challenges.

7 See Section 3: Discussion of zero-carbon bunker fuels for details on the process steps.

3. DISCUSSION OF ZERO-CARBON BUNKER FUELS

The alternative zero-carbon fuels examined in this report have been selected for their ability to reduce greenhouse gas (GHG) emissions from shipping. To achieve these potential reductions, they also need to be economically viable, technically feasible, and safe to handle. This section reviews the existing literature to collate information on the key characteristics of each alternative zero-carbon fuel option.

3.1 RELEVANT STUDIES

Our review includes a number of studies in order to provide sufficient breadth of coverage and depth of detail. Table 4 summarizes the types of fuel and key considerations covered by the studies reviewed in this report, highlighting greenhouse gas impacts, economic viability, and technical and safety considerations. It also distinguishes those studies that conduct quantitative analysis or original modelling from those that do not. The following sections consider the performance of each fuel category against these metrics.

TABLE 4: SUMMARY OF THE RELEVANT STUDIES ON ZERO-CARBON FUELS AND THEIR SCOPE AND METHODOLOGY

STUDY	TYPES OF FUELS INCLUDED	QUANTITATIVE?	GHG IMPACTS	ECONOMIC VIABILITY	TECHNICAL AND SAFETY CONSIDERATIONS
Lloyd's Register and UMAS (2019a)	Green/blue hydrogen, green/ blue ammonia, green synthetic/ biomethanol, green liquefied synthetic methane, liquefied biomethane	yes		√	
Lloyd's Register and UMAS (2019c)	Green/blue hydrogen, green/ blue ammonia, green synthetic/ biomethanol	yes	√	√	√
Lloyd's Register and UMAS (2020)	Biomethanol, biodiesel, biomethane, blue hydrogen, blue ammonia, green synthetic methanol, green hydrogen, green ammonia, green diesel, green liquefied synthetic methane, batteries	yes	√	√	√
Imhof (2019)	Green hydrogen, green ammonia, green liquefied synthetic methane, biofuels		√		
American Bureau of Shipping (2019)	Green/blue hydrogen, green/blue ammonia, biomethanol, biofuels		√		√
DNV GL (2019)	Green/blue hydrogen, green/blue ammonia, blue synthetic methanol, biodiesel	yes	√	√	√
Royal Academy of Engineering (2017)	Bioethanol, biodiesel, biomethanol		√		
SSI (2019)	Biomethanol, bioethanol, liquefied biomethane		√		
ICCT (2019)	Liquefied biomethane, gas, green liquefied methane	yes	√	√	
CE Delft (2020)	Liquefied bio- and synthetic methane	yes	√	√	

When assessing the environmental sustainability of zero-carbon bunker fuels, the following criteria are taken into consideration:

- The operational GHG emissions that determine whether a fuel can be labelled as zero-carbon or effectively zero;
- The potential upstream emissions that determine whether a fuel can be considered "net-zero";
- The potential constraints on the scalability of sustainable energy sources to meet the energy demands;

- The emissions of air pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM); and
- Other unintended consequences for the environment such as indirect land-use change impacts.

As acknowledged in Lloyd's Register and UMAS (2017 and 2019c), there are several key economic parameters for assessing the economic viability of zero-carbon bunker fuels on board. The following economic criteria have been considered for the selection of the most promising zero-carbon bunker fuels in section 3.6:

- The technological maturity and scalability of the key technologies used in the production processes or on board ships (for example, CCS, direct air capture (DAC) and fuel storage systems);
- The economic competitiveness over time; and
- The overall energy efficiency.

The economic analysis used to inform this study's estimates takes a total cost of ownership perspective, including amongst others both the price of the fuel and the costs associated with its use on the ship. In practice, as the total cost of ownership in most cases is dominated by the voyage costs (and therefore the fuel price), this is often the main determinant of the economic viability of each option (Lloyd's Register and UMAS 2017a and 2019c).

Many zero-carbon fuels face technical and safety issues with regard to production, transport, storage, and use on board a vessel, which can hinder their adoption and require the implementation of standards and safety systems. The American Bureau of Shipping report (2019) assesses the following technical and safety considerations, which are used to select the most promising zero-carbon fuels in section 3.6:

- The physical and technical characteristics of the fuels such as the temperature required for liquid storage;
- The storage volume requirement on board a vessel;
- The toxicity to humans and aquatic life; and
- The flammability.

It should be noted that energy density considerations are factored into economic viability assessments because storage costs and space lost due to storage volume influence the overall cost of operation. The temperature for liquid storage and boiling points have a direct impact on the practicality and cost of storage.

3.2 BIOFUELS

This section reviews the key characteristics of three prominent biofuels for their use as zero-carbon bunker fuels for shipping, namely bioethanol, biomethanol, and liquefied biomethane. The energy-intensive process steps considered in this section for the production of these fuels are outlined in Table 5.

TABLE 5: BIOFUELS AND THEIR ASSOCIATED PROCESS STEPS

FUEL CATEGORIES	FUEL	PROCESS STEP: BIOFUEL SYNTHESIS	ELECTROLYSIS OF WATER	SMR WITH CCS	HABER-BOSCH PROCESS	DAC	HYDROGENATION FOR ALCOHOL SYNTHESIS
Biofuels	Liquefied biomethane	√					
	Bioethanol	√					
	Biomethanol	√					

3.2.1 Lifecycle GHG emissions and air quality impacts

Lifecycle GHG emissions

Biofuels are derived from biomass or waste streams of biogenic origin. First-generation biofuels are often in direct competition with the production of food and feed crops since they are produced from food crops containing sugar or starch. To avoid this unintended competition, second and third generation biofuels (such as bioethanol or biomethanol) are based on different types of feedstock such as lignocellulosic biomass.[8]

Bioethanol, biomethanol, and liquefied biomethane can either be burned in an internal combustion engine or chemically converted into electricity using a reformer and a fuel cell. In the latter case, the reformer creates a hydrogen stream that is used in the fuel cell to create electricity and a waste carbon dioxide (CO_2) stream. The resulting electricity can then be used to power an electric motor, thus driving the ship's propeller.

8 Lignocellulosic biomass is any of several closely related substances constituting the essential part of woody cell walls of plants and consisting of cellulose intimately associated with lignin.

Biofuels can be labeled as net-zero-carbon fuels despite emitting CO_2 during their use (in the propulsion machinery on board the ship) in broadly the same quantities as their fossil-derived equivalents. This is due to biofuels also retrieving CO_2 from the atmosphere during their production (the growth of their biogenic feedstock).

However, uncertainty remains around the quantity of CO_2 emissions which can be retrieved from the atmosphere during the upstream phase of biofuel production (RAE 2017). For instance, the production of first-generation biofuels may result in the conversion of natural vegetation or forest to croplands, which in turn may result in the release of soil and plant biomass that was previously serving as an effective carbon sink (RAE 2017). Therefore, when land-use change emissions are included in the GHG emission analysis of first-generation biofuels, they can be seen to have limited lifecycle GHG emission savings, and may in some cases increase overall GHG emissions.

Therefore, second and third generation biofuels (for example, wood, waste streams such as the organic fraction of municipal solid wastes, lignocellulose, and algae) are preferable to first generation biofuels since their feedstocks do not compete with food or feed crops. This can mitigate land-use change pressure associated with using energy crops for biofuels and thus reduce conflicts over food security and other policy aims. Nonetheless, the quantitative availability of resources which can serve as a feedstock for second and third generation biofuels is subject to debate in the literature. For example, the Intergovernmental Panel on Climate Change (IPCC 2019) states that "increasing biomass supply to the extent necessary to support deep decarbonization is likely to involve substantial land-use change," thereby highlighting the potential land-use conflicts that could arise between the production of biomass for second and third generation biofuels and natural habitat or food crop use. Furthermore, afforestation of marginal land should also be noted as an important alternative for the use of the available bioresource as a key strategy in meeting the Paris Agreement's temperature goals, especially the 1.5°C target (IPCC 2019).

The lifecycle GHG footprint is a key issue that must be considered when assessing the sustainability of biofuels. Vaughan et al. (2018) state that improving governance will be essential to ensure biofuels are produced in a transparent, accountable, credible, and sustainable way. Otherwise biofuels could, in some circumstances, be worse for the climate than fossil fuels. Today, only one-third of the bioenergy crops are grown in regions associated with more-developed governance frameworks.

Air quality impacts

When various biofuels are burned in an internal combustion engine, the resulting local air pollutants (for example, NO_x) may not be less than those emitted by conventional fossil fuels. Instead, their actual performance depends on the production method and combustion specifics used (ABS 2019). However, bioderived fuels are rarely worse than their fossil-derived equivalents. Indeed, ABS (2019) claims that per unit of energy, methanol emits only 45 percent and eight percent of the total NO_x

and SO_x emissions that conventional fossil fuels emit respectively. Furthermore, internal combustion engine after-treatment systems can be used to abate certain air pollutants. For instance, selective catalytic reduction can significantly reduce NO_x emissions.

In contrast, when consumed in a fuel cell, a smaller quantity of air pollutants and CO_2 is emitted. However, traditionally, fuel cells are more expensive and less mature as a technology when compared to internal combustion engines.

3.2.2 Future availability for shipping

Two main factors govern the availability of biofuels for shipping. The first factor is the quantity that can be sustainably produced, and the second factor is the competition for the available biomass from other sectors in an increasingly decarbonized economy. A realistic assessment, therefore, should account for both factors.

First, the total future global bioenergy production is uncertain. A general consensus among experts is that approximately 70 to 160 exajoules (EJ) of energy can be produced from sustainable biomass by 2050 (CCC 2018; Smith et al. 2014; IPCC 2018). However, the full range in the literature is much broader and is estimated to range from 30 to 500 EJ (Winning et al. 2018; Fuss et al. 2018; IPCC 2018).

Liquefied biomethane (LBM) has received great attention as a potential future bunker fuel. Regarding its future availability, CE Delft (2020) predicts that the maximum conceivable sustainably produced supply of LBM in 2050 is between 37 and 184 EJ. In contrast, the International Council on Clean Transportation (ICCT) (2019) states that due to the limited available quantity of the most-used feedstock for liquefied biomethane (livestock manure, food-processing waste, and sewage sludge), only a small portion of the fuel demand could be covered. Furthermore, it could be more efficiently used for on-site power generation. Finally, total biomethane production potential (including waste) in 2050 is estimated by Pye et al. (2019) to be 34 EJ, which is in line with the lower bound of CE Delft (2020). These figures appear to be low when compared to shipping's estimated energy demand of approximately 20 EJ in 2050 (UMAS 2020).

According to the European Technology Innovation Platform (2018), the amount of sustainable total biomass feedstock available depends on various elements, such as:

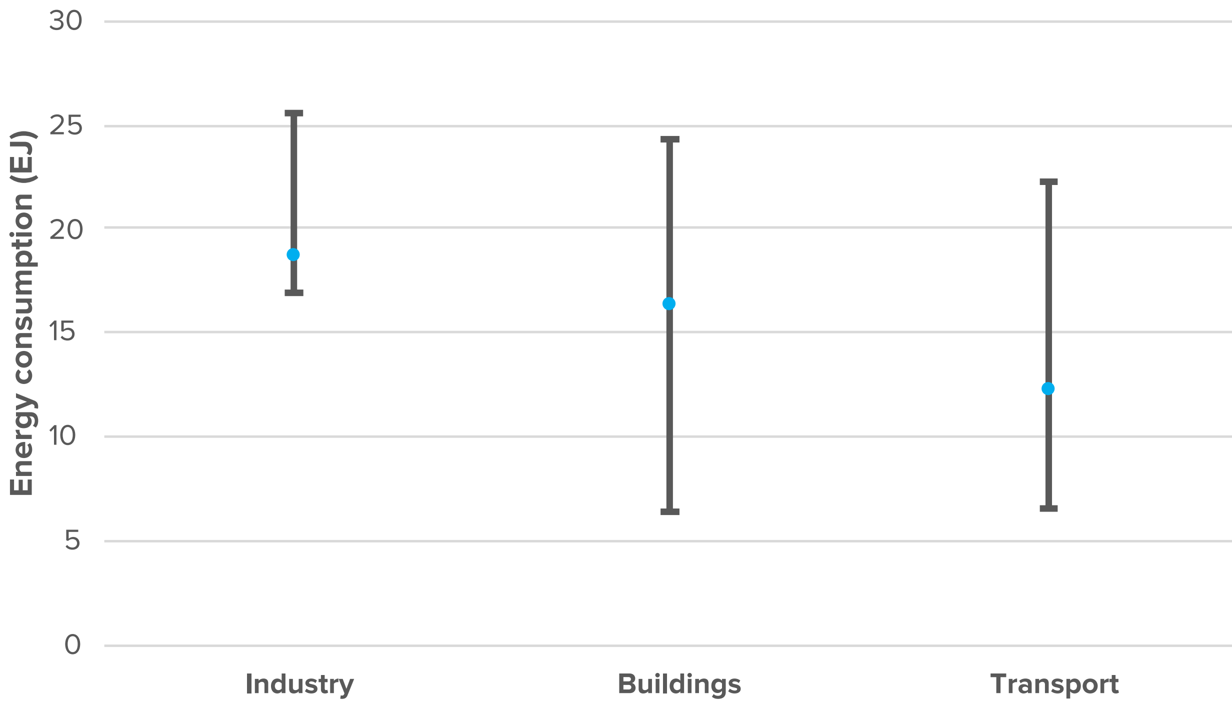
- The total amount of marginal land theoretically available for energy crops and the percentage of this marginal land that can be exploited practically in light of economic, logistical, and environmental constraints;
- The total amount of organic waste and residues that are theoretically available and can be reasonably leveraged; and
- The competition for land for other uses (including housing, conservation, animal grazing, and recreation), and for other bioproducts.

The second factor is cross-sector competition for biomass and biofuels. Biomass and biofuels are versatile commodities that can be used to decarbonize a myriad of different economic sectors. Often, these competing sectors are likely to be either more efficient users of the biomass (for example, on-site power generation, negative emissions with afforestation or bioenergy with carbon capture and storage (BECCS), bioplastic production, and heating), or where the economic value and technical requirement of an energy-dense fuel is even more pressing than in shipping (for example, aviation).

The current literature has not presented any conclusion on how these global markets for biomass and biofuels will evolve by 2050, and the outlook remains uncertain. Different scenarios exist at an energy system level. For example, IPCC (2018) provides the total primary energy requirement, the biomass availability, and the share of primary energy supply under various 1.5°C scenarios. The share of bioenergy is expected to increase to an estimated range of 15 to 25 percent of the total energy supply (IPCC 2018). Despite electrification, bioenergy continues to be important to industry, buildings, and transport sectors (for example, the aviation sector is a major demand player) as well as biomass combustion for electrical power in combination with CCS to provide a carbon "sink"—that is, BECCS to achieve net reductions in atmospheric CO_2 (IPCC 2018).

Figure 6 shows the median value and confidence range of bioenergy use for all pathways in line with a 1.5°C scenario under the Paris Agreement. Based on this analysis, approximately 6 to 22 EJ of biofuels would be available for the total transport sector (IPCC 2018).

FIGURE 6: BIOENERGY CONSUMPTION BY SECTOR FROM THE INTEGRATED ASSESSMENT MODEL PATHWAYS[9]



Using a similar system approach for the United Kingdom energy system, the Committee on Climate Change (CCC) (2018) concluded that the priority uses of biomass should be in the construction sector as wood for building material and in the energy sector to produce aviation fuel, hydrogen, and electricity, provided that BECCS applications become available. They recommend no use of biomass in shipping until 2050 as other zero-carbon options are more likely to better fulfil this role.

This report therefore suggests that only low volumes of biomass will be available for shipping's use and recommends that the economic consequences of the supply-and-demand dynamics are to be carefully factored in. These are discussed further in section 3.2.3.

3.2.3 Economic viability

Biofuels may appear to be more cost-effective than the synthetic fuels when a cost of production perspective is taken into consideration, and when considering only the cheaper-to-produce biofuel products. However, when projecting their economic viability out to 2050, the potential consequences of supply-and-demand dynamics need to be considered.

9 Points represent median energy (EJ) of the Integrated Assessment Model 1.5DS-All pathways; confidence ranges correspond to 25 to 75 percentiles. 1.5DS pathways combines both high and low overshoot 1.5 °C-consistent pathways. The graph is based on data from IPCC (2018).

Of the studies reviewed, CE Delft (2020) is by far the most optimistic regarding the ability to generate enough biofuel for the maritime industry. This is countered by Lloyd's Register and UMAS (2017 and 2019b), SSI (2019), RAE (2017), and Imhof (2019). The CE Delft (2020) conclusion may be explained by the narrow demand side perspective applied (using only demand from shipping). This makes the study an outlier to an extensive wider body of literature that is much less optimistic about the potential of biofuels. The other studies conclude that, while biofuels may be part of the fuel mix, bioenergy is unlikely to play more than a minor role in the decarbonization of the shipping sector. Therefore, bioenergy will face supply and/or economic viability constraints before reaching a significant share in the market for zero-carbon bunker fuels.

The physically constrained supply in combination with the potential for high cross-sector demand means that the future price projections for biofuels are highly uncertain. The pricing information used in this report for the assessment of economic viability of biofuels takes this into account. It uses the assumption that pricing will be driven by the cost of substituting fossil fuels with the cheapest non-volume-constrained alternative fuel and not by the current costs of producing alternative fuels (Lloyd's Register and UMAS 2020).

3.2.4 Technical and safety considerations

Bioethanol and biomethanol can be stored as liquids at ambient temperatures using cost-effective tank materials. However, it should be noted that both are corrosive and require the use of special materials, coatings, and corrosion inhibitors (European Maritime Safety Agency 2015 and ABS 2019).

LBM is chemically similar to liquefied natural gas (LNG), which is a globally traded commodity and already used as a bunker fuel. The standards and protocols needed for its adequate handling, storage, and use are therefore well-established. The major technical challenge for adoption is its storage temperature: LBM is cryogenically stored at approximately -162 °C in heavily insulated fuel tanks.

From a safety perspective, all biofuels considered in this report can pose a risk to humans due to asphyxiation if they leak, especially in small enclosed places. Methanol is particularly toxic to humans and can lead to skin and eye burns. In the case of leakage, LBM would not spread in water and poses no issue for aquatic life, while ethanol and methanol readily dissolve in water and rapidly biodegrade in the natural environment. The impact of fuel spillage is therefore limited.

Bioethanol, biomethanol, and LBM are flammable fuels that require the use of appropriate standards, protocols, and safety equipment. However, several methanol pilot projects such as Stena Germanica or GreenPilot have demonstrated that safety considerations are not a barrier to the use of methanol fuel systems on ships (European Maritime Safety Agency 2015 and DNV GL 2019).

3.3 HYDROGEN AND AMMONIA

The following sections review the key characteristics of hydrogen and ammonia as bunker fuels for shipping. Table 6 shows the fuels and energy-intensive process steps considered in this section.

TABLE 6: PROCESS PATHWAYS FOR THE PRODUCTION OF HYDROGEN AND AMMONIA

FUEL CATEGORIES	FUEL	PROCESS STEP: BIOFUEL SYNTHESIS	ELECTROLYSIS OF WATER	SMR WITH CCS	HABER-BOSCH PROCESS	DAC	HYDROGENERATION FOR ALCOHOLS SYNTHESIS
Hydrogen and ammonia	Green hydrogen		√				
	Blue hydrogen			√			
	Green ammonia		√		√		
	Blue ammonia			√	√		

3.3.1 Lifecycle GHG emissions and air quality impacts

Lifecycle GHG emissions

Hydrogen and ammonia fuels do not contain any carbon (this is why they are also referred to as synthetic non-carbon-based fuels) and do not release any CO_2 when used on board a vessel. The following lifecycle GHG assessment focuses accordingly on the production, distribution, and storage processes. As can be seen from Table 6, hydrogen and ammonia can be produced via two main pathways denoted as “green” and “blue.”

“Green” fuels are derived from hydrogen produced from the electrolysis of water powered by renewable electricity. When used directly as a fuel, green hydrogen is usually liquefied to improve its volumetric energy density. In order to avoid any related GHG emissions, the liquefaction process must use renewable electricity.

BOX 3: A DESCRIPTION OF ELECTROLYSIS

Electrolysis uses electricity to split water into a hydrogen stream and an oxygen stream. If renewable electricity is used, then there are no GHG or air quality concerns associated with the process. A lack of access to sufficient quantities of fresh water may require desalination plants to convert sea water into fresh water.

If not used directly as a fuel, green hydrogen can serve as a feedstock in a transformation process producing other fuels such as ammonia. Green ammonia is produced by combining green hydrogen with nitrogen using the Haber-Bosch nitrogen fixation process (see Box 4). The energy required for the Haber-Bosch process also needs to come from renewable energy in order to generate green ammonia.

BOX 4: HABER-BOSCH PROCESS

The Haber-Bosch process is the most common method for producing ammonia from previously processed hydrogen and nitrogen harvested from the air. The production of ammonia from hydrogen is straightforward, with a virtually unlimited supply of nitrogen available from the atmosphere.

The Haber-Bosch process requires energy input to perform the fixation. This energy needs to come from a form of renewable energy in order to generate green ammonia. The Haber-Bosch process only represents about six percent of the electricity demand of a typical green ammonia plant, while the electrolyzers consume about 92 percent (Ash and Scarbrough 2019).

When powered by renewable electricity, green hydrogen and green ammonia do not create any GHG emissions across their entire lifecycles, from production to use. Therefore, they represent true zero-carbon fuels. It should be noted, however, that depending on the propulsion system and type of ignition or pilot fuel, ammonia engines can emit unburnt ammonia, carbon monoxide, hydrocarbons (e.g., from unburnt ignition or pilot fuel), NO_x, and nitrous oxide (N_2O) (Grannel et al. 2009, Hansson et al. 2020). Ammonia can be used with a spark-ignited internal combustion engine, with a compression ignition internal combustion engine in combination with a pilot fuel, or with fuel cells (Hansson et al., 2020, Grannel at al. 2009). Spark-ignited internal combustion engines, when using a hydrogen/ammonia fuel mix, were found to emit NO_x and N_2O but no hydrocarbon or carbon monoxide (Hansson et al. 2020). On the contrary, compression-ignition internal combustion engines emit carbon monoxide and hydrocarbon proportionally to the concentration of the pilot fuel in the fuel mix. They also emit N_2O (Grannel et al. 2009). However, these emissions can be handled with after-treatment such as three-way catalyst or selective catalytic reduction/exhaust gas recirculation (Hansson et al. 2020).

Blue fuels are similar to green fuels, with the main difference being the hydrogen production method. Blue hydrogen is produced using fossil fuels whose carbon emissions are captured and stored rather than being released into the atmosphere. This report considers hydrogen production from natural gas using steam methane reforming (SMR) in combination with CCS. While autothermal reforming is also in use, SMR represents the most widespread technology for hydrogen production from natural gas at large scale today. It is also likely to remain the dominant technology in the near term thanks to its favorable economics and the large number of existing SMR units globally (IEA 2019).

BOX 5: A DISCUSSION OF CCS

The CCS process captures the carbon from the SMR process as CO_2, compresses it and stores it underground in geological storage sites. Traditionally, CCS plants have not captured all generated CO_2 emissions, with capture rates estimated to be between 90 to 95 percent (IEA 2014c). However, the International Energy Agency Greenhouse Gas R&D Program (IEAGHG) (2019) also finds that there are no technical barriers to achieving capture rates greater than 99 percent. They also indicate that the additional costs are modest in comparison with the cost of achieving the more traditional 90 percent capture rate.

As a real-world example, IEAGHG (2017) references the hydrogen plants at the Idemitsu Kosan Hokkaido refinery, which have shown a capture rate of 99.9 percent. The IEAGHG (2019) study calls for these higher rates to be further demonstrated at scale across the full range of the available capture technologies. The study also notes that, as CO_2 capture rates increase, the indirect emissions from fossil fuels become the dominant factors in the lifecycle carbon emissions of the resulting blue hydrogen. Blue hydrogen is likely to be consistent with the Initial IMO GHG Strategy to reduce emissions from international shipping by at least 50 percent over the next 30 years. However, over the long term the remaining upstream emissions (that is emissions produced during the extraction of natural gas and SMR) still need to be captured and stored, too. This suggests that it may be better to phase out blue hydrogen in favor of 100 percent decarbonized green fuels.

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CCS is seen as a key technology in the decarbonization journey of many developed nations, with a number of active CCS plants around the world in North America or countries like Norway. Its importance is also noted in many decarbonization scenarios at the energy system level where an important role is given to CCS in order to achieve the Paris Agreement's temperature goal. However, CCS technology is not yet a mainstream technology that is routinely applied to abate GHG emissions from fossil fuels or to store CO_2 extracted from the atmosphere. This is partly because its sole value is in capturing and storing CO_2. Therefore, the industry usually requires a high carbon price or policy signal to support the substantial investments needed. As well as a suitably scaled supply chain and finance, CCS also needs particular geological features to allow the safe and long-term storage of the compressed CO_2. This implies that some countries are better endowed with the ability to use CCS than others.

Full-scale blue fuel supply is dependent on the availability of equivalent scale CCS plants, which is subject to some uncertainty according to Lloyd's Register and UMAS (2019b).

As with green hydrogen, blue hydrogen can be used as a bunker fuel or as a feedstock to produce blue ammonia. As discussed above, the lifecycle GHG performance of blue hydrogen and blue ammonia is a function of the GHG emissions associated with the extraction of the natural gas and the capture rate of the CCS technology. As CCS technology capture rates advance as per IEAGHG (2019), then upstream activities linked to methane leakage during the extraction of natural gas become the dominant source of emissions and need to be strictly controlled. Based upon this literature review and the definition applied in Box 2 in section 1, blue hydrogen and blue ammonia are deemed to be zero-carbon fuels.

Next to SMR, methane pyrolysis represents another production pathway to produce blue[10] hydrogen (ESMAP 2020). Following this production pathway which is also called methane splitting, high temperatures are applied to break methane into hydrogen and carbon. The process heat energy required to enable the reaction can be provided by fossil fuels with CCS, renewable energy, or the hydrogen itself. In contrast to SMR, the methane pyrolysis reaction yields solid carbon as a by-product, which can be easily stored or commercialized as a feedstock for industrial processes (IEA 2019). The end-use is critically important to the characterization of the lifecycle GHG emissions of this source of hydrogen. The hydrogen produced can only be considered equivalent to other zero-carbon hydrogen if the solid carbon product is permanently sequestered or stored with no risk it may subsequently oxidize and enter the atmosphere as a GHG. Having the carbon in solid rather than in gaseous form eliminates the requirement for complex and costly CCS. However, methane pyrolysis technology is still at an early stage of development (Pöyry 2019). While methane pyrolysis has not been considered further in this report, this alternative production pathway of blue hydrogen may provide an additional option in countries where widespread deployment of CCS may not be possible.

10 Though hydrogen from methane pyrolysis is sometimes also referred to as "turquoise" hydrogen.

Nonetheless, as for SMR, lifecycle GHG emissions matter. Not only the origins of the process heat in methane splitting can have a significant impact on the lifecycle GHG performance of the hydrogen produced but also the upstream emissions in the natural gas supply chain. In fact, lifecycle GHG emissions of blue hydrogen are estimated to be similar for methane pyrolysis using process heat from renewable electricity or SMR with CCS. Yes, they are still higher than in the case of green hydrogen from electrolysis powered by renewable electricity—the decisive factor being the methane leakage associated with the natural gas supply (Timmerberg et al. 2020).

Air quality impacts

Regarding air pollutants, hydrogen is considered to be the cleanest bunker fuel currently available (ABS 2019), emitting no NO_x emissions when used in a fuel cell. Ammonia can also be used in a fuel cell system and NO_x emissions were not detected in the exhaust gas from such a set up (Okanishi et al. 2017).

When used in an internal combustion engine, hydrogen can emit NO_x, with the level of emissions depending on the operating strategy used (a “rich” versus “lean” air/fuel ratio), which can produce from almost zero emissions (as low as a few ppm) to high NO_x, while ammonia produces unburned ammonia and NO_x when used in an internal combustion engine. In both instances, exhaust clean-up technologies such as selective catalytic reduction can be used to decrease emissions.

3.3.2 Economic viability

Hydrogen fuel costs

The cost of hydrogen depends on the production method: green versus blue hydrogen. Currently, and for the foreseeable medium term, green hydrogen costs more to produce than blue hydrogen. The IEA (2019), for example, provides hydrogen production costs for different technology options, and estimates that the cost of producing green hydrogen could range from \$2 to \$4 /kgH_2 in 2030, while the cost of producing blue hydrogen could range from \$1.5 to \$3.2 /kgH_2. The limiting factor for the availability of blue hydrogen in both the mid- and long-term is the available CCS capacity (as discussed in Box 5).

In the long term, the rapid development of electrolyzer technologies and a transition to inexpensive renewable electricity supply (IEA 2014a and Lloyd’s Register and UMAS 2019a) are expected to reduce the cost of green hydrogen until 2050. Consequently, blue hydrogen is expected to be the less expensive fuel in the medium term (until 2030), while green hydrogen is likely to be cheaper than blue hydrogen in the longer term (2030 to 2050).

Ammonia fuel costs

Ammonia needs to be produced from hydrogen (either green or blue) as a feedstock, giving hydrogen a natural cost advantage. However, when considering hydrogen versus ammonia from a shore-side price perspective, there is a clear trade-off to make: hydrogen requires liquefaction to cryogenic temperatures (-235°C) to improve its energy density to a useful level, thereby requiring expensive storage and transport systems. These storage and shore-side transport challenges of hydrogen result in an economic cost that can be weighed against the cost of the Haber-Bosch process needed to create ammonia from hydrogen. When compared to hydrogen, ammonia is more energy-dense on a volumetric basis and can be stored in liquid form at much higher temperatures (-33°C), making it significantly cheaper to transport and store. This results in a comparable shore-side cost for both hydrogen and ammonia. The exact balance of these costs will be a function of the storage volumes and the distances from production locations to points of consumption. Therefore, it is estimated that liquefied hydrogen and ammonia will have similar costs as zero-carbon bunker fuels.

In summary, blue hydrogen and blue ammonia are expected to be less expensive in the medium term (to 2030), while green hydrogen and green ammonia are expected to be cheaper out to 2050, respectively.

Overall economic viability

Other economic factors influence the viability of hydrogen and ammonia. These factors include the capital cost of onboard storage, and the reduction in revenue due to the loss of cargo space. This loss in cargo space is driven by the relative energy densities of the fuels when compared to each other and to heavy fuel oil. When onboard storage costs of and cargo revenues losses from hydrogen are compared with those of ammonia, the balance is tipped in favor of ammonia. Lloyd's Register and UMAS (2019a) calculate this trade-off for a specific ship type and size, providing an example of the overall cost of ownership trade-off. The study concludes that amongst all the zero-carbon fuel alternatives, green ammonia consistently turns out to be the most cost-effective alternative fuel in the long run, with blue ammonia being the least costly in the medium term followed by green ammonia to 2050.

It is important to note that internal combustion engines running on ammonia are not commercially available for ships yet. However, the largest manufacturers of ship main engines have ongoing development programs and have announced plans that such engines will be in production by 2024. For instance, the Finnish engine manufacturer Wärtsilä and the Norwegian shipping group Grieg Star are planning to launch an ammonia-fueled tanker by 2024 (Wärtsilä 2020). Similarly, major engine manufacturer MAN Energy Solutions aims to offer a commercially available two-stroke ammonia engine by as early as 2024, and an ammonia retrofit package for existing vessels from 2025 (MAN 2020).

3.3.3 Technical and safety considerations

The technical and safety considerations are identical for blue and green varieties of both hydrogen and ammonia. This section therefore discusses hydrogen and ammonia generally.

The first technical consideration is the storage temperature. As mentioned previously, hydrogen is stored at -235°C and ammonia at -33°C. This makes ammonia much cheaper and easier to store. From an energy-density perspective, liquefied ammonia is also superior, with a volumetric energy density that is approximately 40 percent greater than liquefied hydrogen.

One area where hydrogen scores over ammonia is when considering toxicity to humans and aquatic life. Ammonia is a particularly toxic substance and can lead to skin and eye burns. Furthermore, any spillage of ammonia would damage aquatic life. The safety hazards posed by ammonia therefore require careful management. However, it is worth noting that ammonia already is a globally traded commodity with mass transport via ammonia tankers. The major challenge would be to leverage and translate existing safety protocols so that ammonia can also be used as a propulsion fuel.

Conversely, hydrogen is non-toxic and disperses quickly in the natural environment. However, hydrogen is highly flammable and once again appropriate standards, protocols, and safety equipment will be required before hydrogen can be used on board a vessel. Both hydrogen and ammonia can cause asphyxiation (risk of suffocating) if they leak, particularly in small, enclosed places, and this must be considered in vessel design.

3.4 SYNTHETIC CARBON-BASED FUELS

The following sections review the key characteristics of green liquefied synthetic methane, green synthetic methanol, and blue synthetic methanol as bunker fuels for shipping. As in the previous section, "green" is used to denote fuels that use hydrogen from electrolysis and "blue" denotes fuels based on hydrogen from SMR combined with CCS. Table 7 shows the fuels and energy-intensive process steps considered in this section.

TABLE 7: PROCESS PATHWAYS FOR THE PRODUCTION OF SYNTHETIC CARBON-BASED FUELS.

		PROCESS STEP					
FUEL CATEGORIES	FUEL	BIOFUEL SYNTHESIS	ELECTROLYSIS OF WATER	SMR WITH CCS	HABER-BOSCH PROCESS	DAC	HYDROGENERATION FOR ALCOHOLS SYNTHESIS
Synthetic carbon-based fuels	Green liquefied synthetic methane		√			√	√
	Green synthetic methanol		√			√	√
	Blue synthetic methanol			√		√	√

3.4.1 Lifecycle GHG emissions and air quality impacts

Lifecycle GHG emissions

Synthetic carbon-based fuels (man-made fuels that contain both hydrogen and carbon) require a source of hydrogen and carbon for their production (see Figure 1). During the land-based production process, this carbon input is captured from the atmosphere in the form of CO_2 using DAC technology (see Box 6). When the fuel is used on board a vessel, the CO_2 is released back in the atmosphere, creating a net-zero carbon cycle.

BOX 6: DISCUSSION OF DAC TECHNOLOGY

Direct air capture (DAC) technology captures CO_2 directly from the atmosphere. The challenge for this process is to do so in an efficient and cost-effective manner due to the low concentration of CO_2 in the atmosphere (approximately 400 parts per million). This low concentration leads to large volumes of capture equipment and high renewable energy consumption. Therefore, this form of captured CO_2 is relatively expensive.

As with CCS, there is some uncertainty about the long-term costs and scalability of DAC due to limited industrial experience with plants which do not operate at scale.

The hydrogen used in the production of synthetic carbon-based fuels can be either green or blue, implying the full range of pros and cons previously discussed.

Once the hydrogen and carbon streams become available, they can be combined to synthesize the final carbon-based synthetic fuel. This synthesis consumes considerable amounts of energy that must be provided in a renewable manner to avoid emitting GHG in the fuel production process. The synthesis processes for methane and methanol are mature, using technology already operated at scale.

By using zero-carbon hydrogen, capturing CO_2 from the atmosphere, and using renewable energy to run the various processes, synthetic carbon-based fuels can be deemed true zero-carbon fuels. If the CO_2 is captured from more concentrated combustion gases (for example, exhaust gas from a power plant running on fossil fuels), it cannot be considered to be a zero-carbon fuel as it still relies on fossil-fuel energy (Korean Register 2020). Capturing CO_2 from the consumption of fossil fuels and releasing it in the atmosphere upon the use of the fuel still results in a net increase in CO_2 emissions overall.

Air quality impacts

For the fuels considered in this report, air quality impacts are a function of both the chemical composition of the fuel and the method used to convert that fuel into propulsive effort. Synthetically produced methane and methanol accordingly have the same air quality implications as biomethane and biomethanol. Both can be used in an internal combustion engine or a fuel cell with a fuel reformer. The fuel cell process emits only CO_2 and water, while the internal combustion engine may require abatement measures to reduce NO_x emissions to acceptable levels.

3.4.2 Economic viability

As discussed in previous sections, the economic viability of a particular fuel is tied to several key economic parameters, as shown in section 3.1. Taking these factors in turn, the first issue to consider is the impact of fuel cost on the overall voyage costs. While this section focuses on specific capital and operational expenditures, it is the total cost of ownership which ultimately determines the economic viability of a given fuel, as described in section 3.1.

Synthetic carbon-based fuels involve the greatest number of production steps. Starting with hydrogen, which can be used as a fuel on its own, synthetic carbon-based fuels also require DAC as well as hydrogenation for alcohol synthesis. Both the DAC and synthesis stages require significant capital and operational expenditures (especially in the form of the production of renewable electricity needed as energy input). This makes these synthetic carbon-based fuels relatively expensive compared to hydrogen and ammonia.

The remaining economic parameters of interest are the capital costs required on board vessels and the revenue loss due to the larger fuel tanks required for these fuels. In this respect, synthetic carbon-based fuels face the same cost issues and trade-offs as their biofuel equivalents, as their physical characteristics are a function of their chemistry and not their production method.

Green liquefied synthetic methane shows similar capital costs and storage impacts as biomethane and LNG, while green synthetic methanol and blue synthetic methanol have the same characteristics as biomethanol. While these fuels are generally cheaper and easier to store and transport than liquefied hydrogen—for instance, transporting hydrogen in the form of synthetic methanol may be only marginally more expensive than ammonia (Aurora Energy Research 2021)—these benefits are not likely to outweigh the high fuel production costs associated with synthetic carbon-based fuels in general (Lloyd's Register and UMAS 2020).

3.4.3 Technical and safety considerations

As with the vessel-level cost implications, the technical and safety aspects are a function of fuel chemistry rather than production method. Section 3.2.4 discusses methane and methanol from technical and safety perspectives.

3.5 PRELIMINARY LESSONS LEARNED

The literature review in section 3 has revealed and discussed the complexity of the zero-carbon bunker fuel landscape—in particular the various considerations and trade-offs to be made in selecting the most promising fuels for further analysis:

- While biofuels can serve as acceptable zero-carbon bunker fuels with reasonable costs in the short term, increasing pressure on land-use (food production for a growing population, afforestation for increasing carbon sinks) and anticipated increases in demand from a number of other sectors are likely to result in constraints on the overall supply. For the most critical period of rapid shipping decarbonization from 2030 to 2050, this report therefore concurs with the Committee on Climate Change (CCC 2018) that the role of bioenergy in shipping may be constrained to niche uses only. As a consequence, the major share of the future shipping fuel mix may need to come from another zero-carbon fuel or energy source.

- Hydrogen and ammonia appear to become the cheapest zero-carbon bunkers fuels to produce. However, they present their own challenges: hydrogen is expensive to store and handle, while ammonia is more inexpensive to store and transport but remains toxic to humans and aquatic wildlife.

- Synthetic carbon-based fuels offer technical and safety advantages similar to the selected biofuels. However, while they also offer these benefits relative to hydrogen and ammonia, they appear expensive and inefficient to produce due to the extensive process involved in production. Their use in a decarbonized economy would also depend on a technology such as DAC, which remains unproven at scale so far.

The following section presents an analysis of the information and data reviewed and discussed above. Where available, and directly comparable, quantitative information has been used to allocate red, amber, and green designations.

3.6 IDENTIFICATION OF MOST PROMISING ZERO-CARBON BUNKER FUEL OPTIONS

To select the most promising zero-carbon candidate fuels for the following assessment of potential, the key criteria identified in the literature and discussed in section 3 are used to populate a "Red Amber Green" (RAG) matrix, which is a common decision-making aid. A "RAG" analysis is a visual way of considering a number of options against a wide range of criteria and sources of information. Each option is assessed against a range of criteria and scored red for poor performance against that criteria, amber for a mid-level score, and green for a good score. The information is then presented as a summary table. This RAG matrix and conclusions drawn from it are used to identify the top zero-carbon fuel candidates for further analysis.

As discussed in section 3.1, the most relevant criteria for future zero-carbon bunker fuels identified in the literature can be grouped into three categories: environmental, economic and technical/safety criteria. Figure 7 displays the scoring for each criterion defined in section 3.1 in the RAG matrix. Unless otherwise stated, the coloring of each criterion includes the consideration across the entire lifecycle of the fuel (including the energy source, production methods, transportation, and use on board a ship).

The RAG matrix compiles the findings of the literature review and provides a visual overview of the discussion of each fuel in section 3. In combination with section 4, it allows the reader to draw the following main conclusions on the viability of the various zero-carbon fuels for shipping:

1. **Green versus blue:** In the mid-to-long-term, green hydrogen and green ammonia appear to receive the best overall criteria scores, mainly due to their scalability and excellent environmental and economic scores.
2. **Hydrogen and ammonia:** Green ammonia may be preferred over green hydrogen due to the cost and volume requirements linked to onboard hydrogen storage. However, this assumes that ammonia's toxicity risk can be contained to an acceptable level.
3. **Multiple production pathways:** Both blue and green hydrogen and ammonia fuels benefit from allowing for multiple production pathways. This provides additional strategic strength to their consideration as it further reduces concerns about capacity limits and technology issues. Indeed, it may prove economically beneficial to start shipping's energy transition with blue hydrogen/ammonia and

then transition to their green counterparts as renewable electricity prices drop. However, this could also present a stranded asset risk (for blue hydrogen and ammonia assets), which would need to be carefully assessed.[11]

4. **Role of CCS:** Blue hydrogen and blue ammonia depend on the successful scale-up of CCS technology.

5. **Internal combustion engine versus fuel cells:** All of the fuels considered (including hydrogen and ammonia) can be used in an internal combustion engine. However, the most promising fuels are also compatible with fuel cell solutions, which provide advantages such as increased energy efficiency and lower air pollutant emissions.

6. **Biofuels:** Without a breakthrough in aquatic biomass production, biofuels are likely to be limited by their sustainable availability and the resulting supply-and-demand dynamics. They may well be part of the maritime industries' future fuel mix, but they are unlikely to provide the major share of shipping fuel mix in 2050.

7. **Synthetic carbon-based fuels:** If biomass is constrained and the practical storage and safety issues of hydrogen and ammonia cannot be overcome, then the industry may have to accept the higher costs of green liquefied synthetic methane or green/blue methanol. However, these fuels also depend on a large-scale deployment of currently immature DAC technology

11 Assets that "have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities." (Caldecott, Tilbury, and Carey 2014).

FIGURE 7: RAG MATRIX FOR THE ZERO-CARBON BUNKER FUEL OPTIONS

		LIQUEFIED BIOMETHANE	BIOETHANOL	BIOMETHANOL	GREEN HYDROGEN	GREEN AMMONIA	GREEN SYNTHETIC METHANOL	GREEN LIQUEFIED SYNTHETIC METHANE	BLUE HYDROGEN	BLUE AMMONIA	BLUE SYNTHETIC METHANOL
Feedstock		Livestock manure, food waste, sewage sludge	Lignocellulosic biomass		Non-biogenic renewable energy (solar, wind, geothermal, etc.)				Natural gas		
Energy carriers					Renewable electricity	Renewable electricity & hydrogen			Hydrogen		
Key Technologies					Electrolyzer	Electrolyzer, Haber-Bosch	Electrolyzer, DAC		SMR, CCS	SMR, CCS, Haber-Bosch	SMR, CCS, DAC
Environment	**Carbon and GHG operational emissions**	Red	Red	Red	Green	Green	Red	Red	Green	Green	Red
	Net-zero	Amber	Amber	Amber	Green	Green	Green	Green	Amber	Amber	Amber
	Potential for volume and sustainability constraint	Red	Red	Red	Green	Green	Green	Green	Amber	Amber	Amber
	Air pollutant emissions	Amber	Amber	Amber	Green	Amber	Amber	Amber	Green	Amber	Amber
	Unintended consequence (land-use changes)	Red	Red	Red	Green	Green	Green	Green	Green	Green	Green
Economics	**Key technologies development status**	Green	Green	Green	Amber	Amber	Red	Red	Red	Red	Red
	Key technology scalability	Green	Green	Green	Green	Green	Amber	Amber	Amber	Amber	Red
	Competitiveness today	Amber	Amber	Amber	Red	Red	Red	Red	Red	Red	Red
	Competitiveness in 2030	Red	Red	Red	Red	Amber	Red	Red	Amber	Amber	Red
	Competitiveness in 2050	Red	Red	Red	Amber	Green	Red	Red	Amber	Green	Red
	Energy efficiency	Green	Green	Green	Green	Amber	Red	Red	Green	Amber	Red

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		LIQUEFIED BIOMETHANE	BIOETHANOL	BIOMETHANOL	GREEN HYDROGEN	GREEN AMMONIA	GREEN SYNTHETIC METHANOL	GREEN LIQUEFIED SYNTHETIC METHANE	BLUE HYDROGEN	BLUE AMMONIA	BLUE SYNTHETIC METHANOL
Technical/ safety	Temperature for liquid storage										
	Storage volume on board										
	Toxic to humans										
	Toxic to aquatic life										
	Flammability										

From the reasoning above, ammonia (either green or blue) is considered the most promising zero-carbon bunker fuel option, followed by hydrogen (again green or blue). The preference for ammonia is validated by a range of quantitative analyses in the literature. Both Det Norske Veritas Germanischer Lloyd (DNV GL) (2019) and Lloyd's Register and UMAS (2019c) conclude that ammonia is most likely to become the main zero-carbon fuel by 2050 in a scenario where the use of renewable energy significantly grows and dominates the electricity market. This is also in line with Ash and Scarbrough (2019) and Imhof (2019), who find that ammonia is the most likely fuel pathway for shipping's decarbonization. In ABS (2019); DNV GL (2019); Lloyd's Register and Shipping in Changing Climates (2016); and Lloyd's Register and UMAS (2017) and (2019c), hydrogen-based fuels are all considered to be credible candidates to become a zero-carbon fuel for shipping. When the studies differentiate between ammonia and hydrogen, the former is preferred (DNV GL 2019; Imhof 2019; Lloyd's Register and UMAS 2017).

This fuel analysis helps to provide a clearer framing of the subsequent assessment of countries. It should be noted that, should this analysis be subsequently proven to be inaccurate, and other synthetic fuels (that is, synthetic carbon-based fuels) turn out to become the preferred pathway of the sector, then the subsequent section's assessment will still be valid. The key driver of competitiveness in the production of all these synthetic fuels is the low-cost supply of zero-carbon hydrogen (which depends on either low costs of renewable electricity, or access to low-cost CCS technology). Synthetic carbon-based fuels, in addition, require low-cost renewable electricity for DAC, similar to the electricity requirements for low-cost green hydrogen. All conclusions from section 4 should accordingly be seen as "synthetic fuel agnostic." They remain indicative of a country's likely potential to become a producer in future synthetic bunker fuel supply chains, regardless of the outcome of further work on the most promising synthetic fuel.

When considering potential production countries in section 5, and where appropriate, both production pathways for producing ammonia and hydrogen (blue and green) are included. This is because of the possibility to substitute blue ammonia/hydrogen with green ammonia/hydrogen, should the production costs and lifecycle GHG emissions become more favorable.

4. ASSESSMENT OF THE POTENTIAL OF COUNTRIES TO SUPPLY FUTURE ZERO-CARBON BUNKER FUELS

The previous section 3.6 discussed the most promising zero-carbon bunker fuel options and subsequently selected ammonia and hydrogen, either produced from renewable electricity or natural gas in conjunction with carbon capture and storage (CCS). In this section, a high-level assessment is performed to assess which countries may be well positioned to supply these selected zero-carbon bunker fuels in the future.

This assessment is made against five key criteria and a score is assigned for each criterion. These scores are then combined to create a weighted composite score, and countries grouped accordingly into three tiers ("high potential," "promising potential," and "limited potential or insufficient data") reflecting their potential to produce zero-carbon bunker fuels.

As mentioned in section 3.6, a key input required for all green and blue fuels is the supply of low-cost zero-carbon hydrogen. This means that the competitiveness of a particular country is broadly the same for all hydrogen-derived synthetic fuels. As a consequence, the following high-level assessment looks at each country's potential to produce low-cost zero-carbon hydrogen as a key ranking criterion.

The high-level assessment is repeated for three different energy input scenarios to provide insights into each country's mid-term and long-term zero-carbon bunker fuel production potential:

1. **First scenario:** Countries are evaluated to identify those well positioned to produce ammonia or hydrogen from natural gas in conjunction with CCS.
2. **Second scenario:** Countries are assessed to identify those well positioned to produce ammonia or hydrogen from renewable energy sources.
3. **Third scenario:** Countries are examined to determine those well positioned to produce ammonia or hydrogen from natural gas in conjunction with CCS initially, and move to a production pathway based on renewable energy sources eventually.

The following sections define the assessment criteria chosen and examine the available data to produce an evidence-based composite score. The importance of each criterion is discussed, and corresponding weights are assigned. Finally, results are presented, and conclusions drawn.

4.1 DEFINITION OF THE ASSESSMENT CRITERIA AND DATA SOURCES

To date, it seems likely that no other analysis has evaluated the potential for countries to become major hydrogen and/or ammonia producers using a ranking or sifting method on a global level. However, the International Renewable Energy Agency (IRENA) (2019) and Ash et al. (2019) both highlight individual countries which could be promising candidates and qualitatively justify their choice. The World Energy Council Germany (2020) and IRENA (2020) list several countries where initiatives to increase hydrogen production currently exist, while Ash et al. (2019) conduct two case studies in Morocco and Chile, which could become ammonia producers based on their large untapped renewable energy potential. This report has chosen five criteria to assess whether a country will be well positioned to supply zero-carbon bunker fuels in the form of ammonia or hydrogen in the future:

1. Energy resources required;
2. Shipping volumes;
3. Geographic location;
4. Adequacy of current and projected regulatory framework; and
5. Potential to leverage existing infrastructure.

The following sections detail the indicators and methods used to calculate a score for each of these criteria, as well as the data sources used.

4.1.1 Energy resources required

For a country to become a major producer of zero-carbon ammonia or hydrogen, it is of utmost importance that it can rely on sufficient energy resources. Based on the selected fuel production pathways, this high-level assessment uses three different energy input scenarios:

1. **First scenario: Blue ammonia/hydrogen production only**. Scores are based on current and potential natural gas production, and the potential of CCS of the country under discussion.
2. **Second scenario: Green ammonia/hydrogen production only**. Scores are based on the renewable energy potential of the country under discussion.
3. **Third scenario: Blue ammonia/blue hydrogen first, green ammonia/hydrogen later**. This scenario combines both previous energy input scenarios, with greater emphasis placed on the long-term renewable energy potential.

Currently, this high-level assessment takes into account the energy resources available within a country's national boundaries only.

First scenario: blue ammonia/hydrogen production only

In this scenario, the current natural gas production, the proved natural gas reserves and the CCS potential are examined. Natural gas availability is derived by combining natural gas production and proved reserves with equal weights. The product of normalized natural gas availability and CCS serves as a proxy for the energy resources required for the production of zero-carbon blue ammonia/hydrogen.

Data on the current natural gas production and proved natural gas reserves[12] were collected from the United States Energy Information Administration (EIA) website for the years 2018 and 2020, respectively. It is important to note once again that this high-level assessment assumes that the country under consideration can only take advantage of natural gas resources within its national boundaries.

The CCS Indicator produced by the Global CCS Institute (2018) is used to assess a country's CCS potential. This is a composite indicator tracking the development of commercially viable resources for CCS, based on natural geological storage potential, maturity and confidence of storage resource assessments, and experience in CO_2 storage projects and facilities. Countries which are not reported are given a score of zero.[13] It should also be noted that, similarly to natural gas, this high-level assessment assumes that the country under consideration can only use its own national CCS potential.

Second scenario: green ammonia/hydrogen production only

The second scenario examines the weighted average of two normalized indicators: renewable electricity capacity (weighted at ten percent) and renewable energy

12 Data was missing for Lithuania and South Africa, and a value of zero was imputed as previous years reported zero gas reserves for these countries. United States data was missing for 2020 and therefore 2019 data was reported instead.

13 This is purely due to a lack of data and not an indication for any country's inexistent potential. In fact, Kearns et al. (2017) suggest in a regional assessment that, for most regions, storage capacity is not likely to be a limiting factor for large-scale CCS deployment. To further inform this discussion, the World Bank (2021 forthcoming) is currently developing an additional CCS index for countries.

potential (90 percent). These weights reflect the fact that current renewable electricity capacity is unlikely to indicate the full size of additional capacity available. Once again, only own energy resources within the national boundaries are considered.

The renewable electricity capacity indicator includes current electricity production from all renewables other than biomass. This represents the presence or absence of a renewable electricity supply chain that can be scaled up in the medium or longer term. Current renewable electricity capacity data was collected from the United States Energy Information Administration website for the year 2019 and is expressed in millions of kW (EIA).

The renewable energy potentials indicator represents the surplus of renewable energy resources that could be dedicated to the production of green ammonia/green hydrogen. The sum of several normalized parameters[14] is used as proxies for this indicator: the long-term yearly average of potential photovoltaic electricity production (PVOUT) in kilowatt hour per kilowatt peak (kWh/kWp per day),[15] covering the period 1994 to 2018 provided by the Global Solar Atlas, is used as a proxy for solar potential (Global Solar Atlas).[16] Onshore wind potential has been proxied by the mean power density provided by the Global Wind Atlas in Watt per square meter (W/m^2) in the ten percent windiest areas in the country (Global Wind Atlas).17 Offshore wind potential has been retrieved from the United States Department of Energy and is expressed in Terawatt hour (TWh) and represents absolute potential within 100 nautical miles offshore for each country (United States Department of Energy). Finally, exploitable hydropower potential is taken from (Zhou et al. 2015), who calculate figures based on runoff and stream flow data, turbine technology performance, cost assumptions, and consideration of protected areas. This data is expressed in TWh and is further transformed to W/m_2 for consistency with the solar and wind variables.

Third scenario: blue ammonia/hydrogen first, green ammonia/hydrogen later

The third scenario consists of the production of blue ammonia/hydrogen in the beginning, and a gradual transition toward the production of green ammonia/green hydrogen at a later stage. For this scenario, a weighted average of the first (30 percent) and second (70 percent) scenarios is calculated, reflecting the greater importance of the long-term production of green ammonia/hydrogen.

4.1.2 Shipping volumes

Shipping volumes—defined in terms of capacity of vessels calling at a country's ports and their estimated fuel consumption—are also relevant. Leveraging these

14 In some cases, these parameters refer to the technically exploitable potential without consideration of environmental and social safeguards which can make the full exploitation of the renewable energy resources available challenging or impossible.

15 Kilowatt "peak" is the peak power of a photovoltaic system, calculated under standardized tests for panels

16 Data was compiled for each selected country, except Finland, Greenland, and Iceland, because they are located at a too high latitude for the model to provide any estimation. A value of zero was therefore reported for them.

17 Taiwan, China is not reported; therefore, the wind potential was extracted for an approximated shape on the island. No potential was reported for Gibraltar.

volumes can be the first entry point for countries interested in bringing their zero-carbon fuels to a market. Large volumes at domestic ports provide a competitive advantage in this regard.

The shipping volumes criterion uses the total annual fuel consumption of all the vessels that call at the ports of a country as an indicator. While not a direct representation of the fuel sales opportunity, it still does provide a useful metric for comparing different countries. The indicator is calculated by taking the average size of vessels calling at a country by type (for example, the average container ship size). This average is then converted into an annual fuel consumption based upon its size class (for example, 5000 to 8000 twenty-foot-equivalent units (TEU). This average fuel consumption is then multiplied by the number of port calls that this vessel type makes. The process is repeated for all vessel types. Finally, the total fuel consumption in a country for each vessel type is summed up to create a single figure. This final figure is normalized on a scale from zero to five. The number of arrivals and the average cargo carrying capacity stems from the UNCTAD port call and performance statistics for 2018.[18] The average fuel consumption per ship type and ship size is taken from a UMAS internal dataset.

4.1.3 Geographic location

The geographical location of a country is also critical for its potential to become a major fuel supplier. Countries close to key markets are likely to have a competitive advantage. This report uses the geographic location of a country to define its connectivity with the major international shipping routes and bunkering hubs.

This criterion has two components: The Liner Shipping Connectivity Index (LSCI) and the distance to the closest major bunkering hub (calculated based on fuel sales data as described below). The former serves as a proxy for how well countries are connected to major international shipping routes. The latter indicates the potential of a country to distribute fuel to the closest country hosting a major bunkering hub. The average of both indicators has been used to indicate the relative advantage of a country due to its geographic location.

The LSCI[19] is published on a quarterly basis by the United Nations Conference on Trade and Development (UNCTAD),[20] and consists of the following components:

- Number of scheduled ships calls in the country;
- Deployed annual capacity in TEU;[21]

18 United Nations Conference on Trade and Development, "Port call and performance statistics: time spent in ports, vessel age, and size, annual." https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=170027.

19 LSCI 2019 data was compiled for all countries. The parameter is expressed for each country relative to the 2006 maximum value, which corresponds to 100.

20 United Nations Conference on Trade and Development, "Liner shipping connectivity index, quarterly." https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=92.

21 TEU is defined as the approximate unit of measure of a container. This unit of measure is based on the dimensions of a standard container: height 8.5 feet (2.591 m), width 8 feet (2.438 m) and length 20 feet (6.096 m), which represents an approximate volume of 38.5 cubic meters.

- Number of regular liner shipping services from and to the country;
- Number of liner shipping companies that provide services from and to the country;
- Average size in TEU of the ships deployed by the scheduled service with the largest average vessel size; and
- Number of other countries that are connected to the country through direct liner shipping services.

This has been used as a general proxy for connectivity with major international shipping routes, although it is, strictly speaking, representative only of the liner shipping services.

The distance between a country and major bunkering hubs is associated with the ease and cost with which zero-carbon bunker fuels could be exported for sale. The bunkering hubs have been identified as the top 15 countries by bunker fuel sales using the International Energy Agency's dataset (IEA 2014b). They include, starting with the highest, Singapore, United States of America, United Arab Emirates, Netherlands, China, Republic of Korea, Spain, Hong Kong SAR China, Belgium, Brazil, Japan, Saudi Arabia, Greece, France, and Gibraltar. Average shipping distances between countries are used (Bertoli et al. 2016) and normalized on a scale from zero to five, with five achieved by countries hosting major bunkering hubs.[22]

4.1.4 Adequacy of the current and projected regulatory frameworks

This fourth criterion assesses how well prepared, from a policy perspective, a country is to support and manage the production and distribution of the candidate zero-carbon bunker fuels. It consists of two indicators created for the purpose of this high-level assessment (regulatory framework and national credentials), with the final score being represented by the average of these two indicators.

The "Transition Readiness" score by the Energy Transition Index is used as a proxy for the regulatory framework indicator. The score for each country is taken from the 2019 study *Fostering Effective Energy Transition (World Economic Forum 2019),* which evaluates the commitment of a country to the decarbonization agenda and accordingly how likely it is to implement the necessary framework for fostering the production of green ammonia/hydrogen. The Transition Readiness score is composed of six dimensions:

- Energy system structure;

22 According to Bertoli et al. (2016), the relevant port(s) for countries with access to the sea is defined as the coastal cell of a country that contains the highest number of shipping lines, and each landlocked country is associated to the (foreign) port with the shortest road distance to its capital city. Consequently, landlocked countries whose associated port is in a country representing a major bunkering hub can also achieve a five.

- Regulation and political commitment;
- Capital and investment;
- Human capital and consumer participation;
- Infrastructure and innovative business environment; and
- Institutions and governance.

The national credentials indicator assigns a score to countries based on whether they have already developed a hydrogen industrial strategy, whether they are preparing such a strategy, or whether they are providing any other kind of significant support to foster domestic hydrogen production. This indicates a country's predisposition to support early adoption and roll-out of zero-carbon energy carriers. The indicator is based on existing evidence from the World Energy Council Germany (2020) and IRENA (2020), which identified such countries. Countries highlighted by these soures as of end of March 2021 were given a score of five (that is, strategy developed), four (that is, strategy in preparation), and two (that is, any other support).

4.1.5 Potential to leverage existing infrastructure

The presence of existing hydrogen/ammonia infrastructure assets and industrial activity may enable the production and distribution of zero-carbon ammonia and hydrogen for use in the maritime transport sector. In particular, a country could reuse part of such infrastructure if or when current production methods are converted to zero-carbon production methods.

This criterion is composed of two indicators: the current ammonia and current hydrogen production of each country. These two indicators are normalized on a scale from zero to five, and the average of the two has been used as a proxy for the capacity of a country to scale up its existing production and distribution of ammonia and hydrogen to meet the future maritime demand.

The current production of ammonia (mainly ammonia produced from natural gas and coal) in metric tons by country has been collected from the United States Geological Survey agency for 2018 (United States Geological Survey 2020). For current hydrogen production, the captive hydrogen production capacity at refineries has been used. Data for this indicator has been retrieved from the Hydrogen Analysis Resource Centre of Hydrogen Tools, based on the Oil and Gas Journal Annual Survey (HARCH 2017). Production capacity for 2017 in standard cubic feet per day has been used. If a country is not included in the lists of ammonia or hydrogen producers, its annual ammonia or hydrogen production is assumed to be zero.

4.2 WEIGHTING OF CRITERIA

The previous section described the criteria selected to assess the potential of countries to become producers of future zero-carbon bunker fuels. However, these criteria are not necessarily of equal importance and each criterion is accordingly weighted to provide a composite score. Table 8 shows the weights assigned to each criterion.

TABLE 8: WEIGHTED CRITERIA FOR HIGH-LEVEL ASSESSMENT OF ZERO-CARBON BUNKER FUEL PRODUCTION POTENTIAL

	DESCRIPTION	WEIGHT
Criterion 1	Energy resources required	50 percent
Criterion 2	Shipping volumes	20 percent
Criterion 3	Geographic location	12.5 percent
Criterion 4	Regulatory framework	12.5 percent
Criterion 5	Potential to leverage existing infrastructure	5 percent

- **Criterion 1:** The most important factor for a country to become a major source of zero-carbon bunker fuels appears to be its access to the energy sources required for production. This represents an essential prerequisite, leading to a relatively high impact of 50 percent.

- **Criterion 2:** The shipping volume criterion appears important, especially at the beginning of the energy transition when a country could easily leverage current shipping volumes to serve ships that call at its domestic ports. However, similar to the geographic criterion, a country would still be able to become a major fuel producer even if shipping volumes are relatively low today. This criterion has thus been weighted at a medium-high level of 20 percent.

- **Criterion 3:** The weight of the geographic location criterion seems rather medium-low, with a relative impact of 12.5 percent. Although a convenient geographic location is advantageous, a country could be located further away from shipping activities and still become a major producer/exporter. In general, the costs of transporting fuel to bunkering hubs are expected to be low relative to the current costs of production, potentially representing less than ten percent of the total cost (Lloyd's Register and UMAS 2019a). It is worth noting that if production costs fall over time as technology progresses, then the share of transport in total costs may increase, rendering a strategic geographic location relatively more important.

- **Criterion 4:** The regulatory framework criterion is assigned a rather medium-low weight, too, with an impact of 12.5 percent. Although a favorable regulatory framework offers an advantage when advancing the zero-carbon bunker fuels transition within a country, it is not necessarily a prerequisite for a country to become a large-scale producer of zero-carbon ammonia or hydrogen as long as there is a strong economic driver.

- **Criterion 5:** Although the potential re-use of existing infrastructure appears advantageous, it is neither necessary nor sufficient for a country to produce the volumes of zero-carbon ammonia/hydrogen needed to meet future shipping demand. The assigned weight is rather low accordingly, with a relative impact of 5 percent.

The normalized criteria described above are used to compute a weighted composite score for each country. These composite scores are then used to identify the countries well positioned to produce ammonia and hydrogen under three scenarios: blue ammonia/hydrogen from natural gas in conjunction with CCS, green ammonia/hydrogen from renewable energy sources only, and finally, a combination of blue and green ammonia/hydrogen starting with the production from natural gas in conjunction with CCS, and gradually transitioning to a production pathway based on renewable energy sources. While Figure 8 provides a general overview of the criteria and scoring system used, Appendix A — Criteria and scoring system of highlevel assessment gives a more detailed summary.

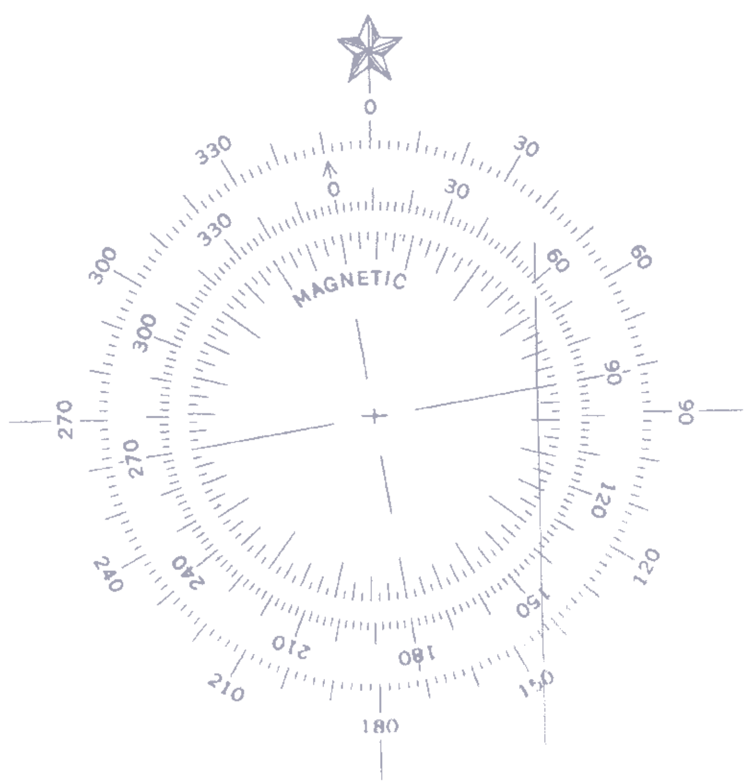
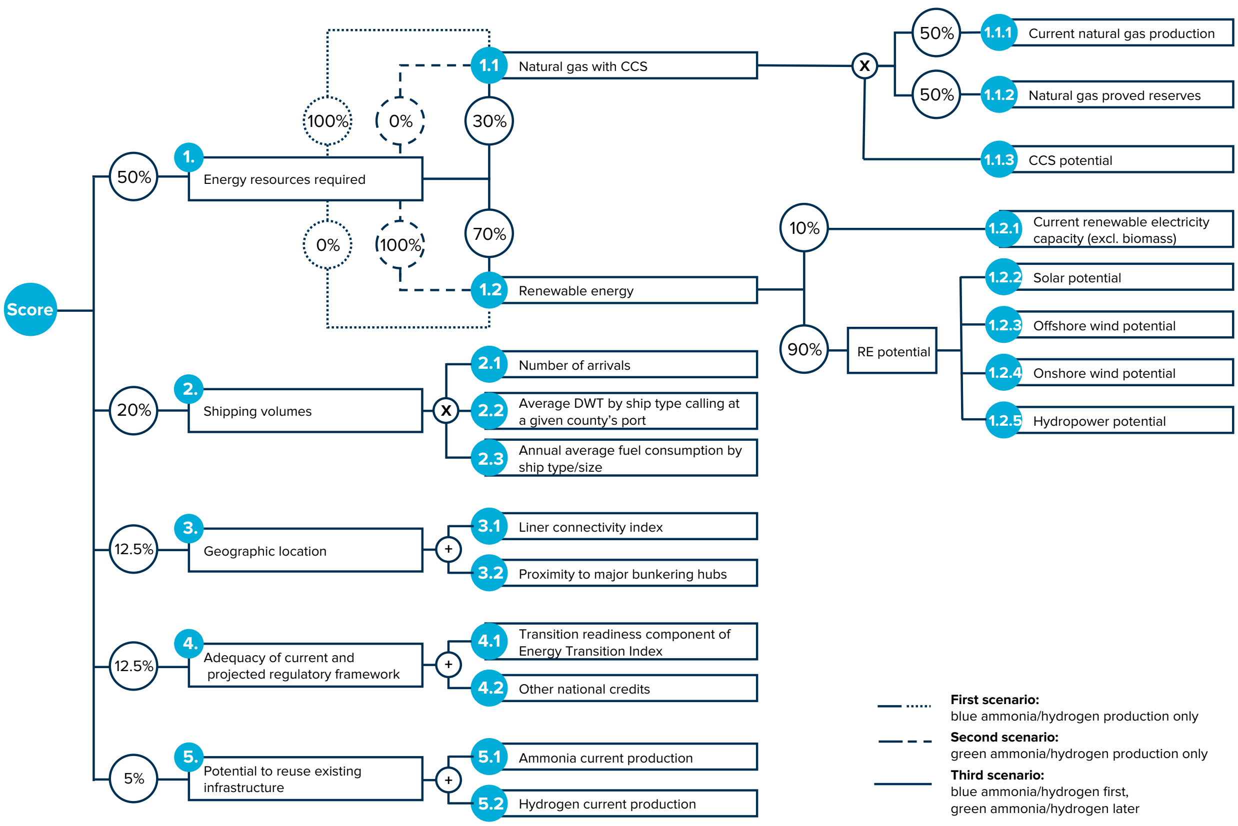


FIGURE 8: OVERVIEW OF CRITERIA AND SCORING SYSTEM OF HIGH-LEVEL ASSESSMENT



4.3 RESULTS AND DISCUSSION

4.3.1 Country selection

This high-level assessment uses a weighted combination of the identified criteria to assess the potential of countries to become major producers of zero-carbon bunker fuels based on ammonia and hydrogen. It covers all World Bank countries, including landlocked countries.[23] Countries are grouped into three categories representing their potential: "high potential," "promising potential," and "limited potential or insufficient data." Countries in the first or second quintile of the assessment are considered to have a "high potential" or "promising potential", respectively.[24] In this logic, all other countries are associated with a rather "limited potential" or "insufficient data" which according to the methodology can lead to lower composite scores, too. The individual results of the high-level assessment can be found in Appendix B– Production Potential of Green/Blue Ammonia/Hydrogen for Shipping by Country.

23 Landlocked countries have not been excluded from the assessment as they can potentially become producers of zero-carbon bunker fuels, too, distributing these fuels by land or inland waterways to existing or emerging bunkering hubs close-by.

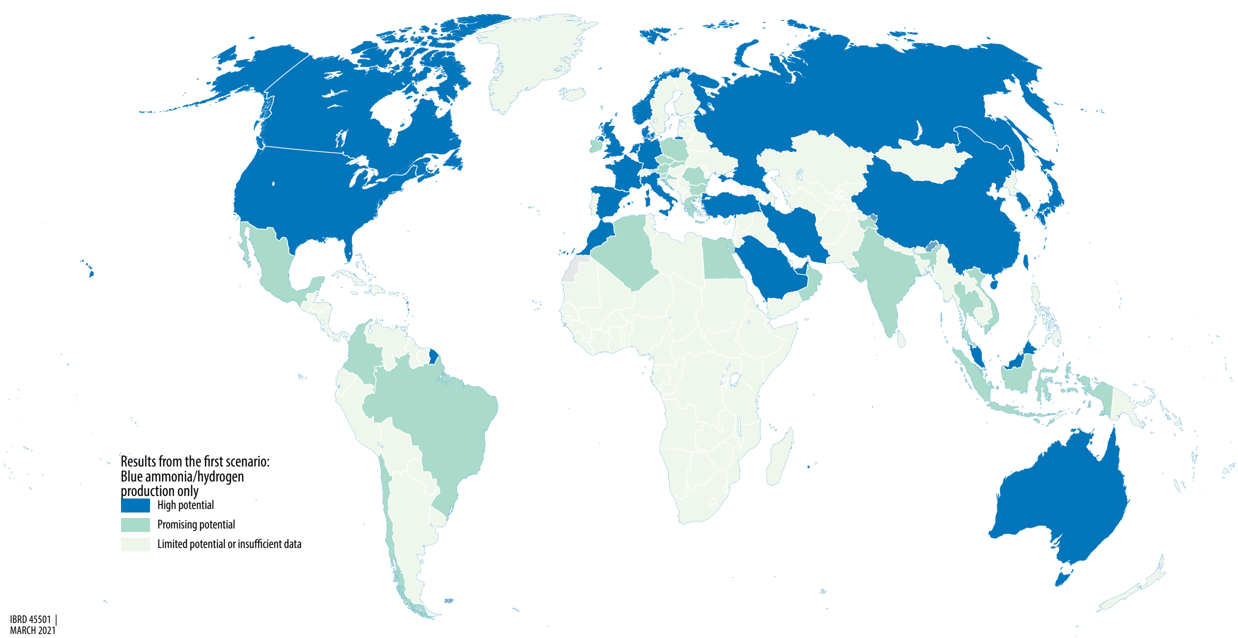
24 For the first scenario, only countries with current natural gas production or proved natural gas reserves are taken into consideration.

First scenario: blue ammonia/hydrogen production only

Figure 9 shows the heatmap for the first scenario where a production pathway based on blue ammonia/hydrogen will provide future zero-carbon bunker fuels. Under this scenario, countries with high or promising potential usually benefit from both large natural gas resources and a very good CCS potential in combination with a reasonable proximity to shipping activities. Among the developing countries assessed with high potential, Brazil turns out to be among the countries well positioned to produce blue ammonia/hydrogen for shipping from natural gas in conjunction with CCS. It has, therefore, been selected for a high-level case study.

Although Brazil also has significant renewable energy potential, its ability to exploit natural gas and CCS places it among the first developing countries in the ranking for blue ammonia/hydrogen production. Brazil would also have high potential to produce green ammonia/ hydrogen, but for the purpose of this report the first scenario is explored further in section 5.2.

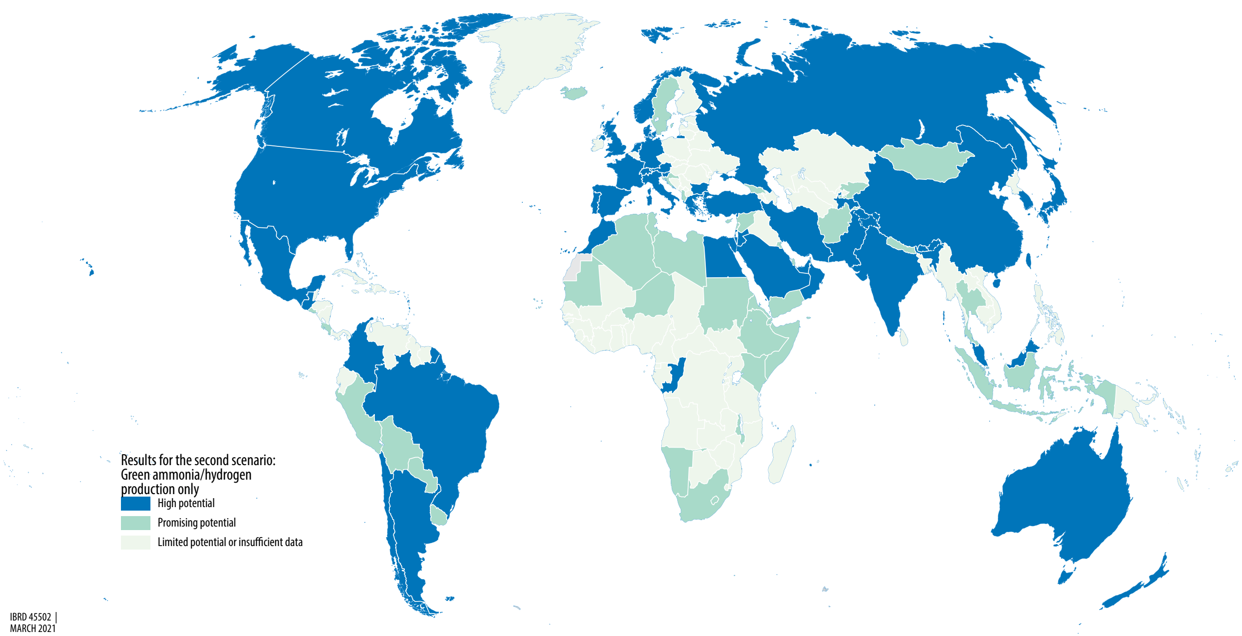
FIGURE 9: HEATMAP INDICATING THE POTENTIAL OF COUNTRIES TO PRODUCE BLUE AMMONIA/HYDROGEN FOR SHIPPING



Second scenario: green ammonia/hydrogen production only

Figure 10 shows the heatmap for the second scenario displaying each country's potential for the production of green ammonia/hydrogen. Countries with high or promising potential benefit both from a high level of renewable energy resources and a degree of proximity to shipping activities. Several developing countries are within this category of high or promising potential. India turns out to be one of the well positioned among this group and has therefore been selected for further analysis in section 5.3. India's relative competitiveness is driven by its close proximity to the key bunkering hubs of Singapore and Fujairah (United Arab Emirates), combined with its vast potential to generate inexpensive renewable electricity.

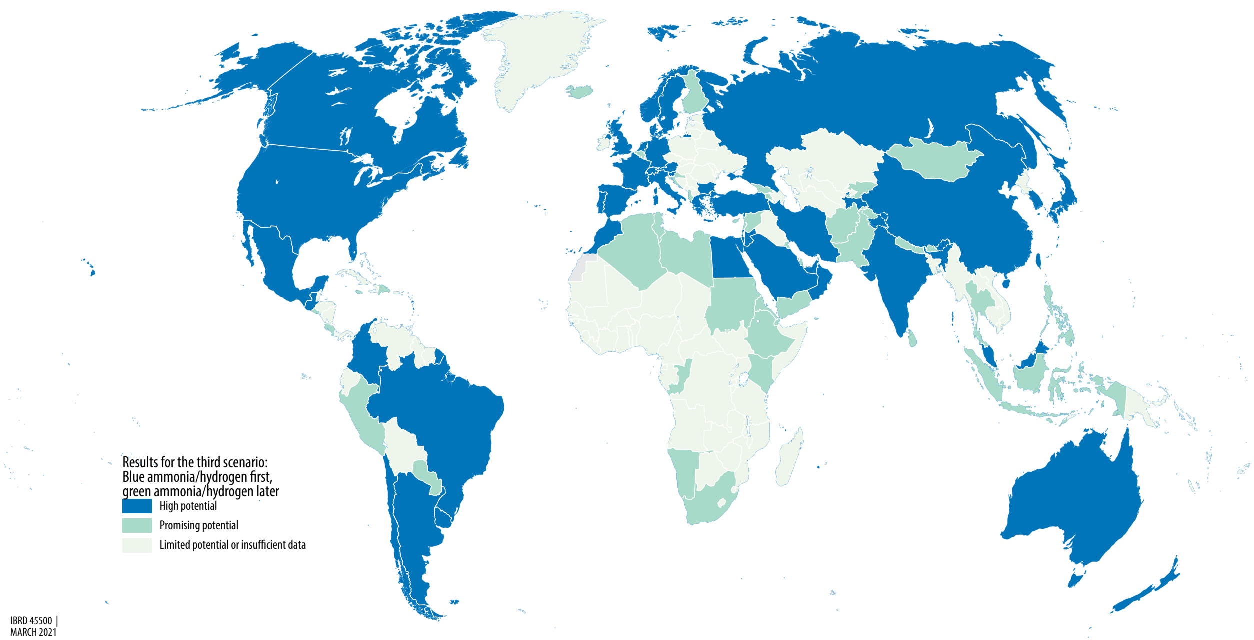
FIGURE 10: HEATMAP INDICATING THE POTENTIAL FOR COUNTRIES TO PRODUCE GREEN AMMONIA/HYDROGEN FOR SHIPPING



Third scenario: blue ammonia/hydrogen first, green ammonia/hydrogen later

Figure 11 shows the heatmap for the third scenario that assumes a transition from blue to green ammonia/hydrogen production in the mid-to-long term. In addition to proximity to shipping activities, the countries with high or promising potential in this scenario possess large natural gas resources and CCS potential alongside a large potential to leverage renewable energy resources. Among the developing countries with high potential, Malaysia has been identified as one of the well-positioned countries, benefitting from its strategic location near to the world's largest bunkering hub in Singapore and possessing a surplus of renewable energy resources. Although solar energy is currently not extensively exploited, Malaysia has significant potential to expand this renewable energy source, in addition to its natural gas reserves and CCS potential, which could be leveraged in the first phase of fuel deployment. Malaysia has, therefore, been selected for a high-level case study in section 5.5.

FIGURE 11: HEATMAP INDICATING THE POTENTIAL FOR COUNTRIES TO PRODUCE BLUE AMMONIA/BLUE HYDROGEN INITIALLY, AND GREEN AMMONIA/GREEN HYDROGEN EVENTUALLY



Final selection of case studies

Ultimately, this high-level assessment has led to three-plus-one high-level case studies of countries being well positioned to produce zero-carbon hydrogen and ammonia bunker fuels: Brazil, India, Malaysia, and Mauritius. The first three countries do not necessarily represent the best-positioned countries in the final rankings overall. Instead, they figure among the top-ranked developing countries. The small island developing state of Mauritius has also been selected to counterbalance the larger nations already analyzed and to ensure equal regional representation. Mauritius warrants special analysis based upon its geographic location, its size, and its national development goals.

4.4 LIMITATIONS

Obviously, no assessment is perfect, and certain limitations in the analysis of this report need to be highlighted:

- **Cost competitiveness:** First, it should be noted that this high-level assessment does not represent a definitive estimate of the economic competitiveness of a country with regard to producing blue/green ammonia/hydrogen in the long-term. The results should be viewed as indicative as they simply seek to identify the most obvious candidate countries for producing hydrogen and ammonia on a preliminary basis.

- **Imports/exports:** The option a country may have to use resources from a neighboring country (for example, energy resources like renewable energy, natural gas, CCS potential, etc.) is not taken into account. For instance, in some cases it may be a more efficient use of resources for countries to import natural gas from abroad and export CO_2 to be stored elsewhere. This would allow countries without an initially high or promising potential in this assessment to also become competitive.

- **Nuclear energy:** The potential of nuclear as an energy resource to produce green ammonia/hydrogen is not considered in this assessment. In general, nuclear energy is not expected to be cost-competitive with solar and wind, but a country could still choose to invest in production infrastructure for green ammonia/hydrogen using nuclear energy, which is not reflected in the criteria currently selected.

- **Business strategy:** Finally, it is important to note that this assessment is mainly based on the physical potential of a country to become a major producer of zero-carbon bunker fuels. Consequently, this assessment does not take into account any future market drivers of competitor countries, which may have less physical potential, but a superior business strategy.

The following sections provide the case studies for the selected countries.

5. CASE STUDIES

5.1 INTRODUCTION

This section aims to gauge, at a high-level, the quantities of zero-carbon ammonia bunker fuel that could be produced and sold in each of the selected case study countries (either green ammonia, blue ammonia, or "first blue then green" ammonia). It then estimates the corresponding level of capital expenditure needed to realize a range of zero-carbon ammonia fuel production scenarios.

Each high-level case study includes:

- An overview of the country's current shipping traffic and port activities;
- An overview of the renewable energy potential and/or fossil resources to be leveraged to produce ammonia based on the selected production pathway;
- An estimate of the amount of ammonia produced under the different hypothetical fuel demand scenarios;
- An estimate of the daily fuel supply and energy resources required; and
- The scale of investment needed to build the corresponding fuel supply infrastructure in order to meet the assumed demands.

The ammonia fuel demand for each case study is derived from the global ammonia demand in 2050, which is estimated to be approximately 17.8 EJ (UMAS 2020). Under the 2050 decarbonization scenario, ammonia represents 98 percent of total shipping demand (in energy terms) in 2050 (UMAS 2020). The global demand is broken down into regional demands using the regional market share defined in Appendix C – Estimates of regional market shares. The potential ammonia demand is estimated by assuming a certain market share that a country would be able to capture in its regional area and neighboring regional areas. The country market share has been suggested considering the maximum amount of green/blue ammonia that could be theoretically produced—if production was constrained only by renewable energy/fossil resources within the country.

For the case of green ammonia, the fuel supply infrastructure does not include the operational or capital expenditures for the corresponding renewable electricity generation infrastructure. For the case of blue ammonia, the fuel supply infrastructure does not include the upstream infrastructure needed to extract and transport the natural gas feedstock. Further details on the fuel supply investment assumptions are provided in Appendix D – Estimated relationship between ammonia demand and capital investments.

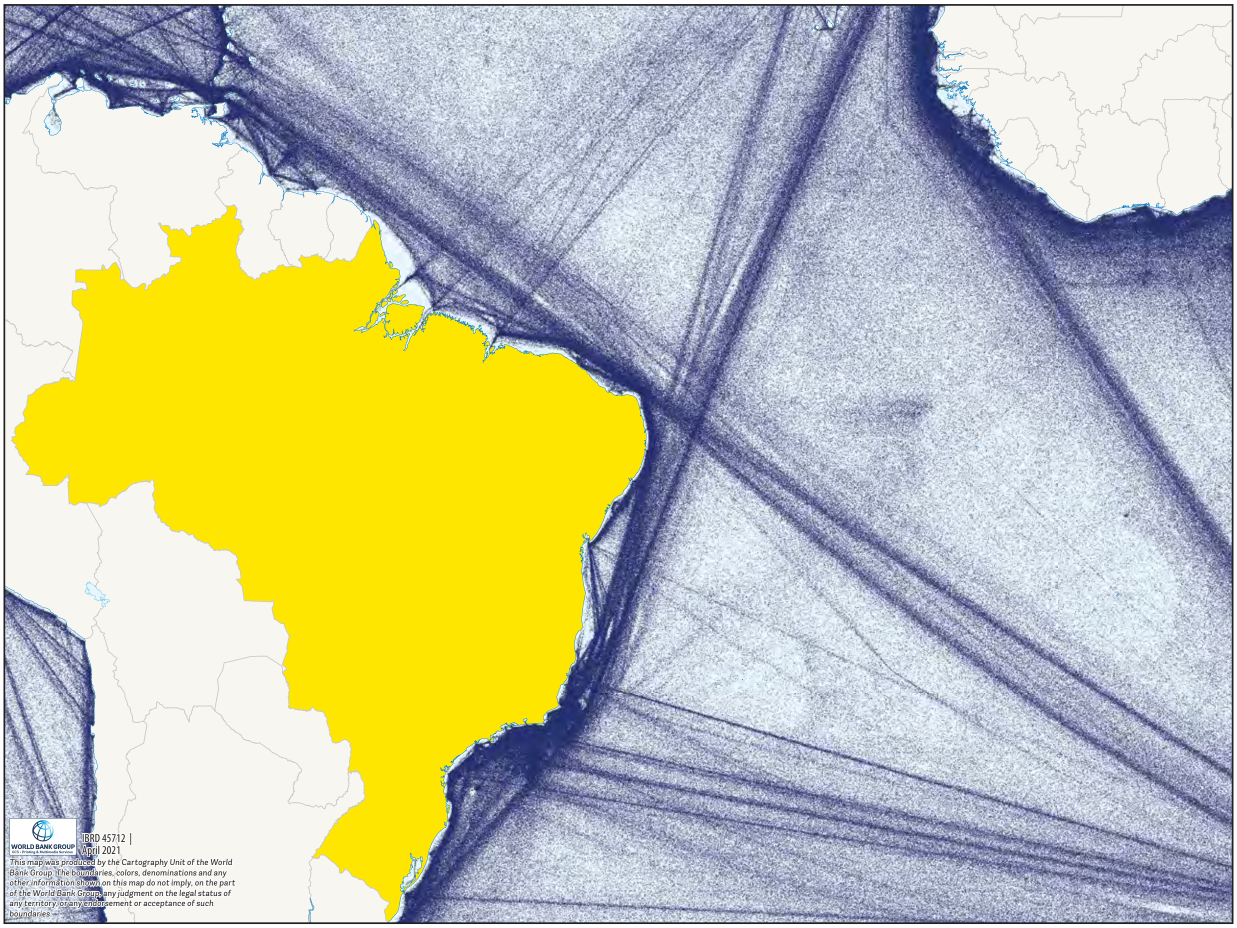
5.2 CASE STUDY 1: BRAZIL - BLUE AMMONIA

This first case study looks at the potential of Brazil to produce blue ammonia.

5.2.1 Brazil's port activities and shipping traffic

Brazil handles approximately 10.5 million TEUs of cargo each year, of which an estimated 40 percent passes through the Port of Santos alone (NEA 2020). This has resulted in the Port of Santos being listed as one of the top 50 largest ports globally in terms of cargo handled (Lloyd's List 2019). Brazil is located on the shipping routes from the Cape of Good Hope to Central and North America, and from Europe and North America to South America.

FIGURE 12: SHIPPING TRAFFIC IN BRAZIL FOR 2015-2020

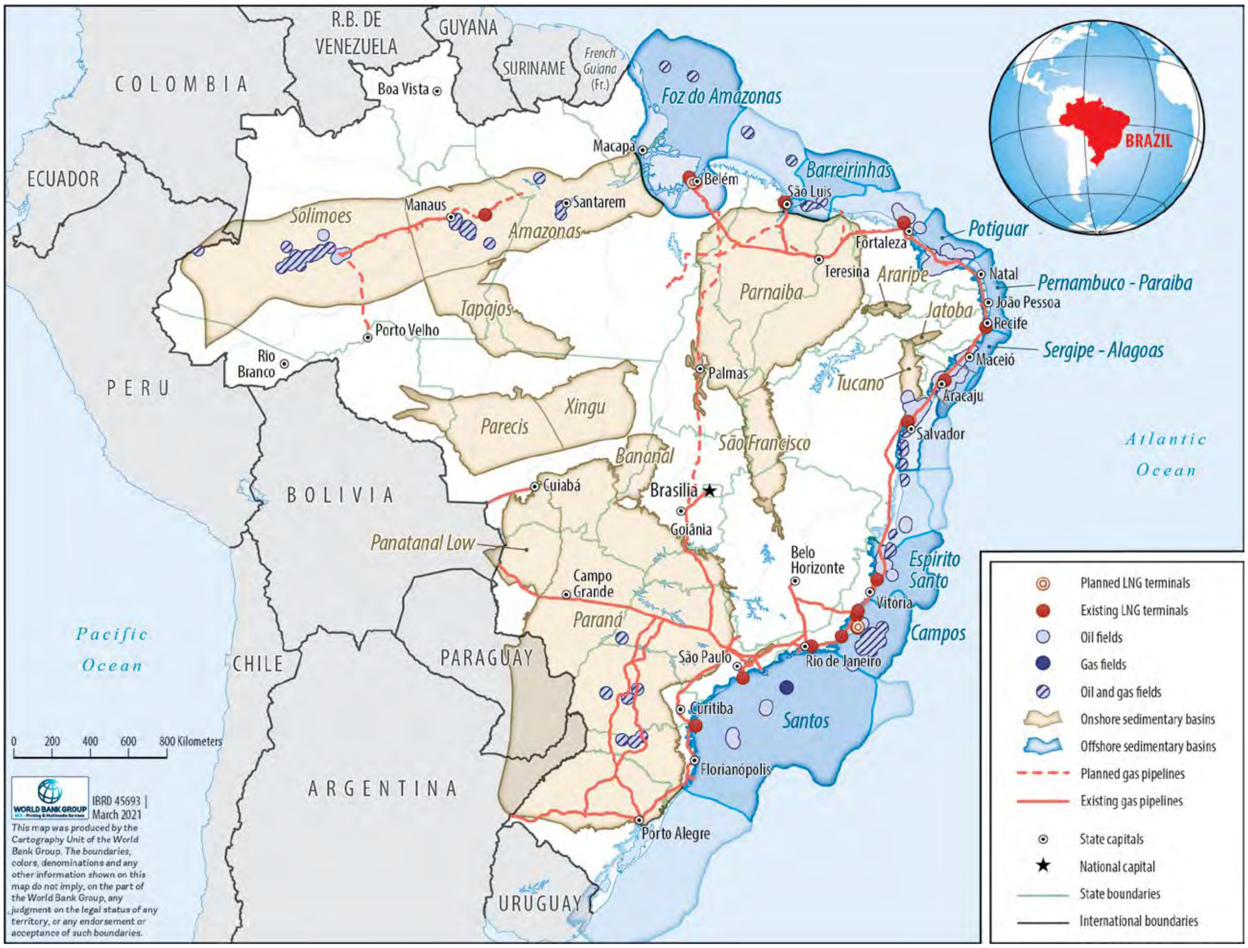


Source: IMF's World Seaborne Trade monitoring system (Cerdeiro et al. 2020)

5.2.2 Brazil's natural gas resources and CCS potential

Brazil's natural gas production reached 846 billion cubic feet (bcf) in 2017, of which more than 99 percent is currently consumed nationally. For comparison purposes, the United States and Russia (the world's largest gas producers in 2017) each produced more than 20,000 bcf for the same period. Proven Brazilian reserves of natural gas in 2019 were estimated at 13.1 trillion cubic feet (tcf)(EIA), which represents less than one percent of the world's estimated reserves. Brazil's reserves are mostly located in the Parana, Solimoes, Amazonas, Reconcavo, and Sao Francisco Basins, as shown in Figure 13.

FIGURE 13: ONSHORE AND OFFSHORE BRAZILIAN BASINS FOR CONVENTIONAL AND UNCONVENTIONAL HYDROCARBON RESERVES AND OIL AND GAS SPOTS



Source: Da Rocha, dos Anjos, and de Andrade 2015

Brazil has significant potential for carbon capture and storage (CCS) due to large sedimentary basins covering an area of approximately 6.4 million km^{2}. Some of these basins are considered likely to be good candidates for carbon storage (Ketzer et al. 2014), as shown in Figure 13. Some 75 percent of these basins are located onshore (Ketzer et al. 2014), which may present a limit to the CCS potential of Brazil in the future.25 Further analysis of this point is beyond the scope of this case study. Currently, Brazil's CCS potential is estimated to be 2,030 gigatons (Consoli and Wildgust 2017). Brazil already has one active CCS plant in the Santos Basin Pre-Salt Oil Field, which has been in operation since 2013 with a capture capacity of one million tons per annum (Santos 2018).

25 Offshore CCS might be more acceptable as leaks would be unlikely to cause any negative impacts on the population; however, the preferences of the public are not clear.

5.2.3 Estimated ammonia demand scenarios in Brazil

Brazil currently accounts for about 2.2 percent of global fuel sales, but could increase these sales by becoming a future node in the shipping fuel supply chain (UMAS internal data). If Brazil were to produce blue ammonia for shipping, it would be well-placed to supply blue ammonia to more than one regional market. Potential sales beyond South America and into Central America and the Caribbean, Asia, and Northern Europe are therefore considered (see Appendix C – Estimates of regional market shares for more details).

Table 9 summarizes the hypothetical shipping demand scenarios for ammonia produced in Brazil ranging from 19 to 85 million tons of blue ammonia per annum. These figures are also presented in terms of the fraction of the total shipping ammonia demand needed in 2050 under a decarbonization by 2050 scenario as well as for each of the regional markets considered (South America, Central America and the Caribbean, Asia, North Europe).[26] In addition, the hypothetical shipping demand scenarios for ammonia are also presented in terms of fraction of the shipping total fuel demand in 2016 in energy terms.

TABLE 9: SHIPPING'S AMMONIA DEMAND SCENARIOS FOR BRAZIL

	SHIPPING ANNUAL AMMONIA DEMAND FOR BRAZIL IN 2050 (MILLION TONS)	% OF GLOBAL AMMONIA DEMAND FOR SHIPPING, ASSUMING FULL DECARBONIZATION BY 2050	CORRESPONDING % OF THE 2016 GLOBAL ENERGY SHIPPING DEMAND	SHARE OF AMMONIA SHIPPING DEMAND ON REGIONAL MARKETS, ASSUMING FULL DECARBONIZATION BY 2050			
				SOUTH AMERICA	CENTRAL AMERICA & THE CARIBBEAN	ASIA	NORTH EUROPE
Scenario A	19	2 percent	5 percent	50 percent	0 percent	0 percent	0 percent
Scenario B	32	3 percent	9 percent	50 percent	50 percent	0 percent	0 percent
Scenario C	85	9 percent	24 percent	50 percent	50 percent	10 percent	10 percent

5.2.4 Energy resources required to produce blue ammonia in Brazil

This report has identified Brazil as one of the countries well positioned to produce blue ammonia through the reforming of natural gas in conjunction with CCS.

If the only constraints on ammonia production were the country's natural gas reserves and CCS capacity, Brazil would have the potential to produce approximately 430,000 million tons of blue ammonia cumulatively across the period considered.

26 Under the 2050 decarbonization scenario, ammonia represents 98 percent of total shipping demand (in MJ) in 2050 (UMAS 2020).

This corresponds to roughly 60 million tons per day if consumed over 20 years. This figure serves as an indication of the upper limit of production, assuming that all the natural gas reserves and carbon storage are used exclusively for blue ammonia production. The quantities of natural gas and carbon storage per day required to produce blue ammonia under the defined scenarios are presented in Table 10.

TABLE 10: NATURAL GAS AND OF CARBON STORAGE REQUIRED TO PRODUCE BLUE AMMONIA IN BRAZIL

	ESTIMATED BLUE AMMONIA PRODUCTION (THOUSAND TONS/DAY)	NATURAL GAS REQUIRED (MILLION CUBIC FEET/DAY)	CCS REQUIRED (THOUSAND TONS/DAY)
Scenario A	52	2	78
Scenario B	87	3	129
Scenario C	232	7	344

5.2.5 An estimate of the investment needed in Brazil

The capital investment needed to generate the required quantities of blue ammonia is calculated using the estimated relationship between ammonia demand and capital investment (see Appendix D– Estimated relationship between ammonia demand and capital investments for more details). Figure 14 shows the linear relationship used, and the points of intersection with the assumed blue ammonia demand under the three scenarios. In scenario A, Brazil would have to generate approximately 19 million tons of blue ammonia annually with an associated capital investment of $24 billion. In scenario B, 32 million tons of blue ammonia per annum would require $40 billion of investment. In scenario C, 85 million tons of blue ammonia per annum would require $107 billion of investment.

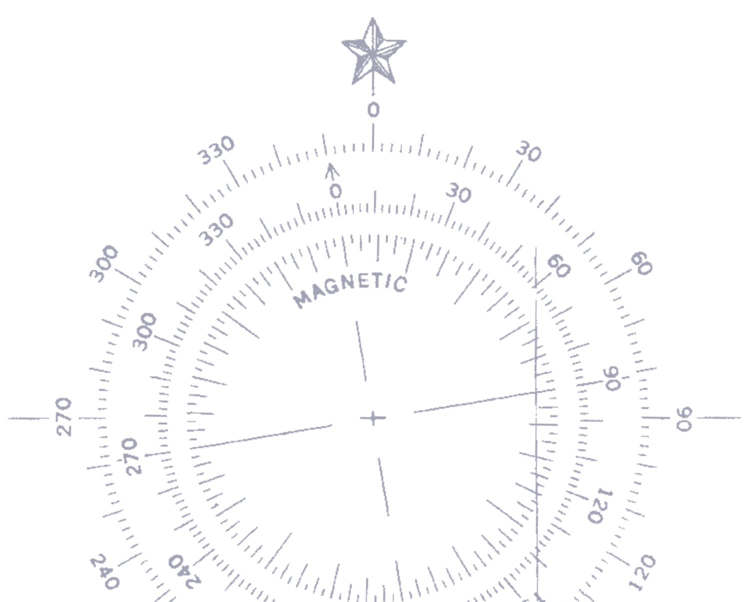
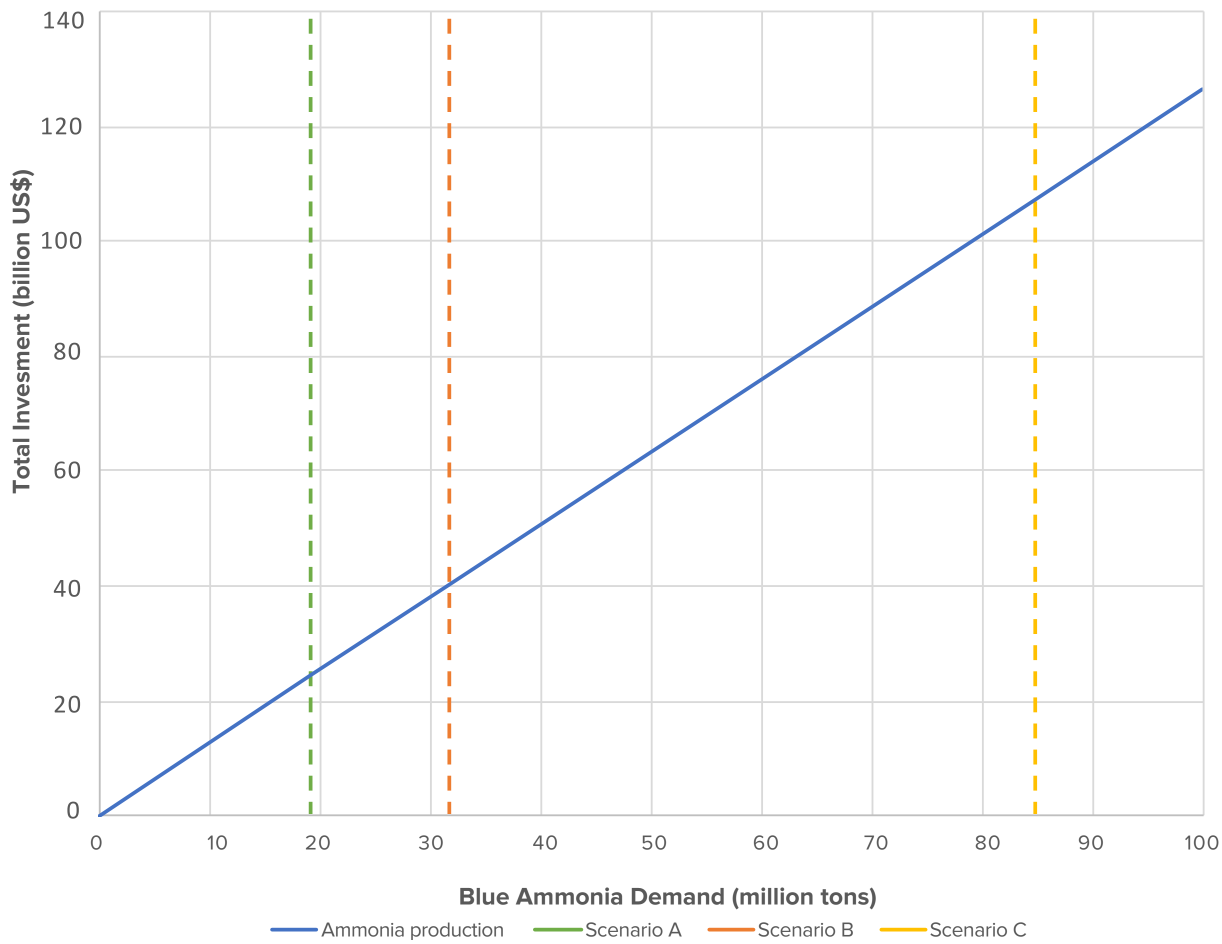


FIGURE 14: BLUE AMMONIA PRODUCTION AND INVESTMENT NEEDED FOR BRAZIL'S ASSUMED BLUE AMMONIA DEMAND



5.2.6 Summary

This case study of Brazil's potential as a supplier of blue ammonia leads to the following conclusions:

- Brazil possesses good natural gas resources and good potential for on- and offshore CCS;
- Brazil's large reserves of natural gas and available CCS sites make it one of the highest-ranking developing countries well positioned to produce blue ammonia;
- These natural gas reserves would enable Brazil to cover its regional market and export some excess production to the international market, for example to the bunkering hubs of Panama or Rotterdam; and
- The required capital investment ranges from $24 billion to meet two percent of global demand in 2050 to $107 billion to meet nine percent of global demand in 2050.

5.3 CASE STUDY 2: INDIA - GREEN AMMONIA

This second case study looks at the potential for India to produce green ammonia. India has strong links to major shipping routes and considerable untapped renewable energy potential, making it a potential leading producer of green ammonia.

5.3.1 India’s port activities and shipping traffic

In 2017, India ranked 11th in the world for annual container port throughput. India’s main ports include Jawaharlal Nehru Port Trust in Mumbai (4.5 million TEUs in 2017), Chennai (1.5 million TEUs in 2017), V.O. Chidambaram Port Trust in Thoothukudi (0.6 million TEUs in 2017), and Kolkata (0.6 million TEUs in 2017) (India Ports Association 2017). India is also strategically located on the major shipping routes between Asia, the Middle East, and Europe (via the Suez Canal).

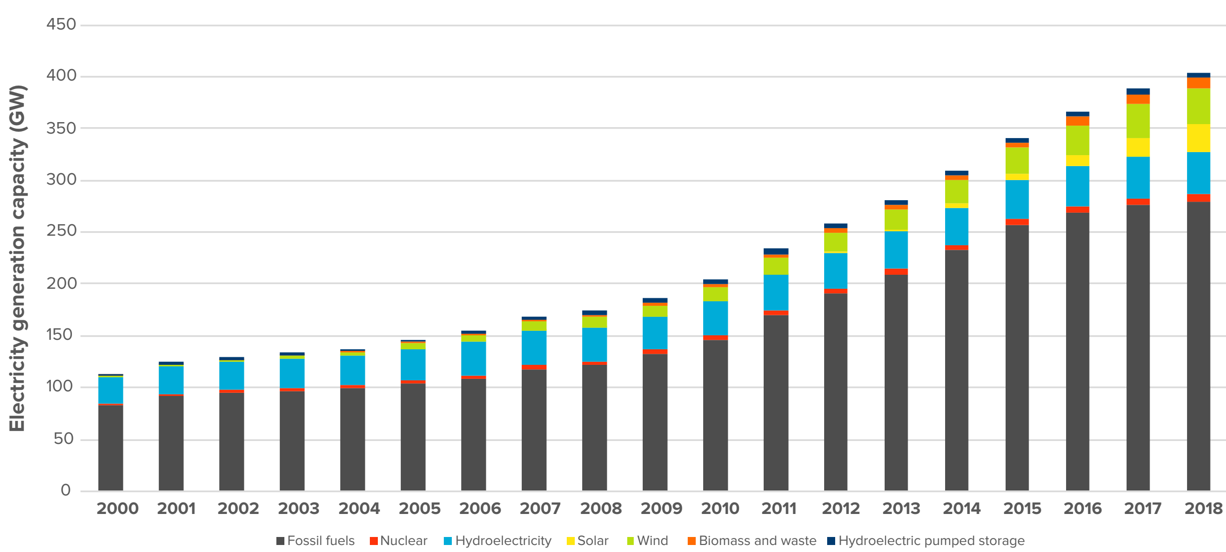
FIGURE 15: SHIPPING TRAFFIC IN INDIA FOR 2015-2020

Source: IMF’s World Seaborne Trade monitoring system (Cerdeiro et al. 2020)

5.3.2 India's renewable energy potential and future developments

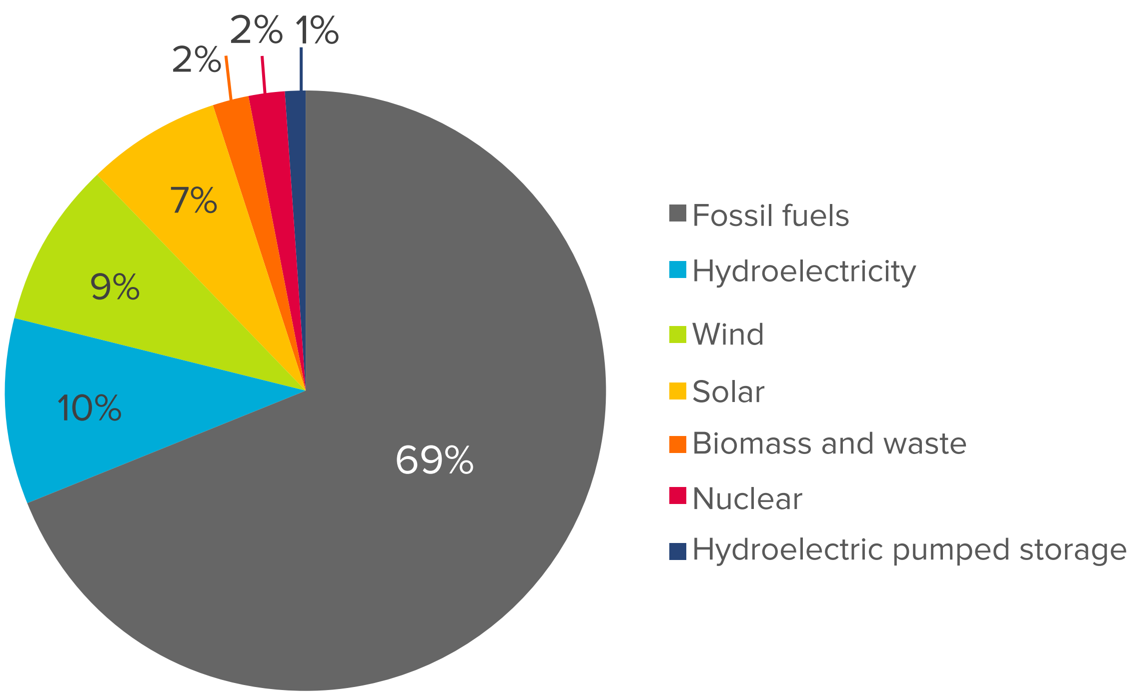
As shown in Figure 16 India's renewable electricity generation capacity has increased steeply since 2010. While fossil fuels still represented 69 percent of India's power generation capacity in 2018 (Figure 17), renewables have grown more than traditional sources in recent years. Renewables (hydro, solar, wind and biomass and waste) have grown by 131 percent between 2010 and 2018, compared to 91 percent growth for fossil fuel powered electricity generation over the same period. As a result, 28 percent of electricity generation capacity was already powered by renewable sources in 2018. Solar-powered generation capacity in particular has grown by a factor of four between 2015 and 2018 as a result of government efforts pursuing a national target of 175 gigawatt (GW) of installed renewable energy capacity by 2022 (IRENA 2015), compared to 113 GW in 2018 (US EIA 2018).

FIGURE 16: ELECTRICITY GENERATION CAPACITY IN INDIA, 2000–2018



Source: EIA

FIGURE 17: ELECTRICITY GENERATION CAPACITY MIX IN INDIA IN 2018

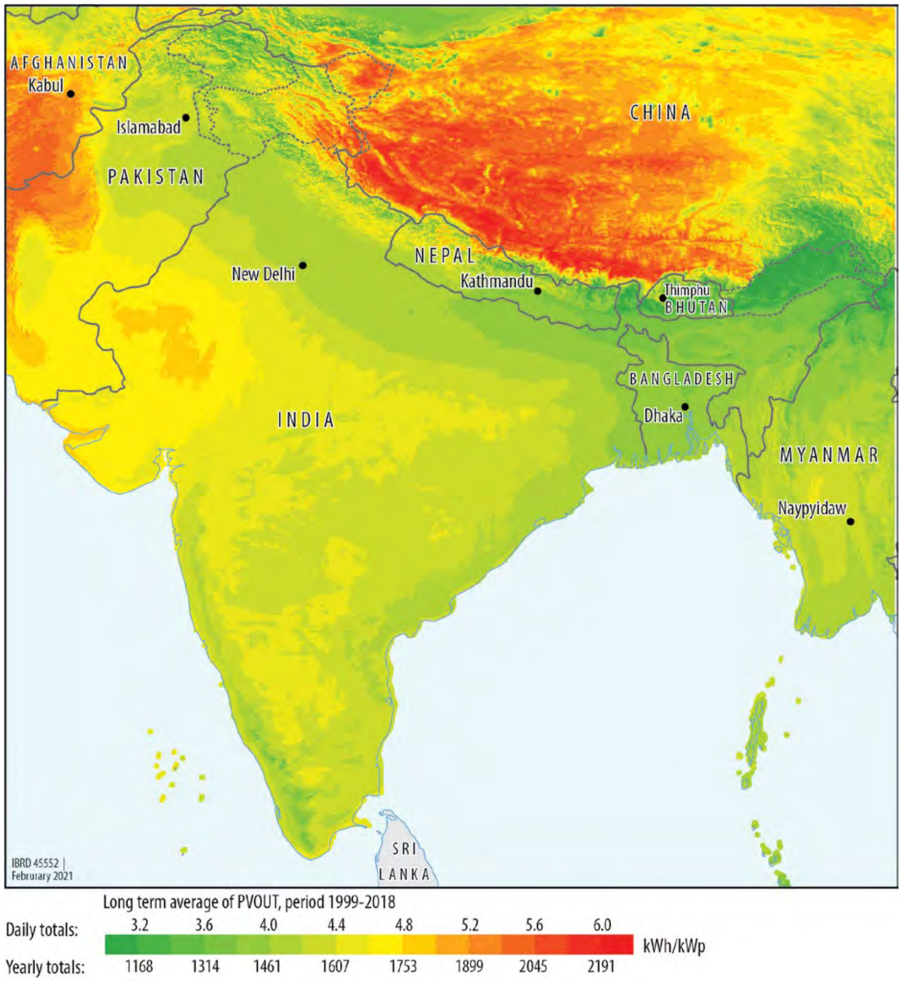


Source: EIA

India has excellent solar power potential, with most areas receiving on average between four to eight kWh/m^{2}/day of solar irradiance (IRENA 2015). The percentage of a country's landmass available for solar farms depends on many factors. An accurate estimate for India is beyond the scope of this report. However, IRENA (2015) uses a figure of three percent based upon a "geographic information system" study. If three percent of India's land is made available for solar farms, this would result in the potential capture of approximately 42,500 Gigawatt hour (GWh)/day of electrical energy (by comparison, onshore wind potential represents 26,000 GWh/day).[27] Since solar represents the largest potential source of renewable production in India, this report treats it as the main potential source of electricity generation for green ammonia production. For reasons of convenience, other renewable energy sources (such as wind, which also plays an increasingly important role in India's generation capacity) have been ignored, even though they will likely represent a share of the future electricity mix in India.

27 US Department of Energy, National Renewable Energy Laboratory, Onshore and Offshore Wind Potential Supply curves by country, https://openei.org/doe-opendata/dataset. Protected, urban, and high-elevation areas are excluded, and certain land cover types. Land up to 5000 miles to load is included.

FIGURE 18: PHOTOVOLTAIC POWER POTENTIAL IN INDIA



Source: Global Solar Atlas

5.3.3 Estimated ammonia demand scenarios in India

India currently accounts for less than one percent of global bunker fuel sales, but may be able to significantly increase its market share due to its status as a major shipping node. If India were to produce green ammonia for shipping, it would be able to supply this fuel to markets beyond Asia, including Oceania and the Middle East (see Appendix C – Estimates of regional market shares for more details).

Table 11: Shipping's ammonia demand scenarios for India summarizes the hypothetical shipping demand scenarios for ammonia produced in India ranging from 95 to 248 million tons of green ammonia per annum. These figures are also presented in terms of fraction of the total shipping ammonia demand needed in 2050 under a full decarbonization by 2050 scenario as well as for each of the regional markets considered (Asia, Oceania, and the Middle East). In addition, the hypothetical shipping demand scenarios for ammonia are also presented in terms of fraction of the shipping total fuel demand in 2016 in energy terms.

TABLE 11: SHIPPING'S AMMONIA DEMAND SCENARIOS FOR INDIA

	SHIPPING ANNUAL AMMONIA DEMAND FOR INDIA IN 2050 (MILLION TONS)	PERCENT OF GLOBAL AMMONIA DEMAND FOR SHIPPING, ASSUMING FULL DECARBONIZATION BY 2050	CORRESPONDING PERCENT OF THE 2016 GLOBAL ENERGY SHIPPING DEMAND	PERCENT OF AMMONIA SHIPPING DEMAND ON REGIONAL MARKETS, ASSUMING FULL DECARBONIZATION BY 2050		
				ASIA	OCEANIA	MIDDLE EAST
Scenario A	95	10 percent	27 percent	25 percent	0 percent	0 percent
Scenario B	190	21 percent	53 percent	50 percent	0 percent	0 percent
Scenario C	248	27 percent	70 percent	50 percent	50 percent	50 percent

5.3.4 Energy resources required to produce green ammonia in India

India is one of the countries worldwide which are well positioned for the potential production of green ammonia. As stated above, this report assumes that solar energy will be the main source for the energy input required by this industry. Figure 19 displays the estimated amount of ammonia production per day under each scenario, and the quantity of renewable electricity required.

Daily green ammonia production could range from 260 to 678 thousand tons per day, with an associated electricity demand between 2,724 and 7,111 GWh/day. This is well below the estimated upper bound of renewable electricity potential of 42,500 GWh/day, which means that a significant potential remains available for India's alternative use of renewable electricity.

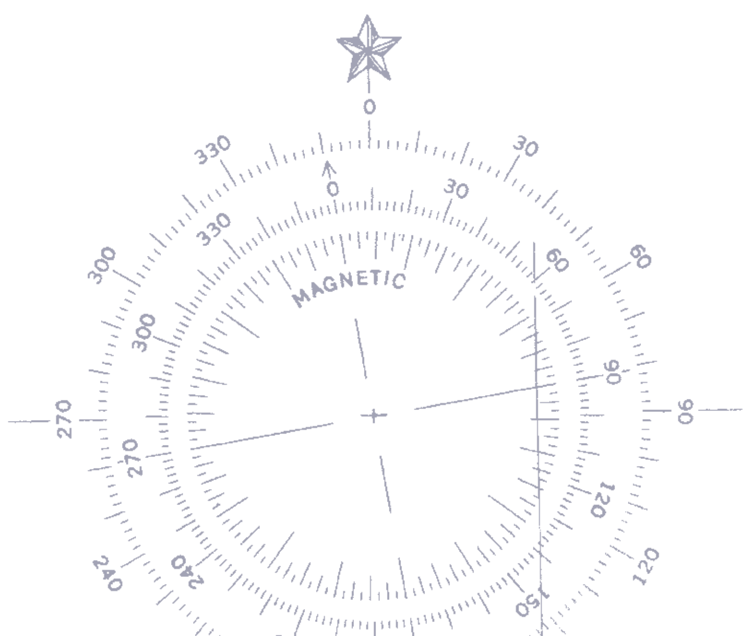
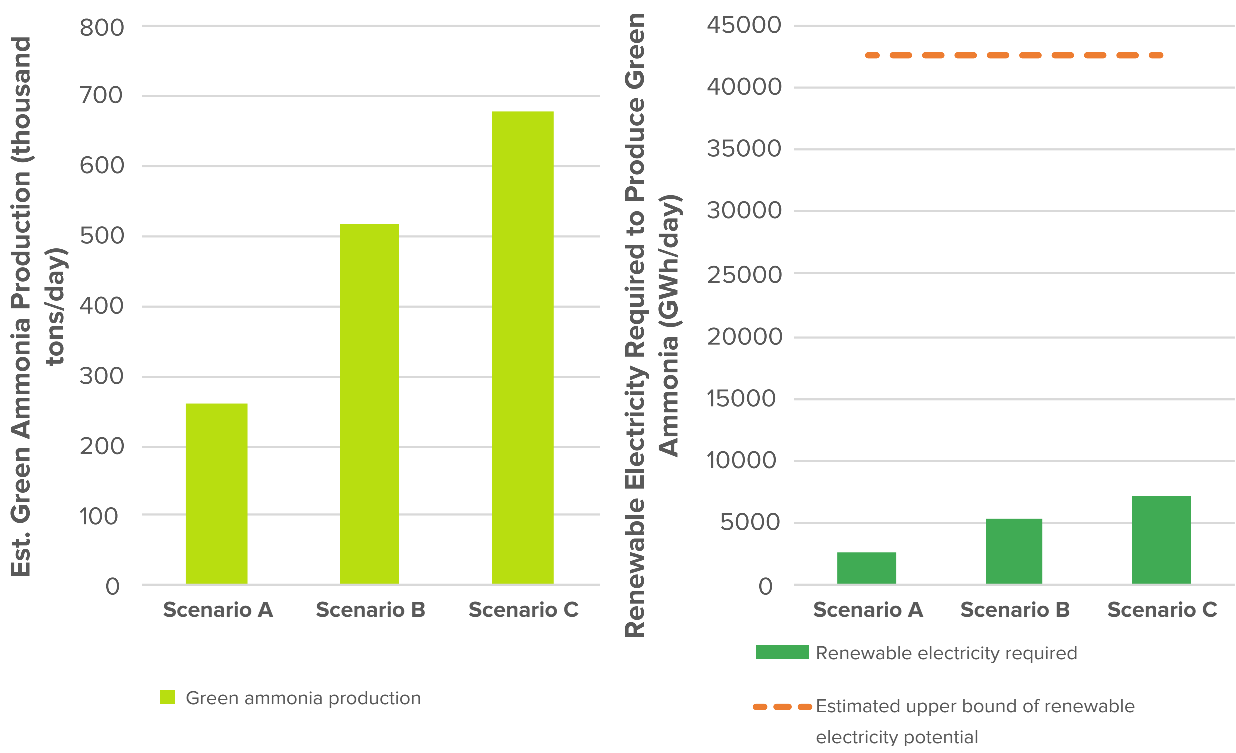


FIGURE 19: RENEWABLE ELECTRICITY REQUIRED TO MEET THE ESTIMATED GREEN AMMONIA PRODUCTION IN INDIA

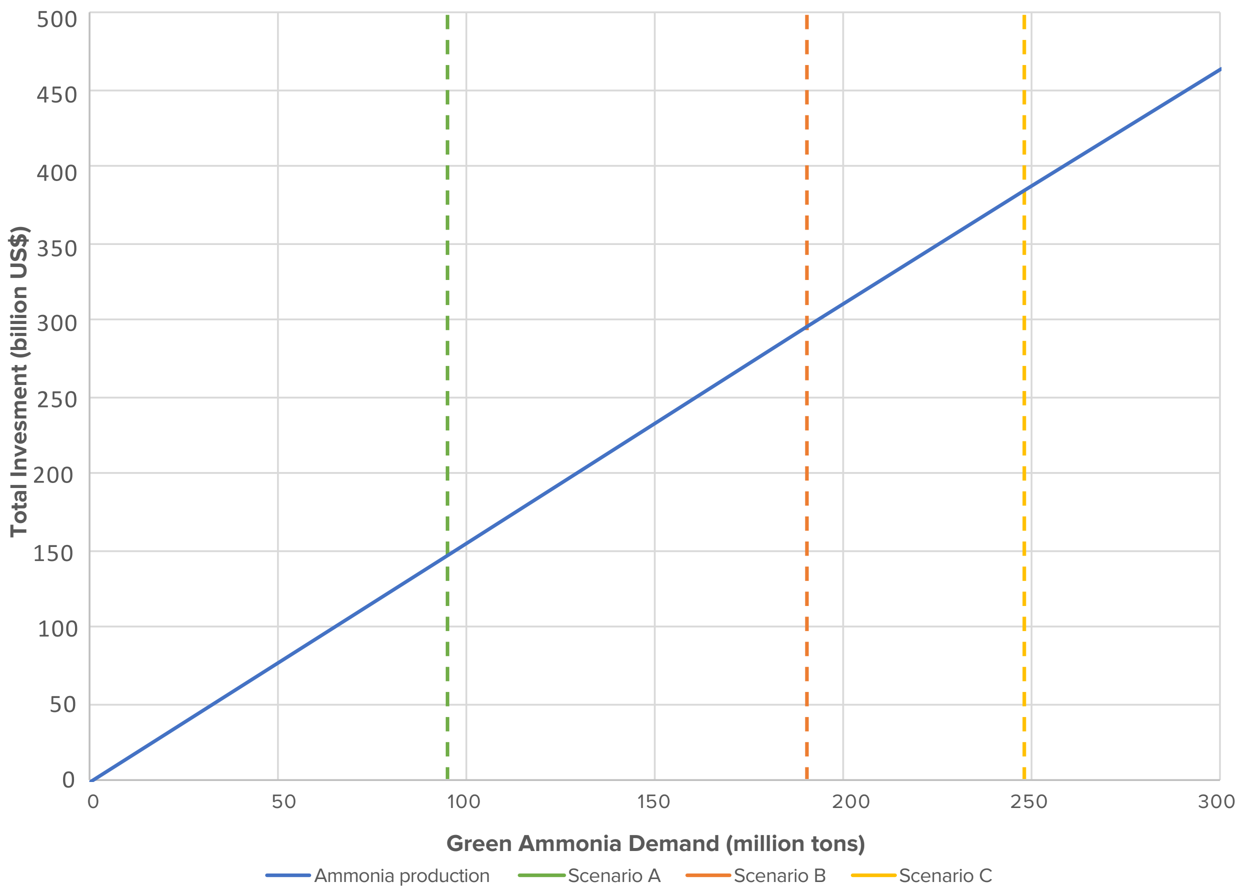


5.3.5 An estimate of the investment needed in India

The capital investment needed to generate the required quantity of green ammonia is calculated using the estimated relationship between ammonia demand and capital investment (see Appendix D – Estimated relationship between ammonia demand and capital investments for more details).

Figure 20 shows the linear relationship used, and the points of intersection with assumed green ammonia demand under the three scenarios. In scenario A, India would have to meet approximately 95 million tons/year of green ammonia demand with an associated capital investment of $147 billion. In scenario B, the production of 190 million tons of green ammonia would require $295 billion of investment, whereas in scenario C the production of 248 million tons of green ammonia would require an investment of $385 billion.

FIGURE 20: GREEN AMMONIA DEMAND AND INVESTMENT NEEDED FOR INDIA'S ASSUMED GREEN AMMONIA DEMAND



5.3.6 Summary

This case study of India's potential as a supplier of "green" ammonia leads to the following conclusions:

- As a potential economic superpower located on the shipping route between China and Europe, India is geographically well placed to service future demand for zero-carbon bunker fuels.
- The production of green ammonia in the required quantities would still leave an excess of solar resource for other uses.
- There can be an additional potential benefit to India of using ammonia production to capture excess solar energy at times of lower domestic demand.
- The required investment ranges from $147 billion to meet ten percent of global demand in 2050 to $385 billion to meet 27 percent of global demand in 2050.

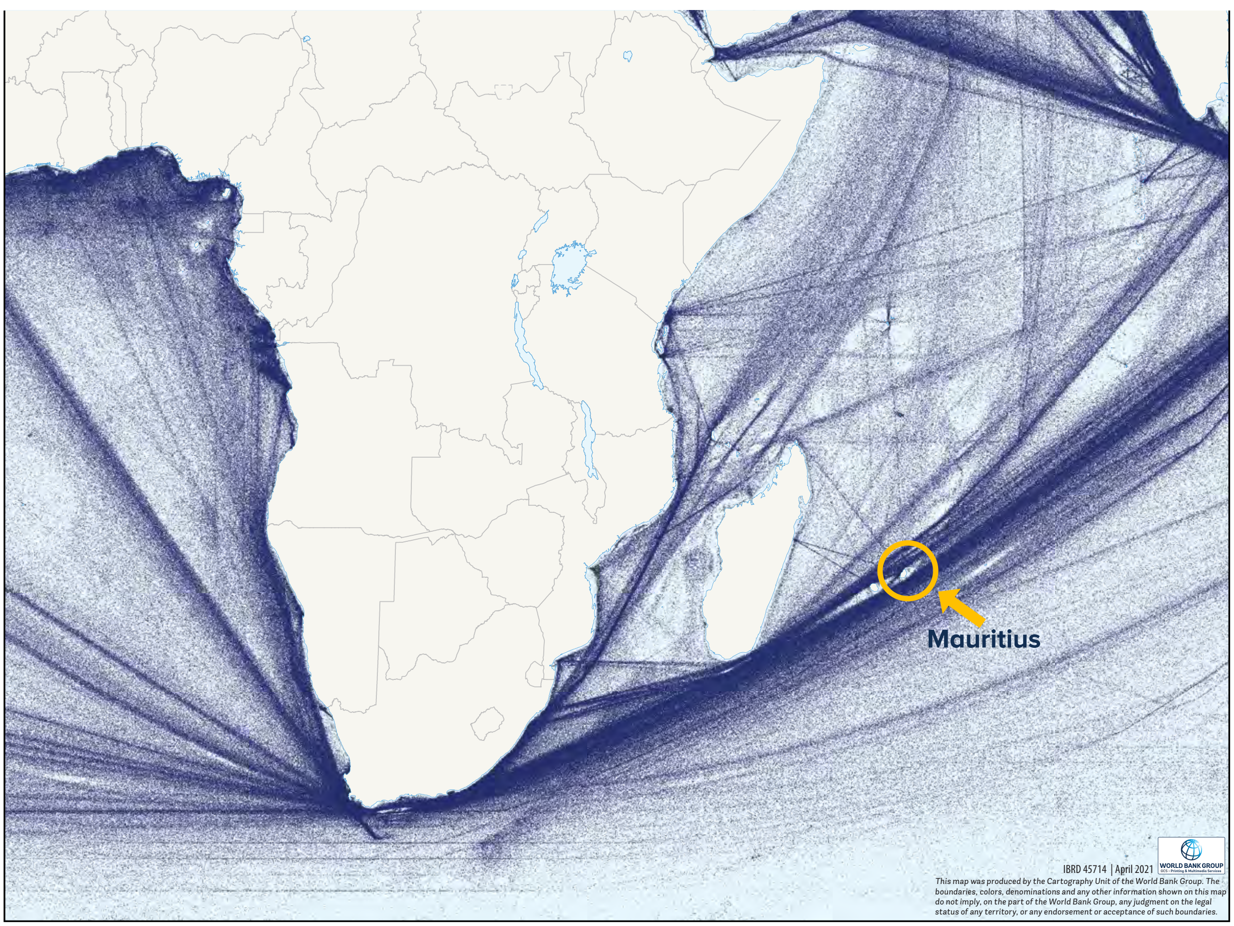
5.4 CASE STUDY 3: MAURITIUS - GREEN AMMONIA

This third case study looks at the potential of Mauritius to produce green ammonia for use as a bunker fuel.

5.4.1 Mauritius's port activities and shipping traffic

Mauritius is located on the East-West trade route in the Indian Ocean, linking Asia, Africa, and South America (Figure 21). Currently, Mauritius's bunkering sales are limited, but the government's "Vision 2030" plan from 2015 sets out an ambition to develop Port Louis into a global bunkering hub. This hub is anticipated to sell one million tons of bunker fuel per year, compared to less than 300,000 tons in 2014. In 2017, Mauritius ranked 92nd in the world in terms of annual container port throughput with 450,000 TEU, and reported slightly less than five million tons of cargo handled in 2014 (compared to more than 500 million tons in 2016 for each of the three largest ports in the world).

FIGURE 21: SHIPPING TRAFFIC IN MAURITIUS FOR 2015-2020

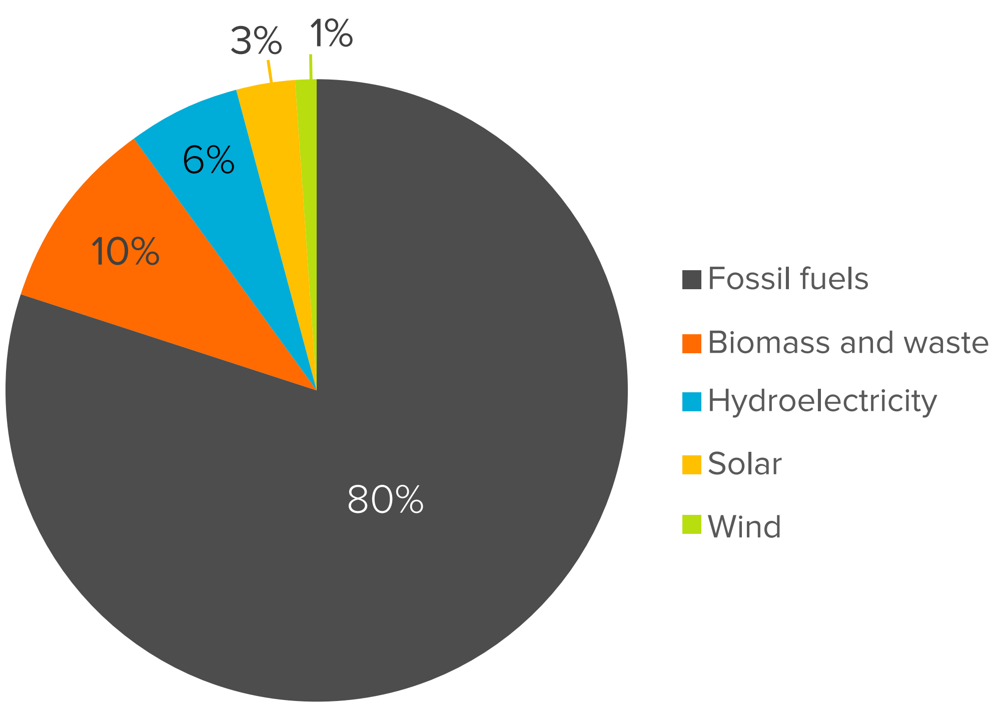


Source: IMF's World Seaborne Trade monitoring system (Cerdeiro et al. 2020)

5.4.2 Mauritius's renewable energy potential and future developments

Mauritius's fossil fuel generation capacity has been broadly constant since 2010. It represented around 80 percent of electricity generation capacity in 2017, as shown in Figure 22.

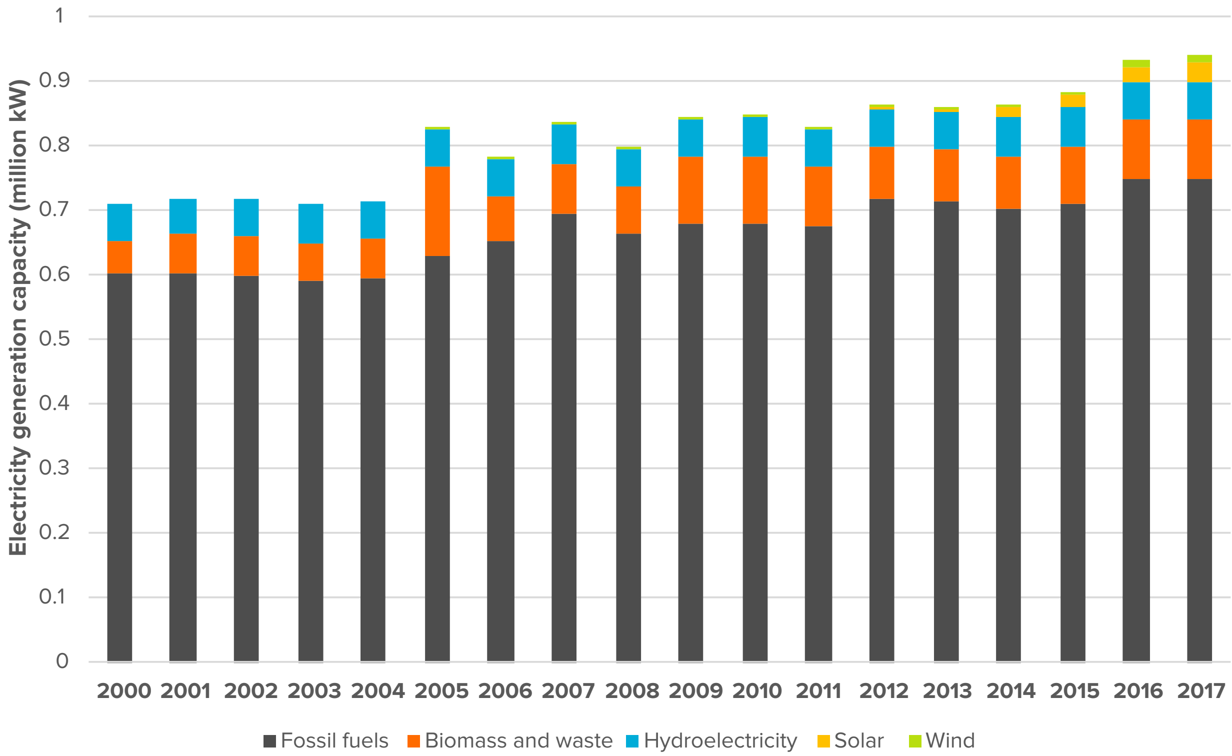
FIGURE 22: ELECTRICITY GENERATION CAPACITY MIX IN MAURITIUS IN 2017



Source: EIA

As shown in Figure 23, after four years of a downward trend, the renewable electricity generation capacity of Mauritius began increasing again after 2012, led by growth in wind and solar. Biomass, waste, and hydroelectricity are currently the largest renewable sources in the energy mix. Mauritius has announced plans to increase the contribution of renewable energy to electricity generation from 21 percent to 35 percent by 2025 by increasing the output of wind, solar, photovoltaic (PV) and biomass renewable energy.

FIGURE 23: ELECTRICITY GENERATION CAPACITY IN MAURITIUS, 2000-2017



Source: Mauritius Ministry of Renewable Energy and Public Utilities 2009.

Mauritius has an excellent solar power potential (see Figure 24) with a solar irradiation rate of six kWh/m^{2}/day (Bundhoo 2018). However, given the limited geographical area of the country, the renewable solar energy potential of Mauritius is small in absolute terms. For example, if three percent of the total land area of Mauritius was made available for solar farms, this would result in an estimated 26 GWh/day of renewable electricity generation.[28]

Mauritius could also leverage its potential to produce energy from wind (Figure 25) due to the presence of strong north-west monsoon winds that average annual wind speeds of up to eight meters per second at 30 meters in height in some regions (Bundhoo 2018). However, the installation of wind capacity is complicated by the potential damage to turbines from cyclones. As a result, the estimates of onshore and offshore wind potential taken from the US Department of Energy National Renewable Energy Laboratory show that 863 km^{2} (45 percent of total area) is available for onshore wind electricity generation, with an estimated potential output of one GWh/day of renewable electricity generation.

For offshore wind, four percent of Mauritius's total water area up to 100 nautical miles from the coast is assumed to be available for wind electricity generation.[29] If we consider only offshore wind production up to 50 nautical miles from the coast,

28 Internal calculation, assuming an average PVOUT of 4.2 kWh/kWp (Global Solar Atlas) and a PV energy efficiency of 0.1 kWp/m^{2}.

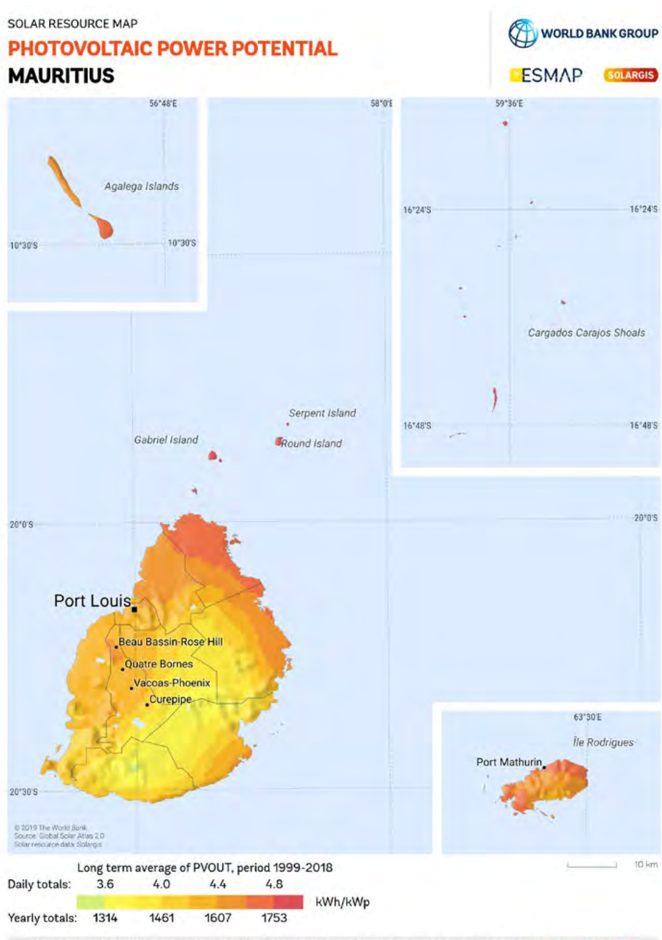
29 Areas within five nautical miles of or farther than 100 nautical miles from shore are excluded, as are protected marine areas. Marine areas are assigned to country based on exclusive economic zones; unassigned or disputed areas are excluded.

and in water that is at most 60m deep, then the potential contribution of offshore wind reaches 223 GWh/day. These assumptions are likely to be accurate as wind turbines are currently installed in water depths of up to 40m, as far as 80km from the shore (IRENA 2016).

Geothermal and hydropower are considered to be negligible for the purpose of this analysis. Although the use of geothermal energy has previously been suggested due to the volcanic nature of the island, its potential is estimated to be very low and exploitation unfeasible (ELC-Electroconsult 2015). Hydropower production has already been mostly tapped into and future potential increases are limited (Bundhoo 2018).

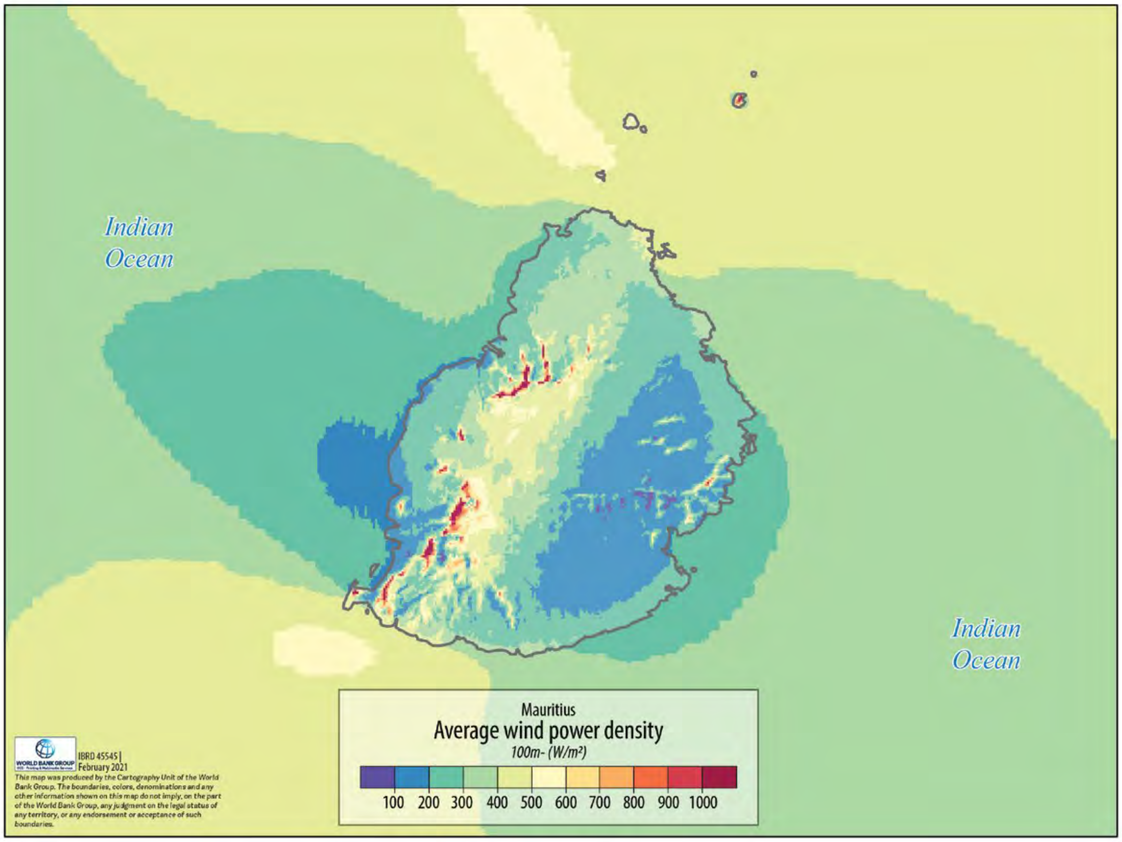
Therefore, a combination of wind and solar energy has been considered for the production of green ammonia, with a combined total output of 249 GWh/day (Worldometer). To put this into perspective, the current electricity supply generated from fossil fuel, solar, and wind energy sources is approximately 6 GWh/day (Worldometer). The production of green ammonia would therefore also provide a unique opportunity for Mauritius to decarbonize its domestic electricity grid.

FIGURE 24: PHOTOVOLTAIC POWER POTENTIAL IN MAURITIUS



Source: Global Solar Atlas

FIGURE 25: MEAN WIND POWER POTENTIAL IN MAURITIUS



Source: Global Wind Atlas

5.4.3 Estimated ammonia demand scenarios in Mauritius

Mauritius currently accounts for less than one percent of global bunker fuel sales. However, it plans to become a bunker fuel hub by supplying fuel for around 35,000 ships that transit Mauritian waters between Asia, Southern Africa, and South America but which do not yet necessarily stop in Mauritius (International Bunker Industry Association 2015). Mauritius could therefore produce green ammonia to export to the regional bunker market, or to use directly at Port Louis if it were to become an international bunker hub. Because of the country's size, the absolute amount of ammonia that Mauritius can produce is limited. In this report, the scenarios assume that Mauritius could produce green ammonia to match various shares of ammonia demand as a shipping fuel in Africa.

Table 12: summarizes hypothetical shipping demand scenarios for ammonia for Mauritius, with total demand ranging from 1 to 1.7 million tons of green ammonia. These figures are also presented in terms of fraction of the total shipping ammonia demand needed in 2050 under a full decarbonization by 2050 scenario, as well as a fraction of the African regional market. In addition, the hypothetical shipping demand scenarios for ammonia are also presented in terms of fraction of the shipping total fuel demand in 2016 in energy terms.

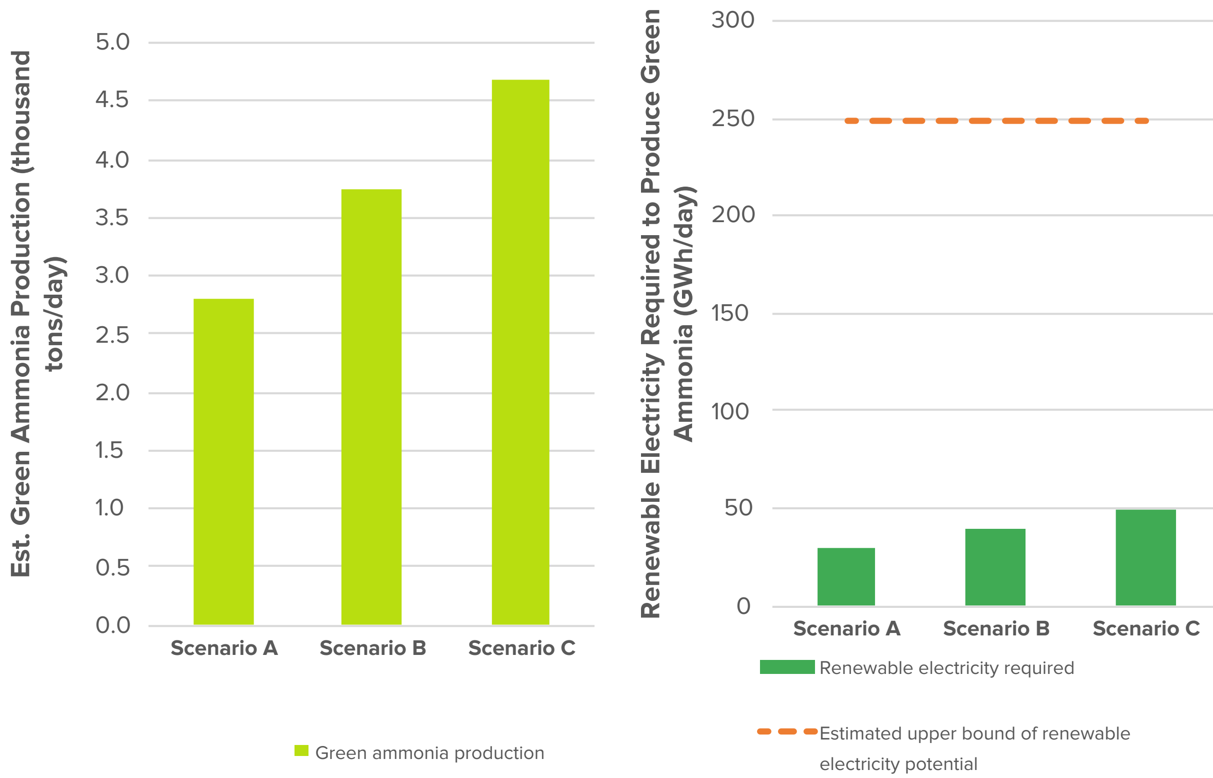
TABLE 12: SHIPPING'S AMMONIA DEMAND SCENARIOS FOR MAURITIUS

	SHIPPING ANNUAL AMMONIA DEMAND FOR MAURITIUS IN 2050 (MILLION TONS)	PERCENT OF GLOBAL AMMONIA DEMAND FOR SHIPPING, ASSUMING FULL DECARBONIZATION BY 2050	CORRESPONDING PERCENT OF THE 2016 GLOBAL ENERGY SHIPPING DEMAND	PERCENT OF AFRICAN AMMONIA SHIPPING DEMAND, ASSUMING FULL DECARBONIZATION BY 2050
Scenario A	1.0	0.1 percent	0.3 percent	3 percent
Scenario B	1.4	0.1 percent	0.4 percent	4 percent
Scenario C	1.7	0.2 percent	0.5 percent	5 percent

5.4.4 Energy resources required to produce green ammonia in Mauritius

Solar and offshore wind could be used to generate the electricity required for the production of green ammonia in Mauritius. Figure 26 displays the estimated quantity of ammonia produced per day and the quantity of renewable electricity required for each scenario. Daily green ammonia production could range from 2.8 to 4.7 thousand tons per day, with an associated daily renewable electricity demand from 29 to 49 GWh/day—well below the estimated upper bound of renewable electricity potential of 249 GWh/day.

FIGURE 26: RENEWABLE ELECTRICITY REQUIRED TO MEET THE ESTIMATED GREEN AMMONIA PRODUCTION IN MAURITIUS

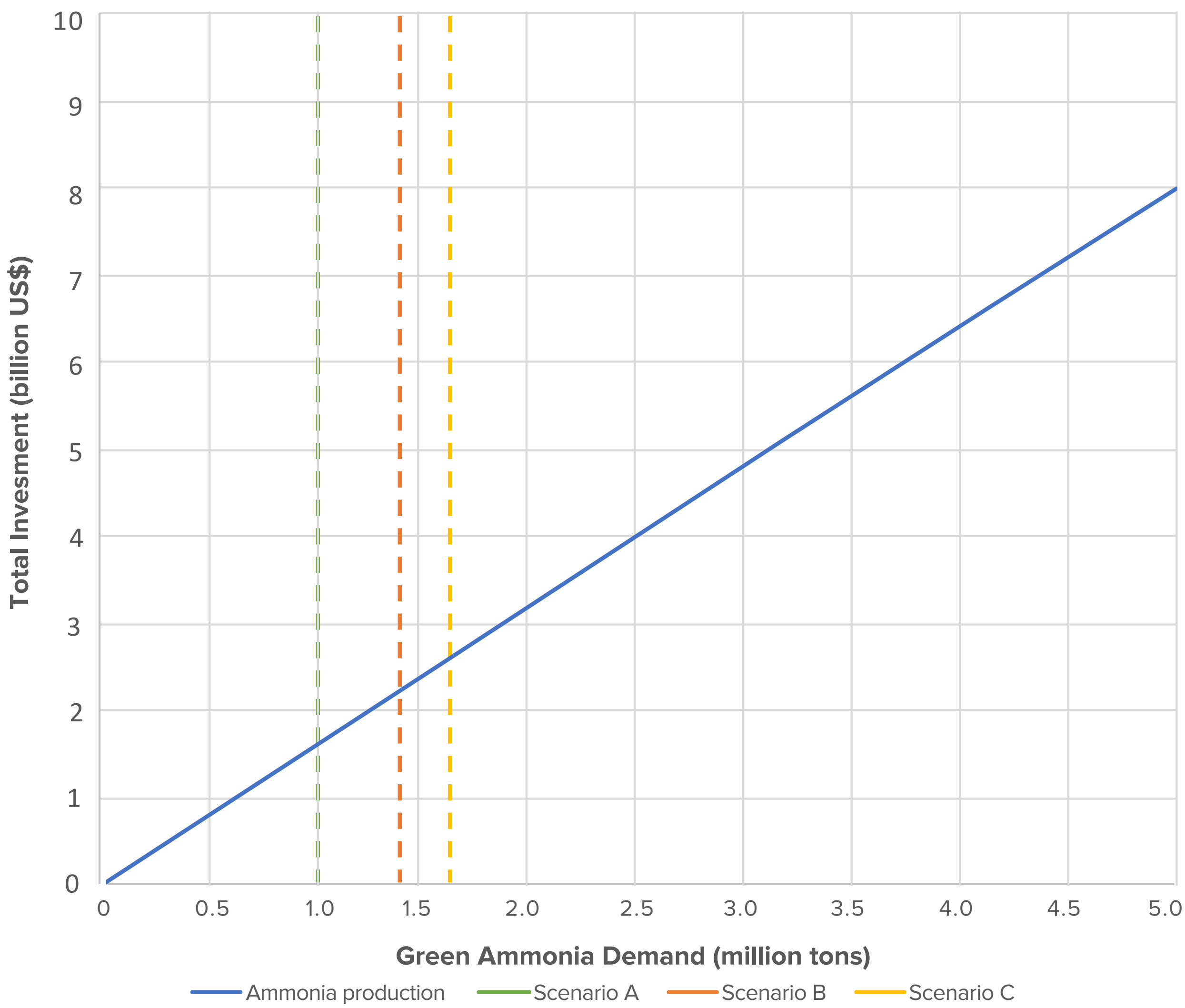


5.4.5 An estimate of the investment needed in Mauritius

The capital investment needed to generate the required quantities of green ammonia is calculated using the estimated relationship between ammonia demand and capital investment (see Appendix D – Estimated relationship between ammonia demand and capital investments for more details).

Figure 27 shows the linear relationship used and the points of intersection with the assumed green ammonia demand under the three scenarios. In scenario A, Mauritius would have to meet approximately one million tons/year of green ammonia demand with an associated capital investment of $1.6 billion. In scenario B, 1.37 million tons of green ammonia demand would require an investment of $2.1 billion. In scenario C, 1.7 million tons of green ammonia demand would require $2.7 billion of investment.

FIGURE 27: GREEN AMMONIA DEMAND AND INVESTMENT FOR MAURITIUS'S ASSUMED GREEN AMMONIA DEMAND



5.4.6 Summary

This case study of Mauritius's potential as a supplier of green ammonia leads to the following conclusions:

- Mauritius is strategically located on the East-West route in the Indian Ocean, linking Asia, Africa, and South America.
- Solar and offshore wind energy sources appear to be best suited to provide the necessary energy sources required.
- Mauritius could cover a small share of the African market. The required investment ranges from $1.6 billion to meet three percent of Africa's demand in 2050 to $2.7 billion to meet five percent of Africa's demand in 2050.

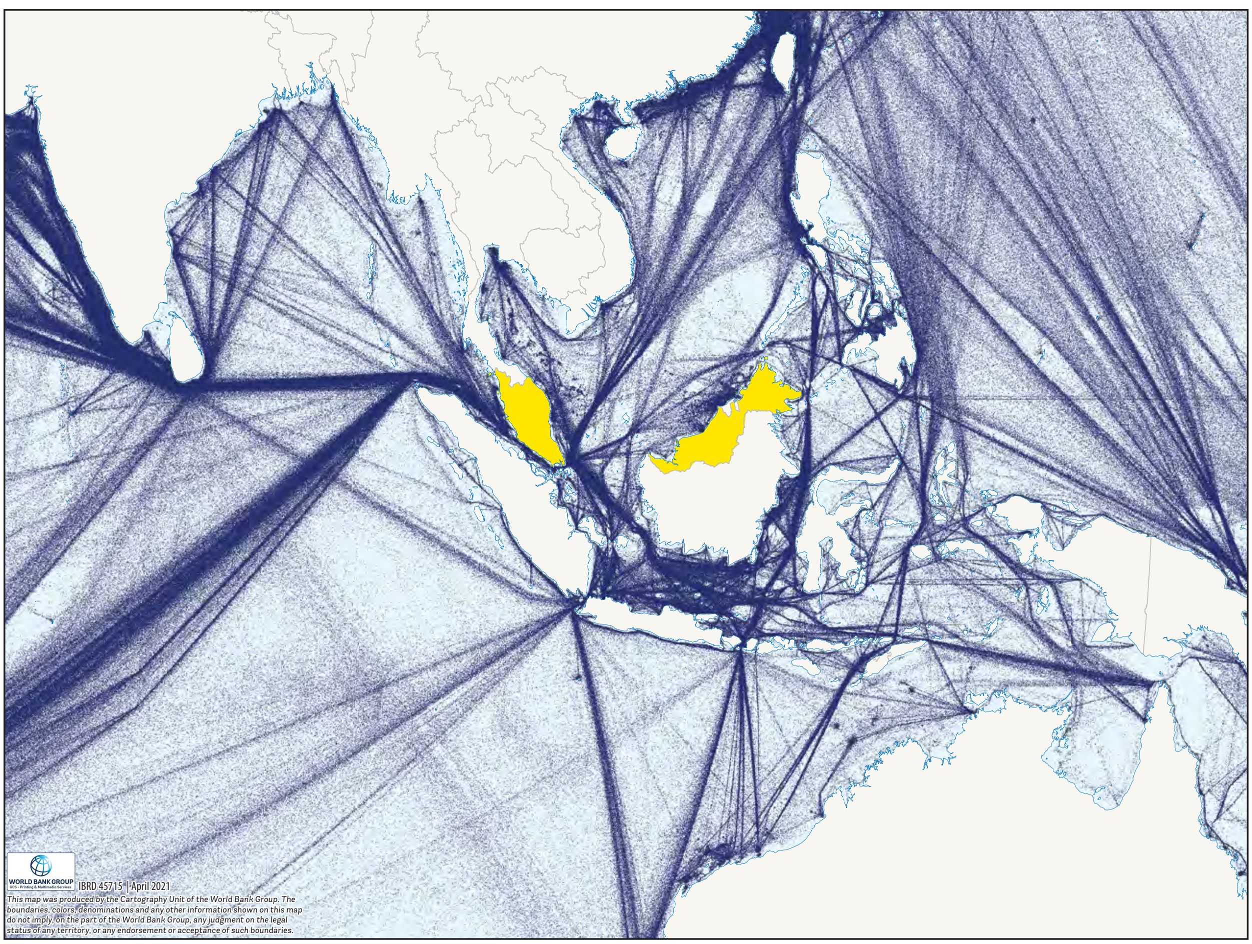
5.5 CASE STUDY 4: MALAYSIA – FIRST BLUE, THEN GREEN AMMONIA

This fourth case study looks at Malaysia's potential to produce zero-carbon ammonia. Malaysia is connected to major shipping routes and closely located to bunkering hubs, notably Singapore. Its combination of renewable energy potential, natural gas reserves, and CCS potential makes this country a potential producer of both blue and green ammonia.

5.5.1 Malaysia's port activities and shipping traffic

Malaysia represents a major hub for container ships and ranked fifth in the world in 2017 for annual container port throughput after China, the United States, Singapore, and South Korea.[30] It is also strategically located on the Straits of Malacca, where heavy maritime traffic travels between Asia and the Suez Canal. Its main ports include Port Klang (12.3 million TEUs in 2018) (Lloyd's List), Port of Tanjung Pelepas (nine million TEUs in 2018) (Lloyd's List), Penang Port (1.2 million TEUs in 2013) (Penang Port) and Johor Port (0.9 million TEUs in 2010) (Jeevan et al. 2015).

FIGURE 28: SHIPPING TRAFFIC IN MALAYSIA FOR 2015-2020



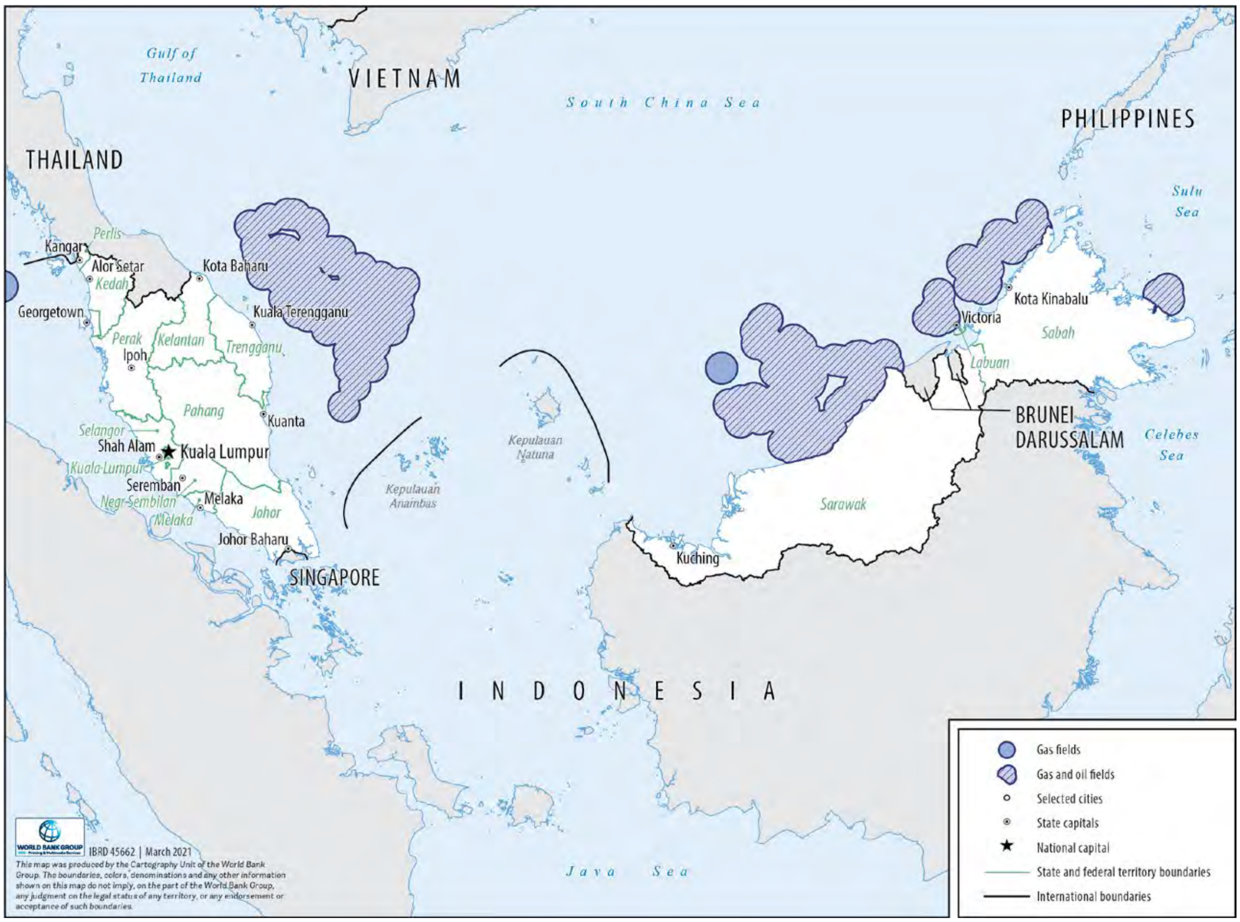
Source: IMF's World Seaborne Trade monitoring system (Cerdeiro et al. 2020)

30 UNCTAD, n.d.

5.5.2 Malaysia's natural gas resources and CCS potential

In 2017, Malaysia's natural gas production reached 2,453 bcf (EIA). This makes the country the world's 13th largest producer of natural gas. Proven reserves of natural gas in 2018 were estimated at 41.8 tcf, which represents less than one percent of the world's estimated reserves (EIA). Of these reserves, 54 percent are located in Sarawak province, 31 percent in the Peninsula and 15 percent in Sabah (Malaysia Energy Commission 2019), as shown in Figure 29.

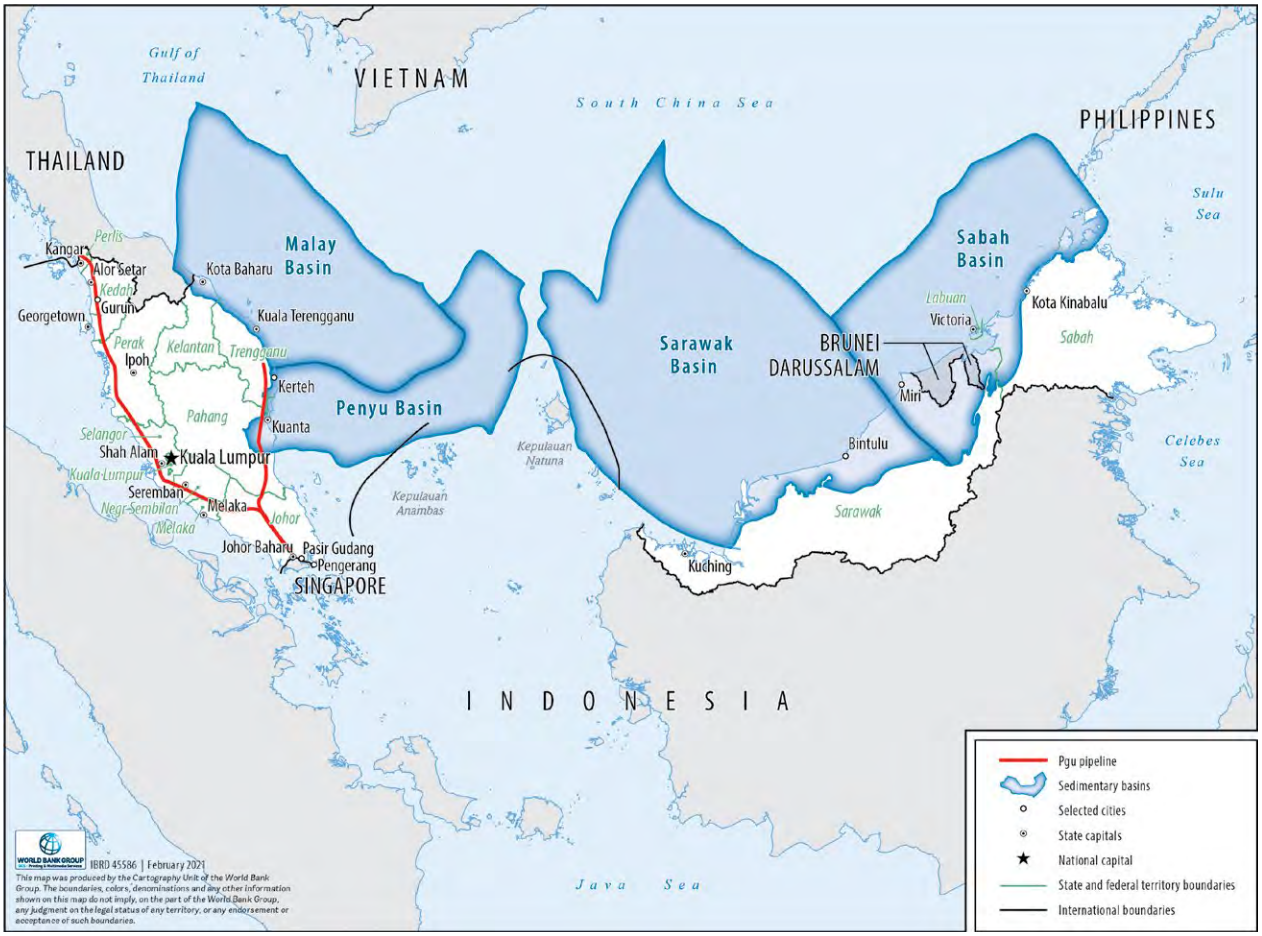
FIGURE 29: OIL AND GAS RESERVES IN MALAYSIA



Source: Coordinating Committee for Geoscience Programmes in East and Southeast Asia

Malaysia has potential for CCS in sedimentary basins both onshore and offshore, as shown in Figure 30. However, there is still a high level of uncertainty around the actual CCS potential (Radzuan and Hasbollah 2016). The CCS potential is estimated to be 28 gigatons (Consoli and Wildgust 2017). For comparison, the United Arab Emirates (which ranks first in Consoli and Wildgust 2017) has an estimated CCS potential of more than 45,000 gigatons.

FIGURE 30: MALAYSIA SEDIMENTARY BASINS

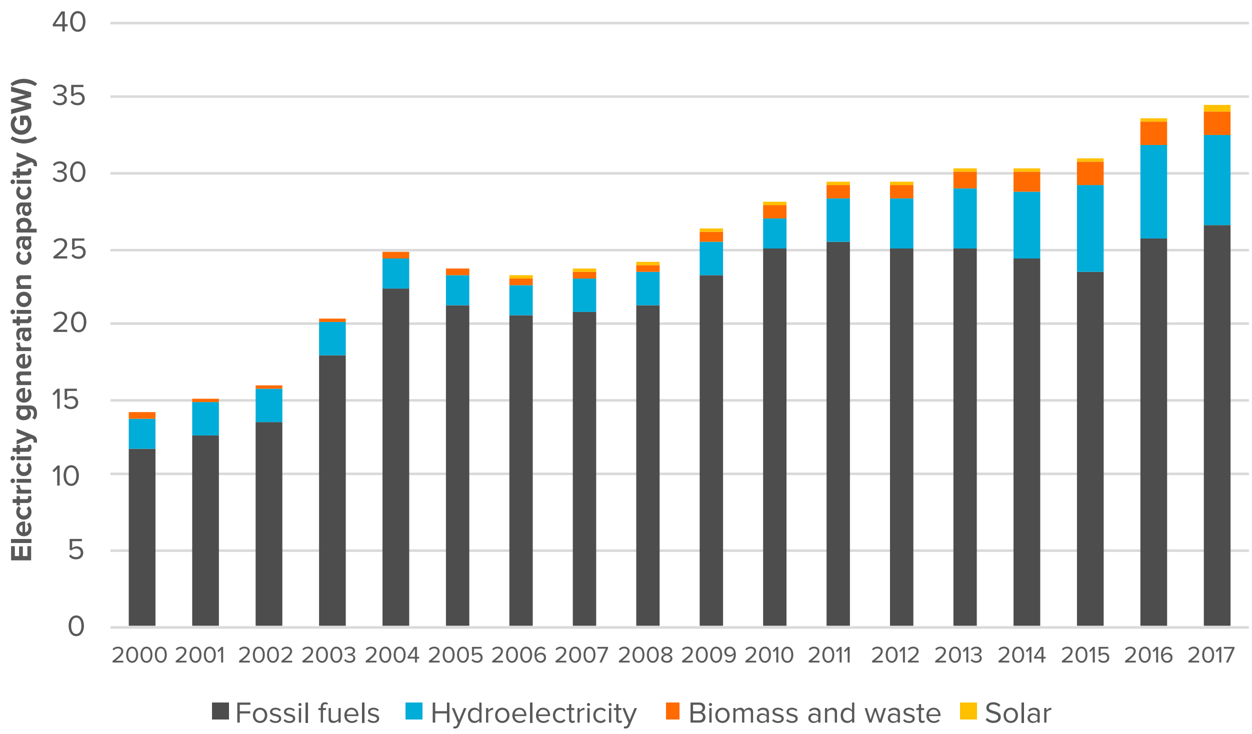


Source: Ahmad et al. 2019

5.5.3 Malaysia's renewable energy potential and future development

Malaysia's total electricity generation capacity amounted to 34 GW in 2018, compared to nearly 1,800 GW in China, more than 1,000 GW in the United States, and 388 GW in India. As shown in Figure 31, renewable electricity generation capacity has steadily increased since 2010 to reach 23 percent of total electricity generation capacity in 2017.

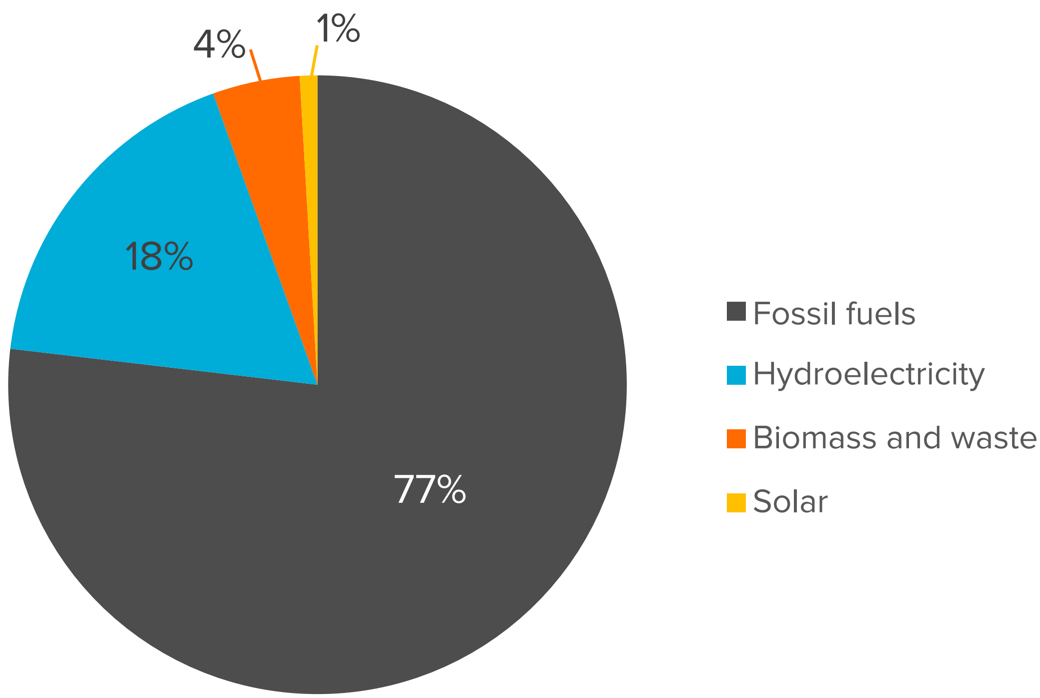
FIGURE 31: ELECTRICITY GENERATION CAPACITY IN MALAYSIA, 2000–2017



Source: EIA

This renewably supply is mostly produced from hydro sources, with some contributions from biomass and waste. Generation capacity based on fossil fuels represented 77 percent in 2018 as displayed by Figure 32. Solar energy generation capacity is still nearly non-existent.

FIGURE 32: ELECTRICITY GENERATION CAPACITY MIX IN MALAYSIA IN 2018



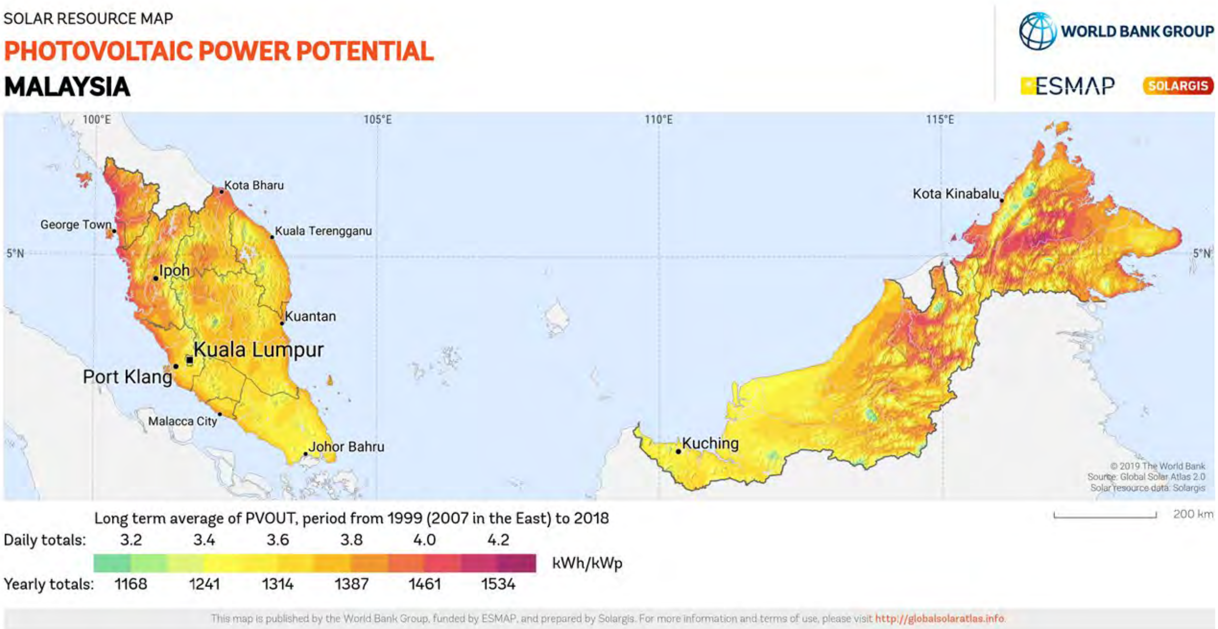
Source: EIA

The lack of solar electricity generation is at odds with the excellent solar power potential of Malaysia (see Figure 33). Most areas receive an annual average daily solar radiation of between 4.21 and 5.56 kWh/m$^{2/}$day (Belhamadia, Mansor, and Younis 2013). In comparison, countries on the Arabian Peninsula—one of the sunniest regions in the world—all have an average solar radiation above 6 kWh/m^2 (Global Solar Atlas 2020).

If three percent of Malaysian land is assumed to be available for solar farms, compared to the latest estimates reserving roughly 23 percent of land for agricultural use (CIA 2011), this would result in approximately 4,000 GWh/day of electrical energy.

The emphasis on solar-powered green ammonia production reflects the limited and varying average wind speed experienced by Malaysia (Belhamadia et al. 2013) and relatively small untapped potential for hydropower compare to solar power potential (Zhou et al 2015).

FIGURE 33: PHOTOVOLTAIC POWER POTENTIAL IN MALAYSIA



Source: Global Solar Atlas

5.5.4 Estimated ammonia demand scenarios for Malaysia

Malaysia currently accounts for less than one percent of global bunker fuel sales. However, its geographic location makes it particularly suited to becoming an exporter to neighboring countries with established bunkering volumes such as Singapore. If Malaysia produced zero-carbon ammonia for shipping, it could exploit the potential to cover a significant share of the fuel needs for the whole of Asia.

Table 13 summarizes the hypothetical shipping demand scenarios for ammonia produced in Malaysia, which range from 11 to 95 million tons of ammonia. These figures are also presented in terms of fraction of the total shipping ammonia demand needed in 2050 under a decarbonization-by-2050 scenario as well as fraction of the Asia regional market. In addition, the hypothetical shipping demand scenarios for ammonia are presented in terms of fraction of the shipping total fuel demand in 2016 in energy terms.

TABLE 13: SHIPPING'S AMMONIA DEMAND SCENARIOS FOR MALAYSIA

	SHIPPING ANNUAL AMMONIA DEMAND FOR MALAYSIA IN 2050 (MILLION TONS)	PERCENT OF GLOBAL AMMONIA DEMAND FOR SHIPPING, ASSUMING FULL DECARBONIZATION BY 2050	CORRESPONDING PERCENT OF THE 2016 GLOBAL ENERGY SHIPPING DEMAND	PERCENT OF ASIAN AMMONIA SHIPPING DEMAND ON REGIONAL MARKETS, ASSUMING FULL DECARBONIZATION BY 2050
Scenario A	11	1 percent	3 percent	3 percent
Scenario B	56	6 percent	16 percent	15 percent
Scenario C	94	10 percent	27 percent	25 percent

5.5.5 Energy resources required to produce ammonia in Malaysia

Malaysia has been selected as one of the countries well positioned to produce both blue and green ammonia—initially blue ammonia, later green ammonia. In 2050, it is assumed that 33 percent of total ammonia is produced from natural gas using CCS (blue ammonia) and the remaining 67 percent comes from renewable electricity (green ammonia).

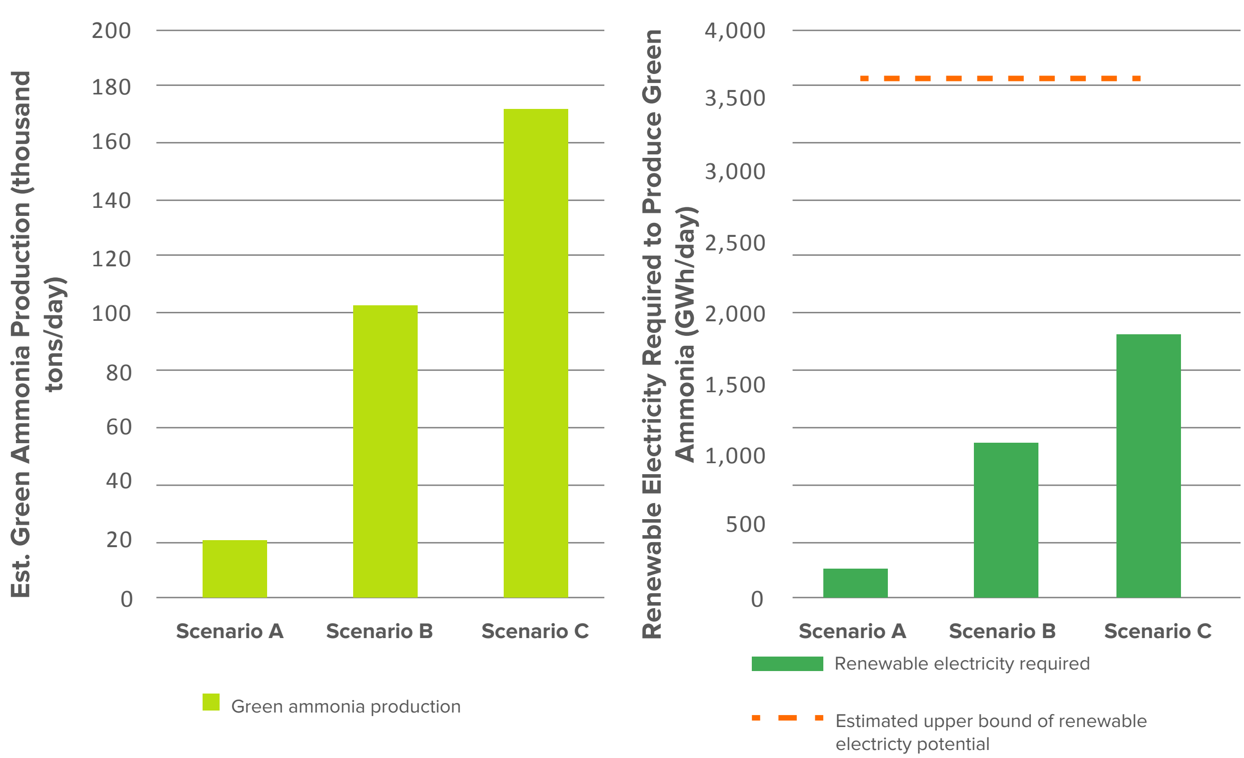
If production were constrained only by current natural gas reserves and CCS capacity, Malaysia would have the potential to produce up to 19,000 million tons of blue ammonia across the whole period, or three million tons per day. This figure serves as an upper limit on production as it assumes that all natural gas reserves and all carbon storage potential are solely used to produce blue ammonia. The quantities of natural gas and carbon storage per day required under the scenarios are illustrated in Table 14.

TABLE 14: NATURAL GAS AND OF CARBON STORAGE REQUIRED TO PRODUCE BLUE AMMONIA IN MALAYSIA

	ESTIMATED BLUE AMMONIA PRODUCTION (THOUSAND TONS/DAY)	NATURAL GAS REQUIRED (MILLION CUBIC FEET/DAY)	CCS REQUIRED (THOUSAND TONS PER DAY)
Scenario A	10	0.3	15
Scenario B	52	1.6	77
Scenario C	87	2.6	129

As previously noted, solar energy is assumed to provide the main source of electricity generation for green ammonia production in Malaysia. Figure 34 displays the quantity of renewable electricity required for each scenario. Daily ammonia production could range from 21 to 173 thousand tons per day, indicating that the daily renewable electricity required would be between 218 and 1,815 GWh/day—well below the estimated upper bound of renewable electricity potential of 3,700 GWh/day.

FIGURE 34: RENEWABLE ELECTRICITY REQUIRED TO MEET THE ESTIMATED GREEN AMMONIA PRODUCTION IN MALAYSIA



5.5.6 An estimate of the investment needed in Malaysia

It is assumed that ammonia demand in Malaysia would be met by steam methane reforming of natural gas in conjunction with CCS to produce blue ammonia at the beginning of the energy transition, and by renewable electricity input to supply green ammonia in the longer term. The capital investment required by this combined production pathway is calculated using an estimated relationship between ammonia demand and capital investments for each of the production methods (see Appendix D – Estimated relationship between ammonia demand and capital investments for more details).

A summary of the ammonia production in the three scenarios considered, and the corresponding required investments, is presented in Table 15.

TABLE 15: AMMONIA ANNUAL PRODUCTION AND INVESTMENTS IN MALAYSIA

	ANNUAL PRODUCTION (MILLION METRIC TONS, 2050)			INVESTMENTS ($BILLION)		
	GREEN AMMONIA	BLUE AMMONIA	TOTAL	GREEN AMMONIA	BLUE AMMONIA	TOTAL
Scenario A	8	4	11	12	5	17
Scenario B	38	19	57	59	24	83
Scenario C	63	32	95	98	40	138

Figure 35 provides the linear relationship between blue ammonia demand and required investment. The points of intersection for assumed blue ammonia demand under the three scenarios are provided. In scenario A, Malaysia produces approximately four million tons of blue ammonia with an associated capital investment of $4.8 billion. In scenario B, 19 million tons of blue ammonia are produced with investment of $24 billion. In scenario C, 32 million tons of blue ammonia are delivered for $40 billion of investment.

FIGURE 35: BLUE AMMONIA DEMAND AND INVESTMENT NEEDED FOR MALAYSIA'S ASSUMED BLUE AMMONIA DEMAND

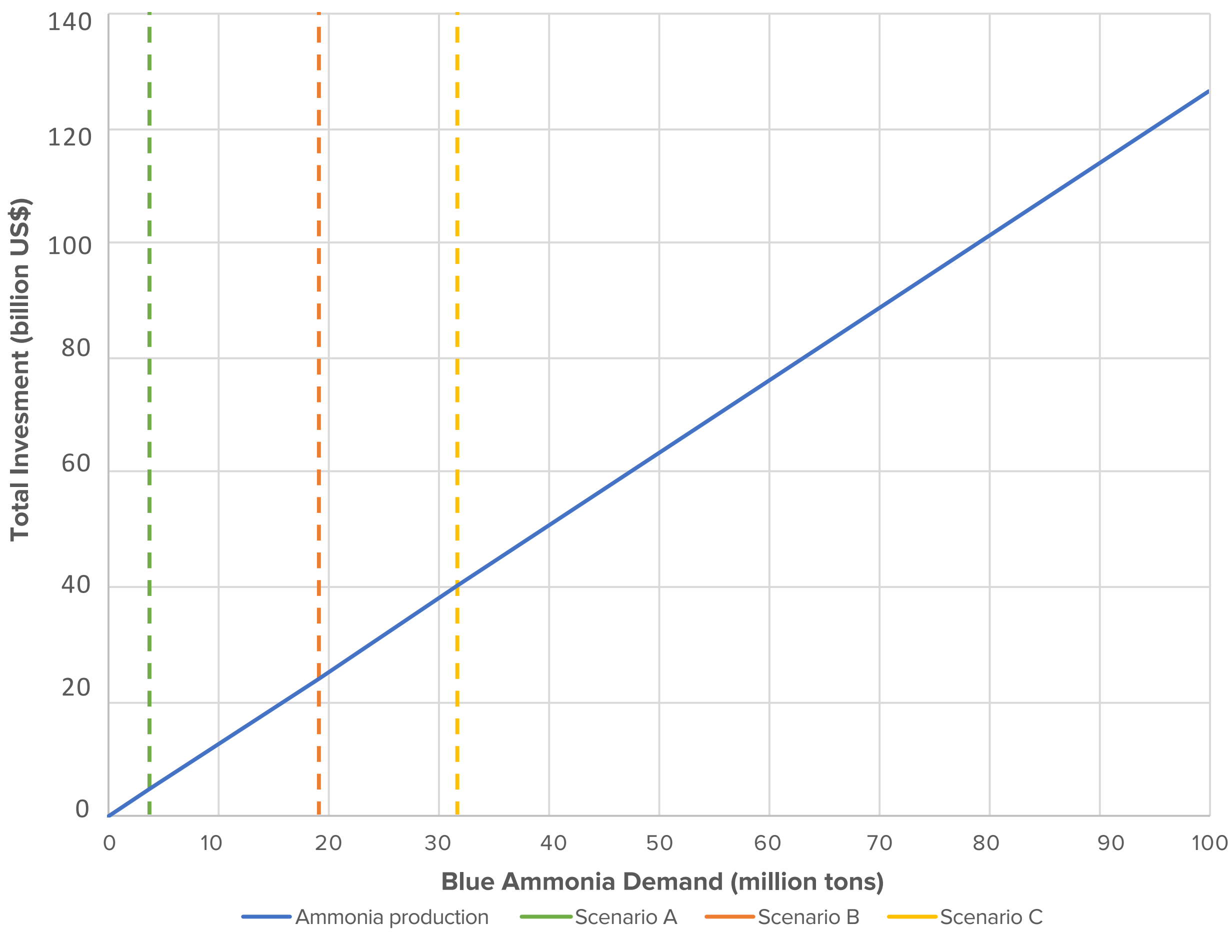
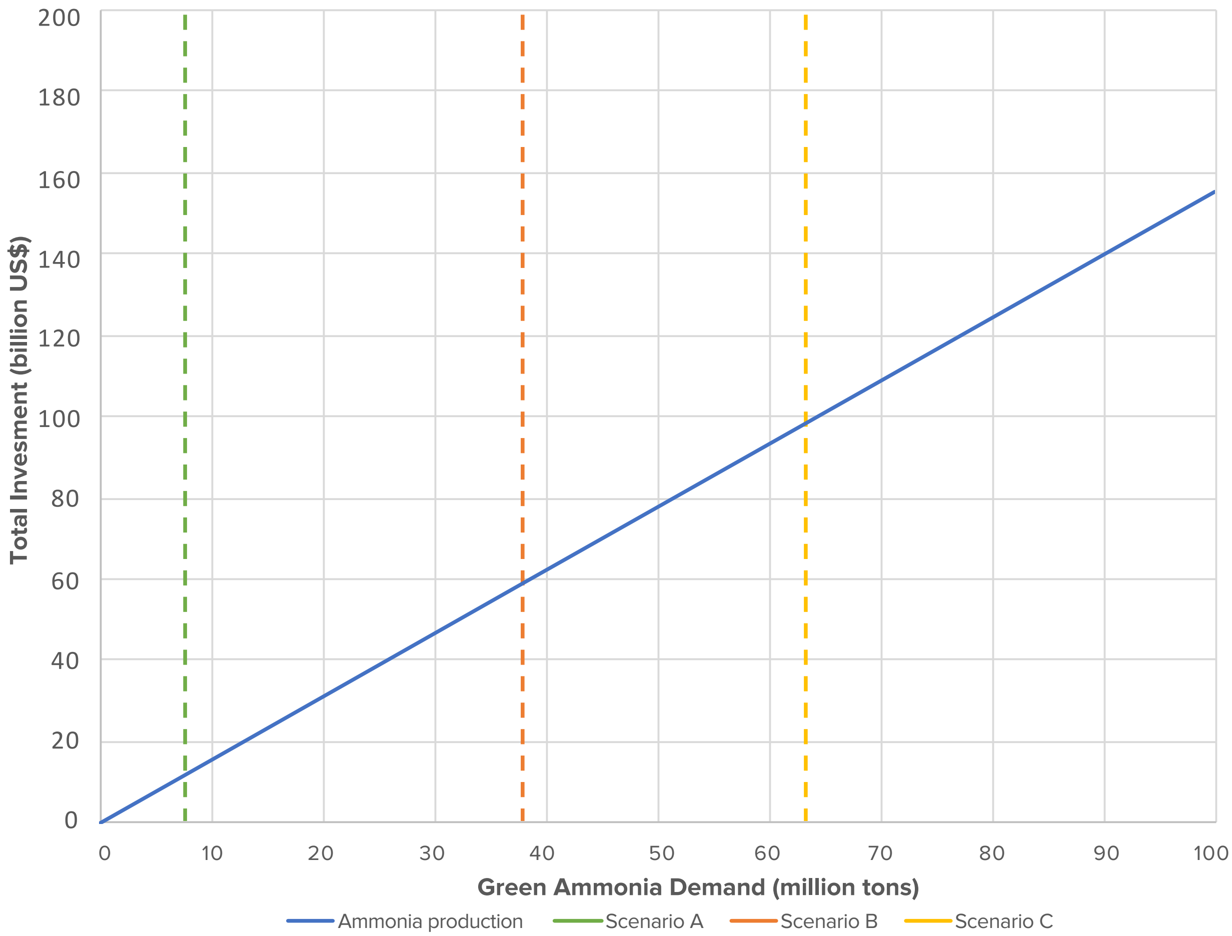


Figure 36 shows the linear relationship between green ammonia demand and required investment, along with the points of intersection of assumed green ammonia demand under the three scenarios. In scenario A, Malaysia would need to generate approximately eight million tons of green ammonia with an associated capital investment of $12 billion. In scenario B, 38 million tons of green ammonia with investment of $59 billion. In scenario C, 63 million tons of green ammonia with investment of $98 billion.

FIGURE 36: GREEN AMMONIA DEMAND AND INVESTMENT NEEDED FOR MALAYSIA'S ASSUMED GREEN AMMONIA DEMAND



5.5.7 Summary

This analysis of Malaysia's potential as a "first blue, then green" supplier of zero-carbon ammonia bunker fuels leads to the following conclusions:

- Malaysia benefits from an excellent geographic location very close to Singapore, the world's largest bunkering hub, and is well positioned to capture demand from continued economic growth in Asia.
- Malaysia has an excess of solar potential that is more than sufficient to meet both its domestic demands and the fuel supply scenarios considered within this case study.
- Malaysia can potentially benefit from using green ammonia as a way to capture excess solar electricity at times of low domestic demand.

- Depending on the fuel supply scenario, the investment required to realize this potential ranges from $17 billion (covering three percent of the Asian market) to $138 billion (covering 25 percent of the Asian market, or ten percent of the world market).

In these high-level case studies, hydrogen as a zero-carbon bunker fuel has not been explicitly taken into consideration. This is because the capital expenditures needed for the supply of liquefied hydrogen to shipping would be very similar to the capital expenditures needed for the supply of ammonia, as can be seen in Appendix E – Hydrogen and ammonia investment comparison. As a consequence, the ammonia-related results in each country can also be considered representative for liquefied hydrogen.

6. CONCLUSIONS AND OUTLOOK

This section presents the key findings of the analysis, some implications for policymakers and industry, as well as recommendations for further research.

6.1 KEY FINDINGS

This report first identifies the zero-carbon bunker fuels that are most promising to be major contributors to shipping's decarbonized future and then seeks to understand, at a global scale, which countries are likely to be well positioned to produce future zero-carbon bunker fuels for the maritime industry.

The most promising zero-carbon bunker fuels have been identified by combining an extensive literature review with a multi-objective "Red-Amber-Green" (RAG) analysis. This methodological approach concludes that "green" ammonia, closely followed by "green" hydrogen, is likely to strike the most advantageous balance of favorable features among a range of different candidate bunker fuels for ships. These features relate to the lifecycle greenhouse gas (GHG) emissions, broader environmental factors, the scalability, the economics, and the technical and safety implications of each fuel. Ammonia or hydrogen also have the advantage of having multiple production pathways, providing a significant strategic advantage which alleviates concerns about capacity limits and technology issues.

Ammonia appears preferable over hydrogen because hydrogen is expensive to store and handle, particularly on board a vessel. However, ammonia is toxic to humans and aquatic wildlife. Fortunately, ammonia is already an important globally traded commodity. Therefore, meeting challenges associated with its safe storage and handling on board a vessel will be achievable through the application of appropriate protocols, compliance with technical standards, and use of safety equipment.

This report concludes that both biofuels and synthetic carbon-based fuels are not expected to become the major power source for achieving shipping's future zero-carbon energy needs. Without a breakthrough in aquatic biomass production, biofuels are likely constrained by their feedstock availability, the potential high demand across multiple sectors of the global economy, and the resulting uncertain supply-and-demand price dynamics. Synthetic carbon-based fuels are penalized by their very high costs relative to other alternatives due to multiple energy-intensive steps involved in their production.

After having identified the most promising zero-carbon bunker fuels, this report has deployed a new methodological approach that seeks to understand, at a global scale, which countries are likely to be well positioned to produce future zero-carbon bunker fuels for the maritime industry. It finds that many countries, including developing countries, are very well-situated to become future suppliers. Well-positioned countries tend to be those endowed with many of the natural resources required to produce the zero-carbon fuels, combined with favorable access to a large volume of shipping activity.

These insights have been used to produce shortlists of countries for which further and deeper investigation appears useful. Four developing countries have been selected for further high-level case studies: Brazil, India, Mauritius, and Malaysia. These case studies discuss the implications of each country becoming a potential future producer of zero-carbon bunker fuels in its regional market. Considering a range of hypothetical ammonia supply scenarios, the capital expenditure requirements have been estimated for each country selected:

- This approach finds that Brazil would need a capital expenditure ranging between $24 billion and $107 billion to meet the full range of blue ammonia supply scenarios.
- India and Mauritius would require between $147 billion and $385 billion and $1.6 billion to $2.7 billion, respectively, to meet the full range of green ammonia supply scenarios.
- Malaysia's capital expenditure to meet first the blue and later the green ammonia supply scenarios would range between $17 billion and $138 billion.

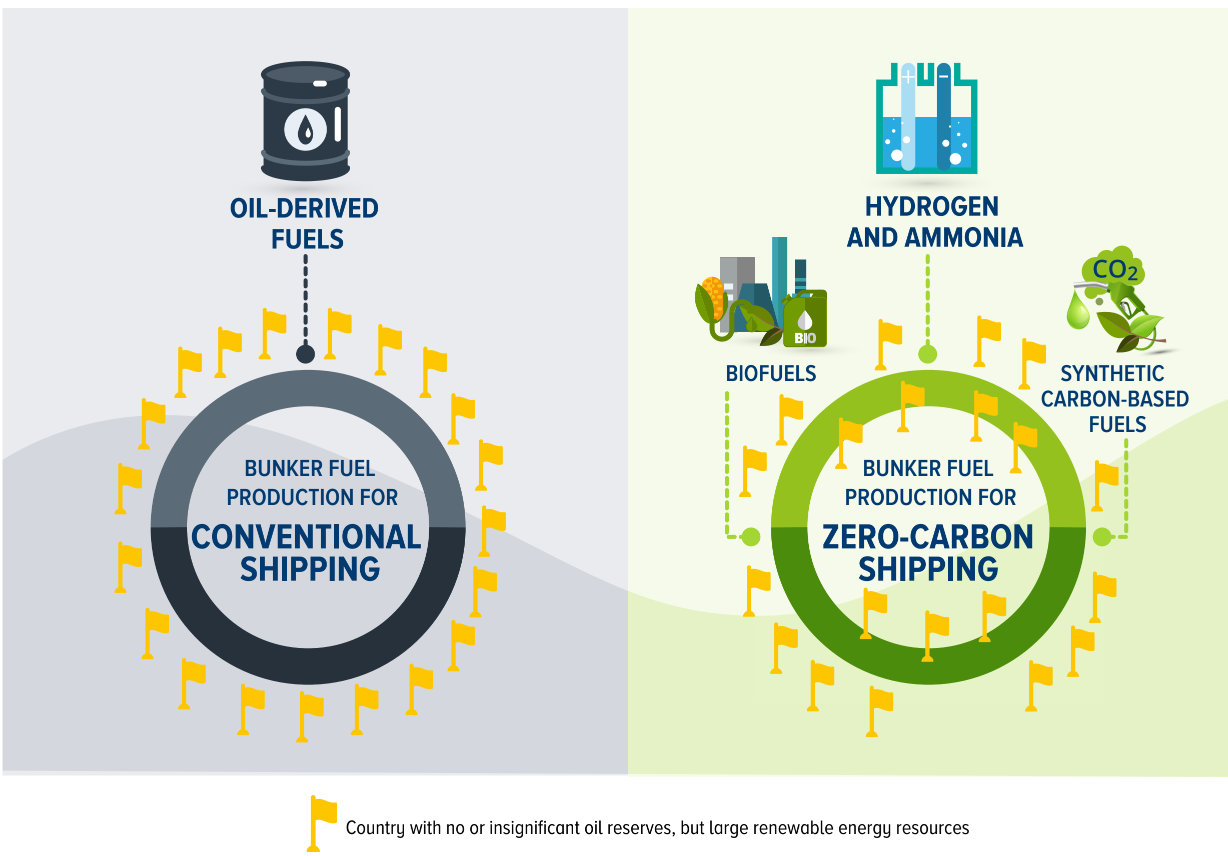
6.2 IMPLICATIONS

The analysis provided in this report leads to the following key implications for policymakers and for the maritime industry.

6.2.1 Implications for policymakers

In the past, the global market for bunker fuels—heavily based on HFO—has been dominated by a limited number of oil-exporting countries. In the future, the emergence of zero-carbon bunker fuels and the decoupling of the energy supply for shipping from crude oil reserves offer a unique opportunity for more countries to enter a more inclusive market—as illustrated by Figure 37. Well-positioned countries include a number of developing countries, characterized by their low-cost renewable energy sources combined with other advantages, such as a strategic geographic proximity to major shipping routes.

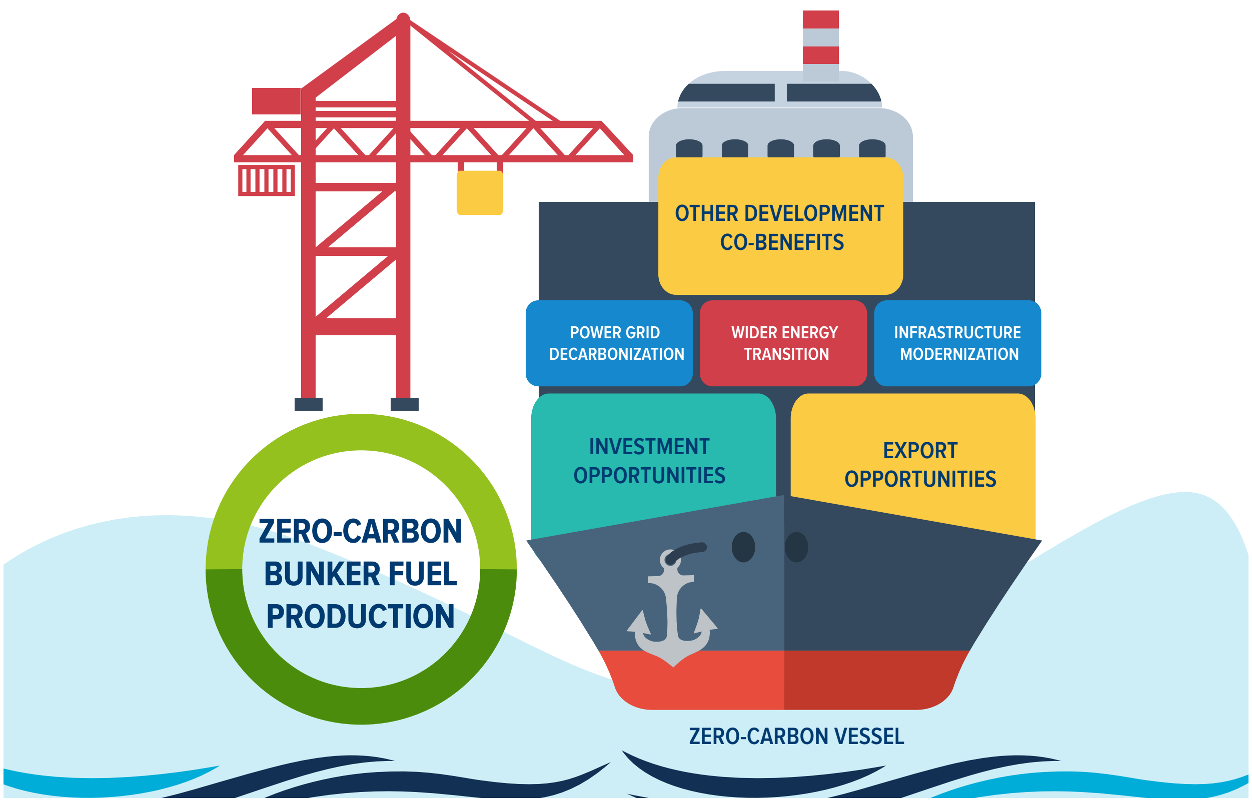
FIGURE 37: POTENTIAL REALIGNMENT OF THE GLOBAL BUNKER FUEL MARKET THROUGH ZERO-CARBON SHIPPING



This realignment of the global bunker fuel market gives policymakers from these developing countries the opportunity to leverage national comparative advantages during the expected period of growing demand for zero-carbon bunker fuels from 2030 onwards. Indeed, policymakers could strategically harness demand for zero-carbon bunker fuels to support investments in the decarbonization of their domestic energy systems. Obvious synergies between both systems could be exploited:

for instance, ammonia/hydrogen could be used as an energy carrier to help compensate for the intermittency of renewable electricity generation; they could be marketed as a commodity for further industrial use within the country, or they could be exported as a low-cost renewable energy resource to other countries where no physical connection through power transmission lines exists. Additionally, these investments are able to create further development opportunities—as shown by Figure 38—like, for instance, maritime and non-maritime infrastructure modernization and contributions to the country's wider energy transition.

FIGURE 38: OPPORTUNITIES FOR DEVELOPMENT CREATED BY ZERO-CARBON BUNKER FUEL PRODUCTION



The potential application of green hydrogen and ammonia in developing countries is broad, thereby offering economies of scale through sector coupling. While sector coupling once referred primarily to electrifying the demand side of sectors like heating and transport based on renewable electricity, the concept has now been broadened to also include the supply side of the power and gas sectors through versatile technologies like power-to-gas. The European Commission, for instance, understands sector coupling as "a strategy to provide greater flexibility to the energy system so that decarbonization can be achieved in a more cost-effective way" (European Parliament 2018).

Besides these policy and industrial strategy considerations for national governments, zero-carbon bunker fuels may also have important implications for the way national governments interact at the IMO to finalize and enhance the Initial IMO GHG Strategy. A meaningful carbon price represents a prime example of a cost-effective policy option that could be instrumental in creating a level playing field between fossil and zero-carbon bunker fuels. Furthermore, carbon pricing can generate revenues which in turn can be used to help support the creation of a global zero-carbon energy supply infrastructure for shipping and ensure a fair and equitable energy transition away from fossil fuels. If this support included targeted investments toward developing countries which are well positioned to produce zero-carbon bunker fuels, this could help to allay some existing controversies in the policy debate about "Common But Differentiated Responsibilities and Respective Capabilities", a guiding principle of both the Initial IMO GHG Strategy and the United Nations Framework Convention on Climate Change.

These opportunities warrant further and more detailed assessment. This report provides the basis for such work by providing a discussion of the most promising zero-carbon bunker fuel options, a robust new method for identifying those countries well positioned to produce these fuels for shipping in the future, and a number of high-level quantitative estimates of the scale of opportunity and capital expenditures needed in four representative developing country examples.

6.2.2 Implications for industry

This report also has clear implications for both incumbents as well as potential new market entrants in the maritime industry. The supply of zero-carbon bunker fuels will impact the whole shipping sector including, for example, fuel producers, fuel suppliers, equipment manufacturers, shipyards, ship owners, charterers, and shipping companies.

With regard to infrastructure, the large capital costs and short timescales likely required for the important expansion in production capacity of zero-carbon bunker fuels imply a significant commercial opportunity, but also a certain level of risk. When considering such investment decisions, several factors influence the assessment of risk and reward. These include concerns such as the scale of initial public support that may be necessary to ensure the economic sustainability of any private sector activity and the availability of specialized financial mechanisms, including different types of bonds (including, for example, impact bonds and green bonds), which can be used in addition to equity and other sources of debt finance. Furthermore, the critical scale at which infrastructure becomes competitive is also an important consideration. This is illustrated by the relatively low green ammonia production capacity in the case of Mauritius in contrast to the much larger capacity of India. In addition to scale, given a regional landscape of potential producers there may be other factors which affect the commercial competitiveness of different countries and therefore their investment capacity.

A key investment risk is the creation of stranded assets. For shipping's energy transition, the focus on blue or green hydrogen—either directly or as a feedstock for ammonia—increases the range of technological options which could make use of a given zero-carbon bunker fuel. However, for individual industry stakeholders who may need to choose which of these options to invest in, this also increases investment uncertainty related to either choice's long-term commercial competitiveness. For example, suppliers that have invested in blue hydrogen may be left with stranded assets should green hydrogen quickly become very competitive, and vice versa.

On the vessel and operational side, ship owners also need to manage their investment risks regarding onboard technologies. For example, many shipowners have expressed their unwillingness to invest in a certain type of vessel until there is a broad understanding of what the dominant zero-carbon bunker fuel will be in 10 or even 30 years. This would have cascading implications for the equipment supply chains associated with each of these fuels. Conversely, the increasing shift toward stronger corporate social responsibility considerations in corporate strategies could present an opportunity for progressive shipping companies, owners, and technology providers to capture new market share by actively contributing to shipping's energy transition away from fossil fuels and toward zero-carbon bunker fuels.

6.3 OUTLOOK FOR FURTHER WORK

The key findings and underlying methods of this report provide an important early indication and framing for assessing which countries may be well positioned as future fuel suppliers. Nevertheless, further work will be required, focusing, for instance, on the following aspects:

- **Cost competitiveness**: Considering the individual cost competitiveness of different developing countries in addition to any competition effects between neighboring countries (including both developing and developed countries) has been beyond the scope of this report, but should be a key topic for any further research.

- **Multi-criteria assessment**: The multi-criteria assessments of the most promising zero-carbon bunker fuels (including the current RAG matrix approach) for shipping should be further developed as first pilots and demonstrator projects conclude and provide practical insights. Additionally, further valuable insights in how to build a future supply chain for zero-carbon bunker fuels could be gained by extending the scope of the assessment to consider opportunities for bilateral energy cooperation between neighboring countries.

- **National datasets**: There is an opportunity to increase the coverage and granularity of national datasets on energy resources. This would enable the assessment framework to better classify the nature and scale of the business opportunity in individual countries.

- **Case studies**: Additional country case studies can make important contributions to validate general global findings on a national scale, and to facilitate comparison among countries.

Ultimately, any further analysis which enables constructive policy design, including carbon pricing in particular, can inform effective policymaking and strategically exploit synergies between global GHG emissions reduction, national development opportunities, and multilateral cooperation at the IMO.

APPENDIX A – CRITERIA AND SCORING SYSTEM OF HIGH-LEVEL ASSESSMENT

TABLE 16: CRITERIA AND SCORING SYSTEM USED IN COUNTRY ASSESSMENTS WITH REGARD TO ZERO-CARBON BUNKER FUEL PRODUCTION POTENTIAL

CRITERIA AND WEIGHT			WEIGHT REASONING	CALCULATION METHOD	ID	ATTRIBUTE	SCORING SYSTEM
#1 Energy resources required 50%	**First scenario:** ammonia/hydrogen production only, using exclusively 1.1 **Second scenario:** green ammonia/hydrogen production only, using exclusively 1.2 **Third scenario:** blue ammonia/hydrogen first, green ammonia/hydrogen later, using 1.1 (weight 30%) and 1.2 (weight 70%)	1.1 Natural gas with CCS	Access to the energy resources required to produce zero-carbon bunker fuels appears to be an essential prerequisite for countries. The relative weight of this criterion is therefore deemed to be very high.	1.1 = (0.5 * 1.1.1 + 0.5 * 1.1.2) * 1.1.3	1.1.1	Current natural gas production	Natural gas production normalized from 0 to 5 range
					1.1.2	Natural gas proved reserves	Natural gas reserves normalized from 0 to 5 range
					1.1.3	CCS potential	CCS storage indicator normalized from 0 to 5 range
		1.2 Renewable energy		1.2 = 0.1 * 1.2.1 + 0.9 * (1.2.2 + 1.2.3 + 1.2.4 + 1.2.5)	1.2.1	Current renewable electricity capacity (excluding biomass)	Renewable electricity capacity normalized from 0 to 5 range
					1.2.2	Solar potential	Photovoltaic power potential, average per country normalized from 0 to 5 range
					1.2.3	Offshore wind potential	Offshore wind potential normalized from 0 to 5 range
					1.2.4	Onshore wind potential	Mean power density, 10% windiest areas normalized from 0 to 5 range
					1.2.5	Hydropower potential	Exploitable hydropower potential normalized from 0 to 5 range

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CRITERIA AND WEIGHT	WEIGHT REASONING	CALCU-LATION METHOD	ID	ATTRIBUTE	SCORING SYSTEM
#2 Shipping volumes 20%	The weight is medium-high, because shipping volumes of a country might not have a strong correlation with the location where the selected fuels will be produced (similar to geographic location), although this can be relatively important especially at the beginning of the transition because a country can instantly exploit its high shipping volumes.	2 = $\sum$ (2.1 * 2.2 * 2.3 per ship type/size)	2.1	Number of arrivals	
			2.2	Average size in deadweight tons, gross tons or twenty foot equivalent units (TEU) by ship type calling at a given country's port	
			2.3	Average annual fuel consumption by ship type/size	
#3 Geographic location 12.5%	The cost of transporting fuel to bunkering hubs is not expected to be very high relative to the cost of producing the fuel, therefore location appears to be of medium-low importance only.	3 = 0.5 * 3.1 + 0.5 * 3.2	3.1	Liner shipping connectivity index	Liner shipping connectivity Index, annual normalized from 0 to 5 range
			3.2	Proximity to major bunkering hubs	Distance between country and major bunkering hub (top 15 countries by bunker fuel sales) normalized from 0 to 5 range
#4 Adequacy of current and projected regulatory framework 12.5%	As this is not a necessary prerequisite, the assigned importance is only medium-low.	4 = 0.5 * 4.1 + 0.5 * 4.2	4.1	Energy Transition Index, "Transition Readiness" component only	Score normalized from 0 to 5 range
			4.2	Other national credits	Hydrogen industrial strategy developed as 5; strategy in preparation as 4; any other kind of significant support to domestic hydrogen production as 2; otherwise 0
#5 Potential to leverage existing infrastructure 5%	The weight is low because it is not indicative of the potential of a country to produce the appropriate volume of low carbon ammonia/ hydrogen.	5 = 0.5 * 5.1 + 0.5 * 5.2	5.1	Ammonia current production	Ammonia production normalized from 0 to 5 range
			5.2	Hydrogen current production	Captive hydrogen production capacity at refineries, normalized from 0 to 5 range

APPENDIX B – PRODUCTION POTENTIAL OF GREEN/BLUE AMMONIA/HYDROGEN FOR SHIPPING BY COUNTRY

TABLE 17: INDIVIDUAL RESULTS FOR THE FIRST SCENARIO: BLUE AMMONIA/HYDROGEN PRODUCTION ONLY

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
1	United States	High income	80.1	High potential
2	China	Upper middle income	54.5	High potential
3	Russian Federation	Upper middle income	51.4	High potential
4	United Kingdom	High income	36.9	High potential
5	Norway	High income	33.0	High potential
6	Spain	High income	30.8	High potential
7	Canada	High income	30.4	High potential
8	Japan	High income	29.8	High potential
9	Netherlands	High income	28.8	High potential
10	Germany	High income	28.4	High potential
11	Denmark	High income	27.6	High potential
12	Korea, Rep.	High income	26.5	High potential
13	France	High income	25.7	High potential
14	Saudi Arabia	High income	24.8	High potential
15	United Arab Emirates	High income	23.2	High potential
16	Italy	High income	22.7	High potential
17	Australia	High income	22.5	High potential
18	Malaysia	Upper middle income	21.5	High potential
19	Iran, Islamic Rep.	Upper middle income	19.5	High potential
20	Morocco	Lower middle income	18.6	High potential
21	Turkey	Upper middle income	17.0	High potential
22	Brazil	Upper middle income	16.9	Promising potential
23	India	Lower middle income	16.9	Promising potential
24	Indonesia	Upper middle income	16.6	Promising potential
25	Greece	High income	16.5	Promising potential
26	Austria	High income	16.2	Promising potential
27	Poland	High income	16.0	Promising potential
28	Oman	High income	15.9	Promising potential

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
29	Colombia	Upper middle income	15.0	Promising potential
30	Ireland	High income	14.2	Promising potential
31	Slovak Republic	High income	13.9	Promising potential
32	Bulgaria	Upper middle income	13.8	Promising potential
33	Chile	High income	13.7	Promising potential
34	Croatia	High income	13.6	Promising potential
35	Slovenia	High income	13.4	Promising potential
36	Algeria	Lower middle income	13.1	Promising potential
37	Romania	High income	12.6	Promising potential
38	Thailand	Upper middle income	12.4	Promising potential
39	Vietnam	Lower middle income	12.2	Promising potential
40	Czech Republic	High income	12.1	Promising potential
41	Mexico	Upper middle income	12.0	Promising potential
42	Egypt, Arab Rep.	Lower middle income	11.9	Promising potential
43	Israel	High income	11.8	Limited potential or insufficient data
44	New Zealand	High income	11.7	Limited potential or insufficient data
45	Qatar	High income	11.3	Limited potential or insufficient data
46	Hungary	High income	11.2	Limited potential or insufficient data
47	Taiwan, China	High income	11.1	Limited potential or insufficient data
48	Argentina	Upper middle income	11.0	Limited potential or insufficient data
49	Philippines	Lower middle income	10.3	Limited potential or insufficient data
50	Pakistan	Lower middle income	10.3	Limited potential or insufficient data
51	Jordan	Upper middle income	10.1	Limited potential or insufficient data
52	Kuwait	High income	10.0	Limited potential or insufficient data
53	Bahrain	High income	10.0	Limited potential or insufficient data
54	Georgia	Upper middle income	9.5	Limited potential or insufficient data
55	Albania	Upper middle income	9.4	Limited potential or insufficient data
56	Brunei Darussalam	High income	9.0	Limited potential or insufficient data
57	Tunisia	Lower middle income	8.6	Limited potential or insufficient data
58	Tajikistan	Low income	8.3	Limited potential or insufficient data
59	Azerbaijan	Upper middle income	8.1	Limited potential or insufficient data
60	Ethiopia	Low income	8.1	Limited potential or insufficient data
61	Ukraine	Lower middle income	7.9	Limited potential or insufficient data
62	Trinidad and Tobago	High income	7.8	Limited potential or insufficient data
63	Peru	Upper middle income	7.8	Limited potential or insufficient data
64	Senegal	Lower middle income	7.7	Limited potential or insufficient data
65	Moldova	Lower middle income	7.7	Limited potential or insufficient data
66	Kazakhstan	Upper middle income	7.7	Limited potential or insufficient data
67	Kyrgyz Republic	Lower middle income	7.5	Limited potential or insufficient data
68	Bangladesh	Lower middle income	7.1	Limited potential or insufficient data
69	Serbia	Upper middle income	7.0	Limited potential or insufficient data
70	Ecuador	Upper middle income	7.0	Limited potential or insufficient data
71	Iraq	Upper middle income	6.9	Limited potential or insufficient data

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
72	South Africa	Upper middle income	6.9	Limited potential or insufficient data
73	Sudan	Low income	6.5	Limited potential or insufficient data
74	Ghana	Lower middle income	6.3	Limited potential or insufficient data
75	Tanzania	Lower middle income	6.3	Limited potential or insufficient data
76	Turkmenistan	Upper middle income	6.2	Limited potential or insufficient data
77	Libya	Upper middle income	6.1	Limited potential or insufficient data
78	Syrian Arab Republic	Low income	5.9	Limited potential or insufficient data
79	Namibia	Upper middle income	5.9	Limited potential or insufficient data
80	Myanmar	Lower middle income	5.8	Limited potential or insufficient data
81	Nigeria	Lower middle income	5.8	Limited potential or insufficient data
82	Yemen, Rep.	Low income	5.6	Limited potential or insufficient data
83	Cuba	Upper middle income	5.6	Limited potential or insufficient data
84	Uzbekistan	Lower middle income	5.5	Limited potential or insufficient data
85	Afghanistan	Low income	5.4	Limited potential or insufficient data
86	Mauritania	Lower middle income	5.1	Limited potential or insufficient data
87	Bolivia	Lower middle income	5.1	Limited potential or insufficient data
88	Belarus	Upper middle income	5.1	Limited potential or insufficient data
89	Benin	Lower middle income	5.0	Limited potential or insufficient data
90	Venezuela, RB	Upper middle income	4.8	Limited potential or insufficient data
91	Cameroon	Lower middle income	4.5	Limited potential or insufficient data
92	Somalia	Low income	4.5	Limited potential or insufficient data
93	Timor-Leste	Lower middle income	4.3	Limited potential or insufficient data
94	Barbados	High income	4.0	Limited potential or insufficient data
95	Mozambique	Low income	3.7	Limited potential or insufficient data
96	Côte d'Ivoire	Lower middle income	3.5	Limited potential or insufficient data
97	Papua New Guinea	Lower middle income	3.3	Limited potential or insufficient data
98	Angola	Lower middle income	3.3	Limited potential or insufficient data
99	Uganda	Low income	3.0	Limited potential or insufficient data
100	Congo, Rep.	Lower middle income	2.8	Limited potential or insufficient data
101	Rwanda	Low income	2.8	Limited potential or insufficient data
102	Gabon	Upper middle income	2.2	Limited potential or insufficient data
103	Equatorial Guinea	Upper middle income	2.0	Limited potential or insufficient data

Note: In this specific scenario assessment, only countries with current natural gas production or proved natural gas reserves are taken into consideration. Countries in the first quintile of the scenario assessment are labelled "high potential;" countries in the second quintile "promising potential"; all other countries "limited potential or insufficient data." The ranking is based on composite scores with many decimals. The scores reported are rounded to the nearest first decimal in order to facilitate readability and to account for the high-level character of the overall assessment.

TABLE 18: INDIVIDUAL RESULTS FOR THE SECOND SCENARIO: GREEN AMMONIA/HYDROGEN PRODUCTION ONLY

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
1	China	Upper middle income	81.1	High potential
2	United States	High income	71.6	High potential
3	Chile	High income	58.8	High potential
4	Spain	High income	51.5	High potential
5	Japan	High income	47.7	High potential
6	Austria	High income	47.2	High potential
7	Switzerland	High income	45.5	High potential
8	United Kingdom	High income	45.3	High potential
9	Italy	High income	43.8	High potential
10	Morocco	Lower middle income	42.2	High potential
11	New Zealand	High income	41.8	High potential
12	Korea, Rep.	High income	41.3	High potential
13	Canada	High income	40.5	High potential
14	France	High income	40.0	High potential
15	Oman	High income	39.4	High potential
16	Guatemala	Upper middle income	39.1	High potential
17	Norway	High income	38.7	High potential
18	Argentina	Upper middle income	38.6	High potential
19	Germany	High income	38.2	High potential
20	Saudi Arabia	High income	38.1	High potential
21	Portugal	High income	37.5	High potential
22	Egypt, Arab Rep.	Lower middle income	37.0	High potential
23	United Arab Emirates	High income	36.9	High potential
24	India	Lower middle income	36.2	High potential
25	Turkey	Upper middle income	35.9	High potential
26	Tajikistan	Low income	35.7	High potential
27	Australia	High income	35.4	High potential
28	Bulgaria	Upper middle income	35.2	High potential
29	Malaysia	Upper middle income	34.6	High potential
30	Congo, Rep.	Lower middle income	34.5	High potential
31	Brazil	Upper middle income	34.5	High potential
32	Russian Federation	Upper middle income	34.2	High potential
33	Jordan	Upper middle income	33.6	High potential
34	Colombia	Upper middle income	33.5	High potential
35	Mexico	Upper middle income	33.5	High potential
36	Denmark	High income	33.5	High potential
37	Slovenia	High income	33.3	High potential
38	Greece	High income	33.3	High potential

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
39	Gibraltar	High income	33.2	High potential
40	Netherlands	High income	33.0	High potential
41	Israel	High income	32.7	High potential
42	Bhutan	Lower middle income	32.3	High potential
43	Iran, Islamic Rep.	Upper middle income	31.8	High potential
44	Pakistan	Lower middle income	31.8	High potential
45	Sweden	High income	31.5	Promising potential
46	Uruguay	High income	31.3	Promising potential
47	Afghanistan	Low income	31.1	Promising potential
48	Qatar	High income	30.9	Promising potential
49	South Africa	Upper middle income	30.7	Promising potential
50	Croatia	High income	30.6	Promising potential
51	Namibia	Upper middle income	30.2	Promising potential
52	Nepal	Lower middle income	29.9	Promising potential
53	Algeria	Lower middle income	29.5	Promising potential
54	Djibouti	Lower middle income	29.4	Promising potential
55	Kuwait	High income	29.4	Promising potential
56	Malta	High income	29.3	Promising potential
57	Lebanon	Upper middle income	29.2	Promising potential
58	Yemen, Rep.	Low income	29.2	Promising potential
59	Singapore	High income	29.1	Promising potential
60	Sudan	Low income	29.0	Promising potential
61	Bahrain	High income	29.0	Promising potential
62	Libya	Upper middle income	29.0	Promising potential
63	Tunisia	Lower middle income	28.9	Promising potential
64	Mongolia	Lower middle income	28.8	Promising potential
65	Paraguay	Upper middle income	28.8	Promising potential
66	Iceland	High income	28.1	Promising potential
67	Ethiopia	Low income	28.0	Promising potential
68	Peru	Upper middle income	27.9	Promising potential
69	Eritrea	Low income	27.8	Promising potential
70	Aruba	High income	27.7	Promising potential
71	Albania	Upper middle income	27.4	Promising potential
72	Costa Rica	Upper middle income	27.4	Promising potential
73	Georgia	Upper middle income	27.2	Promising potential
74	Syrian Arab Republic	Low income	27.1	Promising potential
75	Andorra	High income	27.1	Promising potential
76	Malawi	Low income	26.7	Promising potential
77	Cyprus	High income	26.6	Promising potential
78	Indonesia	Upper middle income	26.6	Promising potential
79	El Salvador	Lower middle income	26.3	Promising potential
80	Kyrgyz Republic	Lower middle income	26.2	Promising potential
81	Kenya	Lower middle income	26.2	Promising potential

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
82	Lesotho	Lower middle income	26.2	Promising potential
83	Niger	Low income	26.1	Promising potential
84	Cabo Verde	Lower middle income	26.1	Promising potential
85	Thailand	Upper middle income	26.0	Promising potential
86	Mauritania	Lower middle income	26.0	Promising potential
87	Bolivia	Lower middle income	25.9	Promising potential
88	Somalia	Low income	25.9	Promising potential
89	Jamaica	Upper middle income	25.8	Limited potential or insufficient data
90	Iraq	Upper middle income	25.7	Limited potential or insufficient data
91	Dominican Republic	Upper middle income	25.7	Limited potential or insufficient data
92	Sri Lanka	Lower middle income	25.6	Limited potential or insufficient data
93	Armenia	Upper middle income	25.4	Limited potential or insufficient data
94	Haiti	Low income	25.4	Limited potential or insufficient data
95	Honduras	Lower middle income	25.3	Limited potential or insufficient data
96	Myanmar	Lower middle income	25.2	Limited potential or insufficient data
97	Virgin Islands (U.S.)	High income	25.1	Limited potential or insufficient data
98	Madagascar	Low income	25.0	Limited potential or insufficient data
99	Philippines	Lower middle income	24.9	Limited potential or insufficient data
100	Chad	Low income	24.8	Limited potential or insufficient data
101	West Bank and Gaza	Lower middle income	24.8	Limited potential or insufficient data
102	Bosnia and Herzegovina	Upper middle income	24.8	Limited potential or insufficient data
103	Azerbaijan	Upper middle income	24.6	Limited potential or insufficient data
104	Northern Mariana Islands	High income	24.4	Limited potential or insufficient data
105	Guam	High income	24.0	Limited potential or insufficient data
106	Bahamas, The	High income	23.9	Limited potential or insufficient data
107	Senegal	Lower middle income	23.9	Limited potential or insufficient data
108	Belgium	High income	23.6	Limited potential or insufficient data
109	Botswana	Upper middle income	23.6	Limited potential or insufficient data
110	Turks and Caicos Islands	High income	23.6	Limited potential or insufficient data
111	Turkmenistan	Upper middle income	23.5	Limited potential or insufficient data
112	Taiwan, China	High income	23.5	Limited potential or insufficient data
113	Sint Maarten (Dutch part)	High income	23.5	Limited potential or insufficient data
114	British Virgin Islands	High income	23.5	Limited potential or insufficient data
115	French Polynesia	High income	23.4	Limited potential or insufficient data
116	Vietnam	Lower middle income	23.4	Limited potential or insufficient data
117	Panama	High income	23.2	Limited potential or insufficient data
118	Montenegro	Upper middle income	23.0	Limited potential or insufficient data
119	St. Kitts and Nevis	High income	23.0	Limited potential or insufficient data
120	Romania	High income	22.9	Limited potential or insufficient data
121	Tanzania	Lower middle income	22.8	Limited potential or insufficient data
122	Nicaragua	Lower middle income	22.8	Limited potential or insufficient data
123	Papua New Guinea	Lower middle income	22.6	Limited potential or insufficient data
124	Zambia	Lower middle income	22.5	Limited potential or insufficient data

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
125	Antigua and Barbuda	High income	22.4	Limited potential or insufficient data
126	Uzbekistan	Lower middle income	22.3	Limited potential or insufficient data
127	Barbados	High income	22.3	Limited potential or insufficient data
128	Mali	Low income	22.3	Limited potential or insufficient data
129	Cayman Islands	High income	22.2	Limited potential or insufficient data
130	Angola	Lower middle income	22.2	Limited potential or insufficient data
131	Korea, Dem. People's Rep.	Low income	22.0	Limited potential or insufficient data
132	Finland	High income	22.0	Limited potential or insufficient data
133	Cuba	Upper middle income	21.9	Limited potential or insufficient data
134	North Macedonia	Upper middle income	21.7	Limited potential or insufficient data
135	Lao PDR	Lower middle income	21.2	Limited potential or insufficient data
136	Zimbabwe	Lower middle income	21.2	Limited potential or insufficient data
137	Poland	High income	21.2	Limited potential or insufficient data
138	Trinidad and Tobago	High income	21.2	Limited potential or insufficient data
139	Venezuela, RB	Upper middle income	21.1	Limited potential or insufficient data
140	Dominica	Upper middle income	21.1	Limited potential or insufficient data
141	Faroe Islands	High income	21.1	Limited potential or insufficient data
142	Slovak Republic	High income	21.0	Limited potential or insufficient data
143	Curaçao	High income	21.0	Limited potential or insufficient data
144	Congo, Dem. Rep.	Low income	20.8	Limited potential or insufficient data
145	St. Lucia	Upper middle income	20.5	Limited potential or insufficient data
146	Grenada	Upper middle income	20.3	Limited potential or insufficient data
147	Cameroon	Lower middle income	20.3	Limited potential or insufficient data
148	St. Vincent and the Grenadines	Upper middle income	20.3	Limited potential or insufficient data
149	Cambodia	Lower middle income	20.1	Limited potential or insufficient data
150	Kiribati	Lower middle income	20.1	Limited potential or insufficient data
151	Gambia, The	Low income	20.1	Limited potential or insufficient data
152	Puerto Rico	High income	19.8	Limited potential or insufficient data
153	Seychelles	High income	19.7	Limited potential or insufficient data
154	Ireland	High income	19.7	Limited potential or insufficient data
155	Hungary	High income	19.7	Limited potential or insufficient data
156	Nigeria	Lower middle income	19.6	Limited potential or insufficient data
157	Timor-Leste	Lower middle income	19.6	Limited potential or insufficient data
158	Estonia	High income	19.5	Limited potential or insufficient data
159	Mozambique	Low income	19.4	Limited potential or insufficient data
160	Bermuda	High income	19.0	Limited potential or insufficient data
161	Kazakhstan	Upper middle income	18.8	Limited potential or insufficient data
162	Mauritius	High income	18.6	Limited potential or insufficient data
163	Guinea	Low income	18.5	Limited potential or insufficient data
164	Guinea-Bissau	Low income	18.3	Limited potential or insufficient data
165	Uganda	Low income	18.3	Limited potential or insufficient data
166	Czech Republic	High income	18.3	Limited potential or insufficient data
167	Burkina Faso	Low income	18.2	Limited potential or insufficient data

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
168	Ghana	Lower middle income	18.2	Limited potential or insufficient data
169	Maldives	Upper middle income	18.1	Limited potential or insufficient data
170	Brunei Darussalam	High income	18.1	Limited potential or insufficient data
171	Nauru	High income	18.0	Limited potential or insufficient data
172	Belize	Upper middle income	18.0	Limited potential or insufficient data
173	Hong Kong SAR, China	High income	17.9	Limited potential or insufficient data
174	Ecuador	Upper middle income	17.9	Limited potential or insufficient data
175	Benin	Lower middle income	17.5	Limited potential or insufficient data
176	Marshall Islands	Upper middle income	17.4	Limited potential or insufficient data
177	Burundi	Low income	17.4	Limited potential or insufficient data
178	Greenland	High income	17.3	Limited potential or insufficient data
179	Bangladesh	Lower middle income	16.6	Limited potential or insufficient data
180	San Marino	High income	16.6	Limited potential or insufficient data
181	Guyana	Upper middle income	16.4	Limited potential or insufficient data
182	Central African Republic	Low income	16.3	Limited potential or insufficient data
183	Comoros	Lower middle income	16.0	Limited potential or insufficient data
184	Suriname	Upper middle income	15.7	Limited potential or insufficient data
185	Ukraine	Lower middle income	15.6	Limited potential or insufficient data
186	Latvia	High income	15.6	Limited potential or insufficient data
187	Serbia	Upper middle income	15.6	Limited potential or insufficient data
188	Luxembourg	High income	15.6	Limited potential or insufficient data
189	Togo	Low income	15.4	Limited potential or insufficient data
190	Eswatini	Lower middle income	15.4	Limited potential or insufficient data
191	Moldova	Lower middle income	15.2	Limited potential or insufficient data
192	Fiji	Upper middle income	15.2	Limited potential or insufficient data
193	South Sudan	Low income	14.9	Limited potential or insufficient data
194	Palau	High income	14.9	Limited potential or insufficient data
195	Sierra Leone	Low income	14.7	Limited potential or insufficient data
196	Tuvalu	Upper middle income	14.4	Limited potential or insufficient data
197	Liechtenstein	High income	14.3	Limited potential or insufficient data
198	Micronesia, Fed. Sts.	Lower middle income	14.3	Limited potential or insufficient data
199	New Caledonia	High income	14.0	Limited potential or insufficient data
200	Côte d'Ivoire	Lower middle income	14.0	Limited potential or insufficient data
201	Rwanda	Low income	13.9	Limited potential or insufficient data
202	Tonga	Upper middle income	13.7	Limited potential or insufficient data
203	Lithuania	High income	13.6	Limited potential or insufficient data
204	American Samoa	Upper middle income	13.5	Limited potential or insufficient data
205	Liberia	Low income	13.0	Limited potential or insufficient data
206	Macao SAR, China	High income	12.6	Limited potential or insufficient data
207	Samoa	Upper middle income	12.4	Limited potential or insufficient data
208	Equatorial Guinea	Upper middle income	12.1	Limited potential or insufficient data
209	Solomon Islands	Lower middle income	11.1	Limited potential or insufficient data
210	Kosovo	Upper middle income	10.9	Limited potential or insufficient data

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
211	Vanuatu	Lower middle income	10.3	Limited potential or insufficient data
212	Gabon	Upper middle income	10.1	Limited potential or insufficient data
213	Belarus	Upper middle income	8.9	Limited potential or insufficient data
214	São Tomé and Principe	Lower middle income	7.8	Limited potential or insufficient data
215	Isle of Man	High income	7.5	Limited potential or insufficient data
216	St. Martin (French part)	High income	6.5	Limited potential or insufficient data
217	Monaco	High income	6.1	Limited potential or insufficient data
218	Channel Islands	High income	2.5	Limited potential or insufficient data

Note: Countries in the first quintile of the scenario assessment are labelled "high potential;" countries in the second quintile "promising potential"; all other countries "limited potential or insufficient data. The ranking is based on composite scores with many decimals. The scores reported are rounded to the nearest first decimal in order to facilitate readability and to account for the high-level character of the overall assessment.

TABLE 19: INDIVIDUAL RESULTS FOR THE THIRD SCENARIO: BLUE AMMONIA/HYDROGEN FIRST, GREEN AMMONIA/HYDROGEN LATER

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
1	United States	High income	74.1	High potential
2	China	Upper middle income	73.1	High potential
3	Spain	High income	45.3	High potential
4	Chile	High income	45.2	High potential
5	United Kingdom	High income	42.7	High potential
6	Japan	High income	42.3	High potential
7	Russian Federation	Upper middle income	39.4	High potential
8	Austria	High income	37.9	High potential
9	Canada	High income	37.5	High potential
10	Italy	High income	37.5	High potential
11	Norway	High income	37.0	High potential
12	Korea, Rep.	High income	36.8	High potential
13	Switzerland	High income	36.2	High potential
14	France	High income	35.7	High potential
15	Germany	High income	35.3	High potential
16	Morocco	Lower middle income	35.1	High potential
17	Saudi Arabia	High income	34.1	High potential
18	United Arab Emirates	High income	32.8	High potential
19	New Zealand	High income	32.8	High potential
20	Oman	High income	32.4	High potential
21	Portugal	High income	32.0	High potential
22	Denmark	High income	31.7	High potential
23	Netherlands	High income	31.7	High potential
24	Australia	High income	31.5	High potential
25	Malaysia	Upper middle income	30.7	High potential

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
26	India	Lower middle income	30.4	High potential
27	Argentina	Upper middle income	30.3	High potential
28	Turkey	Upper middle income	30.2	High potential
29	Guatemala	Upper middle income	29.5	High potential
30	Egypt, Arab Rep.	Lower middle income	29.5	High potential
31	Brazil	Upper middle income	29.2	High potential
32	Sweden	High income	29.1	High potential
33	Bulgaria	Upper middle income	28.8	High potential
34	Greece	High income	28.2	High potential
35	Iran, Islamic Rep.	Upper middle income	28.1	High potential
36	Colombia	Upper middle income	28.0	High potential
37	Tajikistan	Low income	27.5	High potential
38	Slovenia	High income	27.3	High potential
39	Singapore	High income	27.1	High potential
40	Mexico	Upper middle income	27.0	High potential
41	Uruguay	High income	26.6	High potential
42	Jordan	Upper middle income	26.6	High potential
43	Israel	High income	26.4	High potential
44	Gibraltar	High income	25.9	High potential
45	Croatia	High income	25.5	Promising potential
46	Pakistan	Lower middle income	25.3	Promising potential
47	Congo, Rep.	Lower middle income	25.0	Promising potential
48	Qatar	High income	25.0	Promising potential
49	Algeria	Lower middle income	24.6	Promising potential
50	Malta	High income	24.0	Promising potential
51	Paraguay	Upper middle income	24.0	Promising potential
52	Bhutan	Lower middle income	23.8	Promising potential
53	Indonesia	Upper middle income	23.6	Promising potential
54	Kuwait	High income	23.6	Promising potential
55	South Africa	Upper middle income	23.5	Promising potential
56	Iceland	High income	23.5	Promising potential
57	Afghanistan	Low income	23.4	Promising potential
58	Bahrain	High income	23.3	Promising potential
59	Lebanon	Upper middle income	23.2	Promising potential
60	Namibia	Upper middle income	22.9	Promising potential
61	Nepal	Lower middle income	22.9	Promising potential
62	Tunisia	Lower middle income	22.8	Promising potential
63	Djibouti	Lower middle income	22.6	Promising potential
64	Mongolia	Lower middle income	22.5	Promising potential
65	Sudan	Low income	22.3	Promising potential
66	Libya	Upper middle income	22.1	Promising potential
67	Belgium	High income	22.1	Promising potential
68	Yemen, Rep.	Low income	22.1	Promising potential

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
69	Ethiopia	Low income	22.0	Promising potential
70	Albania	Upper middle income	22.0	Promising potential
71	Georgia	Upper middle income	21.9	Promising potential
72	Thailand	Upper middle income	21.9	Promising potential
73	Peru	Upper middle income	21.9	Promising potential
74	Costa Rica	Upper middle income	21.9	Promising potential
75	Cyprus	High income	21.5	Promising potential
76	Finland	High income	21.5	Promising potential
77	Eritrea	Low income	21.1	Promising potential
78	Jamaica	Upper middle income	21.1	Promising potential
79	Sri Lanka	Lower middle income	21.0	Promising potential
80	Andorra	High income	20.8	Promising potential
81	Aruba	High income	20.8	Promising potential
82	Syrian Arab Republic	Low income	20.8	Promising potential
83	Dominican Republic	Upper middle income	20.6	Promising potential
84	Kyrgyz Republic	Lower middle income	20.6	Promising potential
85	Philippines	Lower middle income	20.5	Promising potential
86	Kenya	Lower middle income	20.5	Promising potential
87	El Salvador	Lower middle income	20.3	Promising potential
88	Armenia	Upper middle income	20.2	Promising potential
89	Honduras	Lower middle income	20.2	Limited potential or insufficient data
90	Iraq	Upper middle income	20.1	Limited potential or insufficient data
91	Vietnam	Lower middle income	20.0	Limited potential or insufficient data
92	Romania	High income	19.8	Limited potential or insufficient data
93	Taiwan, China	High income	19.8	Limited potential or insufficient data
94	Mauritania	Lower middle income	19.7	Limited potential or insufficient data
95	Virgin Islands (U.S.)	High income	19.7	Limited potential or insufficient data
96	Haiti	Low income	19.7	Limited potential or insufficient data
97	Bolivia	Lower middle income	19.7	Limited potential or insufficient data
98	Azerbaijan	Upper middle income	19.6	Limited potential or insufficient data
99	Poland	High income	19.6	Limited potential or insufficient data
100	Cabo Verde	Lower middle income	19.6	Limited potential or insufficient data
101	Niger	Low income	19.6	Limited potential or insufficient data
102	Malawi	Low income	19.5	Limited potential or insufficient data
103	Bosnia and Herzegovina	Upper middle income	19.5	Limited potential or insufficient data
104	Somalia	Low income	19.4	Limited potential or insufficient data
105	Myanmar	Lower middle income	19.4	Limited potential or insufficient data
106	Panama	High income	19.3	Limited potential or insufficient data
107	West Bank and Gaza	Lower middle income	19.0	Limited potential or insufficient data
108	Senegal	Lower middle income	19.0	Limited potential or insufficient data
109	Bahamas, The	High income	19.0	Limited potential or insufficient data
110	Guam	High income	19.0	Limited potential or insufficient data
111	Montenegro	Upper middle income	18.9	Limited potential or insufficient data
112	Slovak Republic	High income	18.8	Limited potential or insufficient data

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
113	French Polynesia	High income	18.7	Limited potential or insufficient data
114	Lesotho	Lower middle income	18.5	Limited potential or insufficient data
115	Northern Mariana Islands	High income	18.5	Limited potential or insufficient data
116	Turkmenistan	Upper middle income	18.4	Limited potential or insufficient data
117	Estonia	High income	18.3	Limited potential or insufficient data
118	Madagascar	Low income	18.2	Limited potential or insufficient data
119	Nicaragua	Lower middle income	18.1	Limited potential or insufficient data
120	Ireland	High income	18.0	Limited potential or insufficient data
121	Turks and Caicos Islands	High income	17.9	Limited potential or insufficient data
122	Tanzania	Lower middle income	17.9	Limited potential or insufficient data
123	Chad	Low income	17.9	Limited potential or insufficient data
124	British Virgin Islands	High income	17.8	Limited potential or insufficient data
125	Sint Maarten (Dutch part)	High income	17.7	Limited potential or insufficient data
126	Botswana	Upper middle income	17.4	Limited potential or insufficient data
127	St. Kitts and Nevis	High income	17.4	Limited potential or insufficient data
128	Uzbekistan	Lower middle income	17.3	Limited potential or insufficient data
129	Cayman Islands	High income	17.2	Limited potential or insufficient data
130	Trinidad and Tobago	High income	17.2	Limited potential or insufficient data
131	Korea, Dem. People's Rep.	Low income	17.2	Limited potential or insufficient data
132	Hungary	High income	17.1	Limited potential or insufficient data
133	Cuba	Upper middle income	17.0	Limited potential or insufficient data
134	Antigua and Barbuda	High income	16.9	Limited potential or insufficient data
135	North Macedonia	Upper middle income	16.8	Limited potential or insufficient data
136	Barbados	High income	16.8	Limited potential or insufficient data
137	Zambia	Lower middle income	16.8	Limited potential or insufficient data
138	Papua New Guinea	Lower middle income	16.8	Limited potential or insufficient data
139	Dominica	Upper middle income	16.7	Limited potential or insufficient data
140	Mali	Low income	16.7	Limited potential or insufficient data
141	Faroe Islands	High income	16.5	Limited potential or insufficient data
142	Cambodia	Lower middle income	16.5	Limited potential or insufficient data
143	Angola	Lower middle income	16.5	Limited potential or insufficient data
144	Czech Republic	High income	16.4	Limited potential or insufficient data
145	Lao PDR	Lower middle income	16.4	Limited potential or insufficient data
146	Venezuela, RB	Upper middle income	16.2	Limited potential or insufficient data
147	Hong Kong SAR, China	High income	15.8	Limited potential or insufficient data
148	Zimbabwe	Lower middle income	15.6	Limited potential or insufficient data
149	Cameroon	Lower middle income	15.5	Limited potential or insufficient data
150	St. Lucia	Upper middle income	15.5	Limited potential or insufficient data
151	Kazakhstan	Upper middle income	15.5	Limited potential or insufficient data
152	Nigeria	Lower middle income	15.5	Limited potential or insufficient data
153	Grenada	Upper middle income	15.4	Limited potential or insufficient data
154	Gambia, The	Low income	15.4	Limited potential or insufficient data
155	St. Vincent and the Grenadines	Upper middle income	15.4	Limited potential or insufficient data
156	Puerto Rico	High income	15.3	Limited potential or insufficient data

RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
157	Brunei Darussalam	High income	15.3	Limited potential or insufficient data
158	Congo, Dem. Rep.	Low income	15.1	Limited potential or insufficient data
159	Timor-Leste	Lower middle income	15.0	Limited potential or insufficient data
160	Seychelles	High income	14.9	Limited potential or insufficient data
161	Kiribati	Lower middle income	14.8	Limited potential or insufficient data
162	Curaçao	High income	14.8	Limited potential or insufficient data
163	Mozambique	Low income	14.7	Limited potential or insufficient data
164	Latvia	High income	14.6	Limited potential or insufficient data
165	Ghana	Lower middle income	14.6	Limited potential or insufficient data
166	Ecuador	Upper middle income	14.6	Limited potential or insufficient data
167	Bermuda	High income	14.5	Limited potential or insufficient data
168	Luxembourg	High income	14.4	Limited potential or insufficient data
169	Belize	Upper middle income	14.2	Limited potential or insufficient data
170	Guinea	Low income	14.2	Limited potential or insufficient data
171	Guinea-Bissau	Low income	14.1	Limited potential or insufficient data
172	Mauritius	High income	14.0	Limited potential or insufficient data
173	Maldives	Upper middle income	13.9	Limited potential or insufficient data
174	Bangladesh	Lower middle income	13.7	Limited potential or insufficient data
175	Uganda	Low income	13.7	Limited potential or insufficient data
176	Benin	Lower middle income	13.7	Limited potential or insufficient data
177	Burkina Faso	Low income	13.4	Limited potential or insufficient data
178	San Marino	High income	13.4	Limited potential or insufficient data
179	Greenland	High income	13.3	Limited potential or insufficient data
180	Nauru	High income	13.3	Limited potential or insufficient data
181	Ukraine	Lower middle income	13.3	Limited potential or insufficient data
182	Marshall Islands	Upper middle income	13.2	Limited potential or insufficient data
183	Serbia	Upper middle income	13.0	Limited potential or insufficient data
184	Burundi	Low income	13.0	Limited potential or insufficient data
185	Moldova	Lower middle income	13.0	Limited potential or insufficient data
186	Lithuania	High income	12.5	Limited potential or insufficient data
187	Guyana	Upper middle income	12.5	Limited potential or insufficient data
188	Comoros	Lower middle income	12.0	Limited potential or insufficient data
189	Central African Republic	Low income	11.9	Limited potential or insufficient data
190	Suriname	Upper middle income	11.9	Limited potential or insufficient data
191	Togo	Low income	11.9	Limited potential or insufficient data
192	Palau	High income	11.7	Limited potential or insufficient data
193	Liechtenstein	High income	11.6	Limited potential or insufficient data
194	Sierra Leone	Low income	11.4	Limited potential or insufficient data
195	Micronesia, Fed. Sts.	Lower middle income	11.2	Limited potential or insufficient data
196	Eswatini	Lower middle income	11.1	Limited potential or insufficient data
197	Fiji	Upper middle income	10.9	Limited potential or insufficient data
198	Côte d'Ivoire	Lower middle income	10.8	Limited potential or insufficient data
199	Rwanda	Low income	10.6	Limited potential or insufficient data

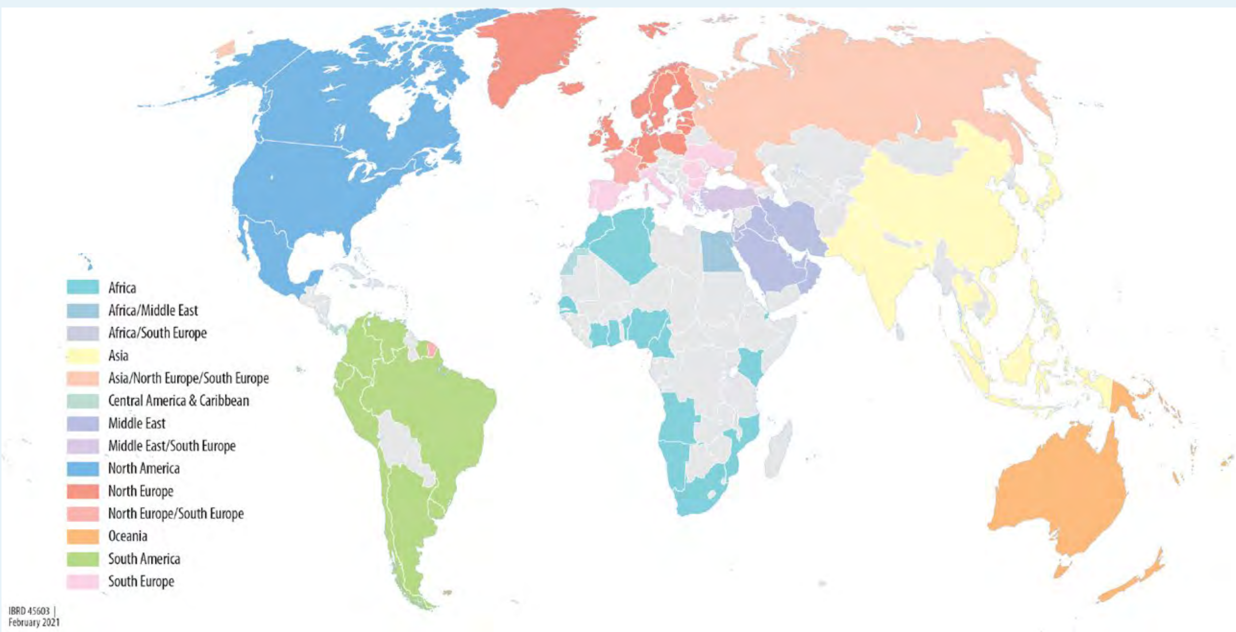
RANK	COUNTRY	INCOME CLASS	COM-POSITE SCORE	TIER
200	Tuvalu	Upper middle income	10.5	Limited potential or insufficient data
201	South Sudan	Low income	10.4	Limited potential or insufficient data
202	Macao SAR, China	High income	10.4	Limited potential or insufficient data
203	New Caledonia	High income	10.3	Limited potential or insufficient data
204	Liberia	Low income	10.1	Limited potential or insufficient data
205	Tonga	Upper middle income	9.7	Limited potential or insufficient data
206	American Samoa	Upper middle income	9.7	Limited potential or insufficient data
207	Equatorial Guinea	Upper middle income	9.1	Limited potential or insufficient data
208	Samoa	Upper middle income	8.9	Limited potential or insufficient data
209	Solomon Islands	Lower middle income	8.6	Limited potential or insufficient data
210	Belarus	Upper middle income	7.8	Limited potential or insufficient data
211	Gabon	Upper middle income	7.7	Limited potential or insufficient data
212	Kosovo	Upper middle income	7.6	Limited potential or insufficient data
213	Vanuatu	Lower middle income	7.6	Limited potential or insufficient data
214	St. Martin (French part)	High income	6.4	Limited potential or insufficient data
215	Monaco	High income	6.1	Limited potential or insufficient data
216	São Tomé and Principe	Lower middle income	6.1	Limited potential or insufficient data
217	Isle of Man	High income	5.3	Limited potential or insufficient data
218	Channel Islands	High income	1.7	Limited potential or insufficient data

Note: Countries in the first quintile of the scenario assessment are labelled “high potential;” countries in the second quintile “promising potential”; all other countries “limited potential or insufficient data.The ranking is based on composite scores with many decimals. The scores reported are rounded to the nearest first decimal in order to facilitate readability and to account for the high-level character of the overall assessment.

APPENDIX C – ESTIMATES OF REGIONAL MARKET SHARES

This analysis uses the International Energy Agency fuel sales statistics to define the regional market shares. This is used as a proxy to indicate the combination of the intra-regional demand (for example, ships solely being used in that region) and a share of inter-regional demand (for example, ships that undertake a port call in the region but are trading in more than one region).

FIGURE 39: REGIONAL DIVISION USED TO ESTIMATE GLOBAL MARKET SHARES



The resulting market shares are provided in Table 20.

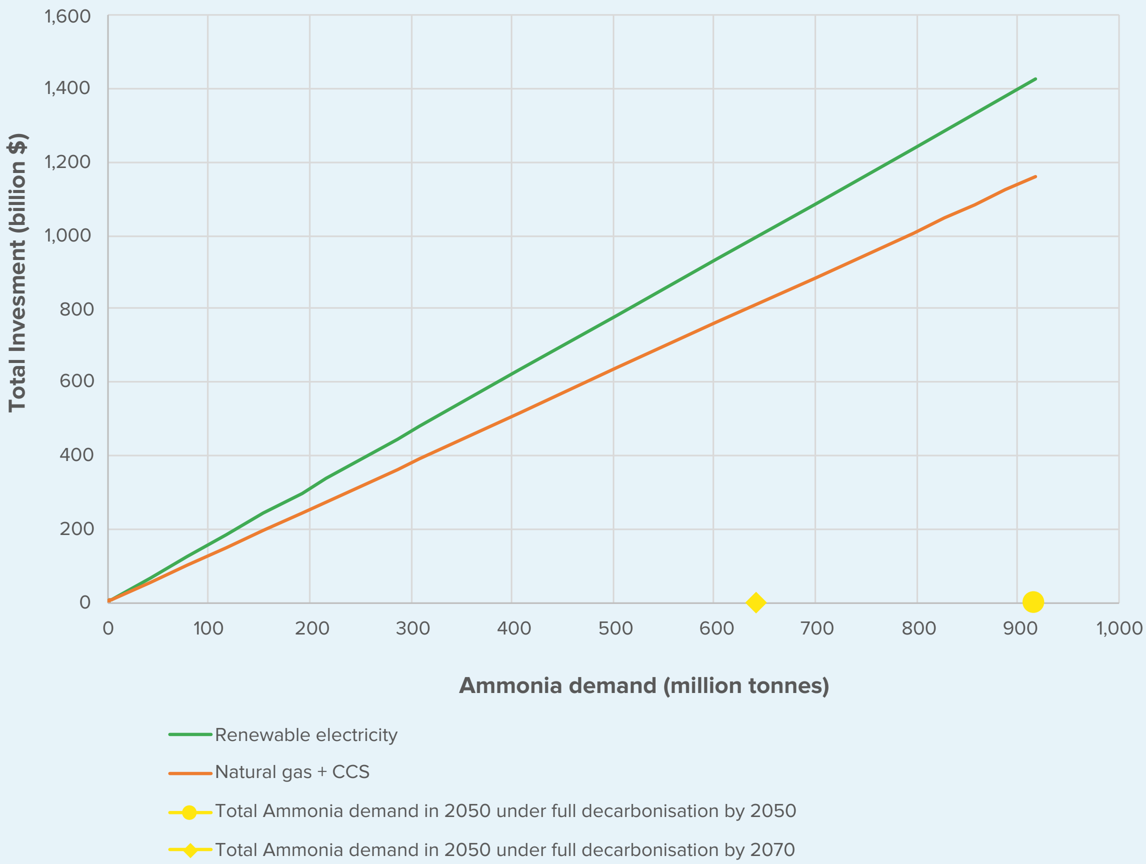
TABLE 20: ESTIMATED REGIONAL MARKET SHARES

REGION NAME	MARKET SHARE
Asia	41 percent
North Europe	16 percent
Middle East	12 percent
North America	11 percent
South Europe	8 percent
South America	4 percent
Africa	4 percent
Central America & Caribbean	3 percent
Oceania	0.5 percent

APPENDIX D – ESTIMATED RELATIONSHIP BETWEEN AMMONIA DEMAND AND CAPITAL INVESTMENTS

This analysis uses the results of the study conducted by UMAS in 2020 to identify the underlying relationship between future ammonia demand and capital investment required. Figure 40 provides the linear relationship obtained from that analysis. The graph also contains two points on the x-axes showing total ammonia demand in 2050 under two scenarios: decarbonization by 2050 and decarbonization by 2070.

FIGURE 40: CORRELATION BETWEEN AMMONIA DEMAND AND CAPITAL INVESTMENT.



Source: UMAS 2020.

Note that the relationship is linear because the underlying assumed capital cost for each technology component is assumed to be constant. This is a limitation of this approach as the capital cost may change over time due to, for example, learning curve effects or size and specific configuration of the plant. The capital cost assumptions of ammonia plants are the same as those provided by UMAS (2020). The investment needed for the production of ammonia with renewable electricity covers the provision of the following elements: water treatment, electrolyzer, Haber-Bosch, hydrogen (H_2) compression and storage, air separation, refrigeration, and ammonia bunkering storage. It does not include capital and operational expenditures for the production of renewable electricity. The investment needed for the production of ammonia with natural gas and carbon capture and storage covers steam methane reforming, carbon capture and storage, Haber-Bosch, H_2 compression and storage, air separation, refrigeration, and ammonia bunkering storage. It does not take into account the costs associated with the extraction and transportation of natural gas.

APPENDIX E – HYDROGEN AND AMMONIA INVESTMENT COMPARISON

The linear relationship identified in Appendix D – Estimated relationship between ammonia demand and capital investments shows the correlation between ammonia demand and capital investment needed. The same analysis can be performed for liquefied hydrogen, which would result in a different investment profile. Once hydrogen is produced, it is stored in liquid form at bunkering ports. This means that the capital investment needed for the supply of hydrogen includes liquefaction and storage, but it excludes the components needed for the production of ammonia. The overall correlation between future hydrogen demand and capital investment needed is provided in Figure 41 and Figure 42 for the cases of production with electrolyzer and production with steam methane reforming and carbon capture and storage (SMR and CCS). The results are compared with the relationship identified for ammonia, and found to be very similar. This means that the capital investment required for the supply of liquefied hydrogen to the maritime industry would be very similar to the capital investment required for the supply of ammonia to shipping.

Note that this analysis assumes a capital cost of the liquefaction plant of $3.30/kg H2 and a capital cost of liquid storage of $18/kg. Hydrogen demand was obtained assuming that the same amount of energy would be demanded as in the scenarios of ammonia provision.

FIGURE 41: HYDROGEN AND AMMONIA CORRELATION BETWEEN FUEL DEMANDS AND CAPITAL INVESTMENT FOR THE PRODUCTION WITH ELECTROLYZER

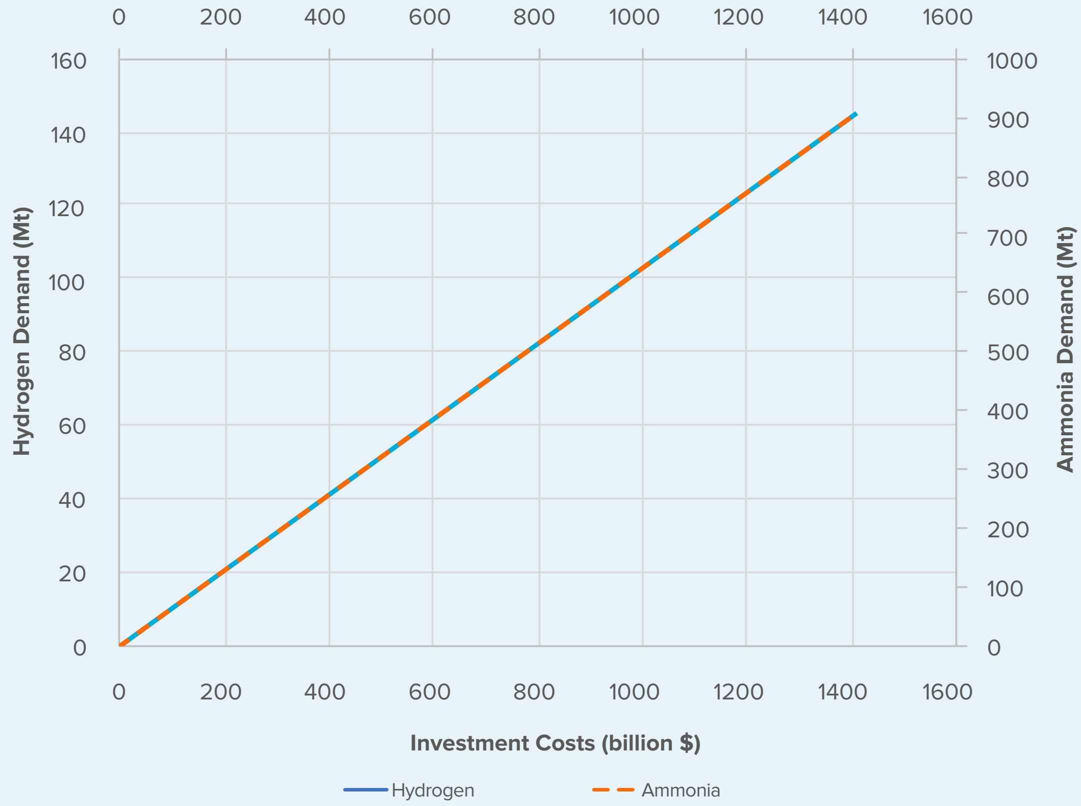
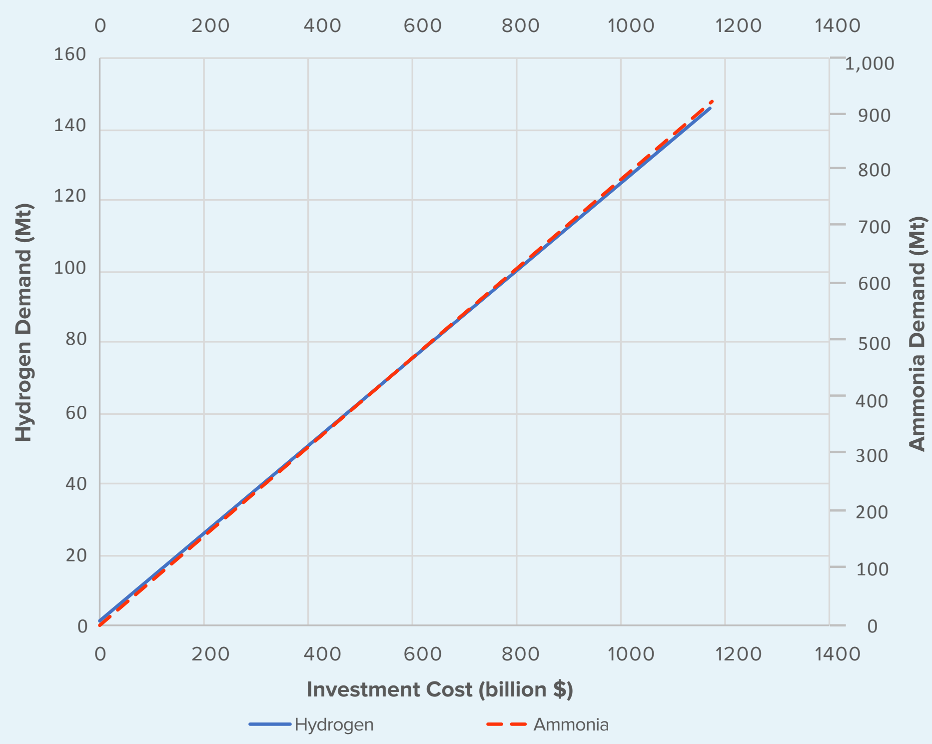


FIGURE 42: HYDROGEN AND AMMONIA CORRELATION BETWEEN FUEL DEMANDS AND CAPITAL INVESTMENT FOR THE PRODUCTION WITH SMR AND CCS



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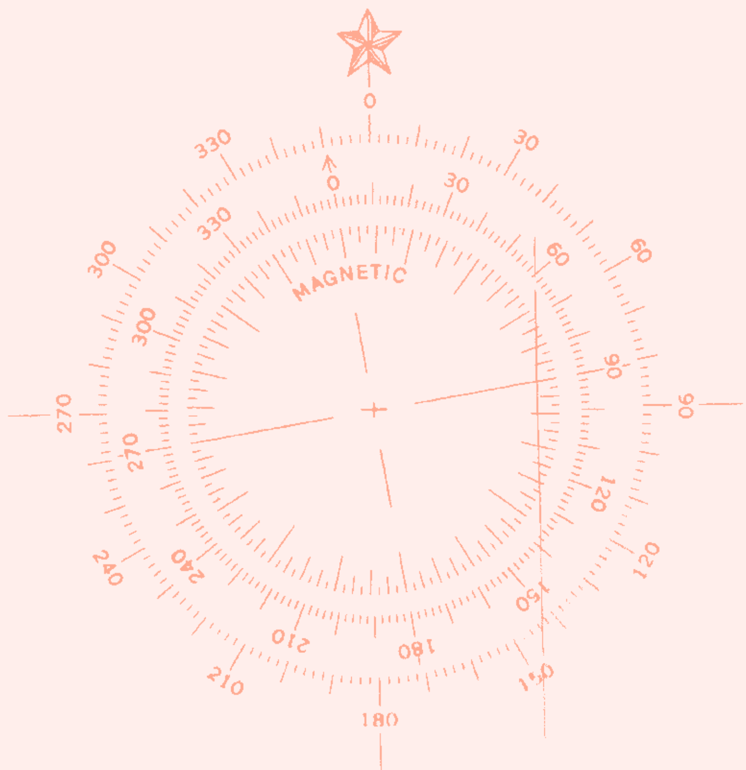

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