Indonesia: fuelling the future of shipping

Low carbon shipping fuels for Indonesia's shipping sector

Revised

By Ricardo
& Environmental Defense Fund

For the
P4G Getting to Zero Coalition Partnership

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The Getting to Zero Coalition

The Getting to Zero Coalition, a partnership between the Global Maritime Forum, Friends of Ocean Action and World Economic Forum, is a community of ambitious stakeholders from across the maritime, energy, infrastructure and financial sectors, and supported by key governments, IGOs and other stakeholders, who are committed to the decarbonisation of shipping.

The ambition of the Getting to Zero Coalition is to have commercially viable ZEVs operating along deep-sea trade routes by 2030, supported by the necessary infrastructure for scalable net zero carbon energy sources including production, distribution, storage, and bunkering.

About P4G

P4G – Partnering for Green Growth and the Global Goals 2030 - is a global delivery mechanism pioneering green partnerships to build sustainable and resilient economies. P4G mobilizes a global ecosystem of 12 partner countries and 5 organizational partners to unlock opportunities for more than 50 partnerships working in five SDG areas: food and agriculture, water, energy, cities and circular economy.

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The Global Maritime Forum is an international not-for-profit organization dedicated to shaping the future of global seaborne trade to increase sustainable long-term economic development and human wellbeing.

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Friends of Ocean Action is a unique group of over 55 global leaders from business, international organizations, civil society, science and academia who are fast-tracking scalable solutions to the most pressing challenges facing the ocean. It is hosted by the World Economic Forum in collaboration with the World Resources Institute.

About the World Economic Forum

The World Economic Forum is the International Organization for Public-Private Cooperation. The Forum engages the foremost political, business, cultural and other leaders of society to shape global, regional and industry agendas. It was established in 1971 as a not-for-profit foundation and is headquartered in Geneva, Switzerland. It is independent, impartial and not tied to any special interests.

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Environmental Defense Fund Europe is an affiliate of Environmental Defense Fund (EDF), a leading international non-profit organisation that creates transformative solutions to the most serious environmental problems. Since 1967, EDF has used science, economics, law and innovative private-sector partnerships to bring a new voice for practical solutions.

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University College London Energy Institute Shipping Group aims to accelerate shipping transition to an equitable, globally sustainable energy system through world-class shipping research, education and policy support. The group specialises in multi-disciplinary research anchored in data analytics and advanced modelling of the maritime sector.

About International Association of Ports and Harbors

The International Association of Ports and Harbors (IAPH) was formed in 1955 and over the last sixty years has grown into a global alliance representing over 180 members ports and 140 port related businesses in 90 countries. The principal aim of IAPH revolves around promotion of the interests of Ports worldwide, building strong member relationships and sharing best practices among our members.

About Ricardo

At Ricardo, our vision is to create a world where everyone can live sustainably: breathing clean air, using clean energy, travelling sustainably, accessing clean water and conserving resources. Adopting zero carbon shipping fuels would bring the world closer to these ideals. Since the 1950s, Ricardo has worked to deliver improvements in air quality and pioneered the use of renewable energy technologies. We are currently working on the implementation of the Paris Agreement on climate change, helping countries to realise their plans for reducing greenhouse gas emissions (GHG).

Website: ee.ricardo.com

Acknowledgements

This report was written by Olivia Carpenter-Lomax, Guy Wilkinson and Victor Martinez from Ricardo Energy & Environment with assistance from Jabulani Nyathi and Mohit Sharma. The authors would like to thank Aoife O'Leary, Marie Cabbia Hubatova and Panos Spiliotis of EDF Europe, Santiago Suarez de la Fuente, Wendela Schim Van Der Loeff of University College London (UCL) and Camilo Velandia Perico and Carlo Raucci from University Maritime Advisory Services (UMAS) for providing their advice and the shipping demand data that are central to the analysis in this report.

The authors would also like to thank the following people and organisations who have helped with reviewing the report: Tristan Smith (UCL), Jeremia Humolong Prasetya and Karenina Lasrindy (IOJI), Ingrid Sidenvall Jegou (Global Maritime Forum), Emma Skov Christiansen (World Economic Forum), Mathias Emil Bengtsson and Thomas Capral Henriksen (Danish Embassy in Indonesia), Florian Kitt and Faela Sufa (Asian Development Bank), and Ronald Halim (Equitable Maritime Consulting). Lastly, the authors would like to thank all participants of the Indonesia round table organized on 30th June 2021, their contributions from which have helped structure this report.

Disclaimer

This report is based on analysis by Ricardo Energy & Environment for the Getting to Zero Coalition, a partnership between the Global Maritime Forum, the Friends of Ocean Action, and the World Economic Forum.

The views expressed are those of the authors alone and not the Getting to Zero Coalition or the Global Maritime Forum, Friends of Ocean Action, or the World Economic Forum.

Update: This report has been revised from its original publication to reflect corrections in shipping energy demand and subsequent investment potential for infrastructure to support 5% adoption of zero carbon vessel technologies by 2030.

Executive Summary

There is an opportunity for Indonesia to deploy infrastructure to supply zero carbon fuels to vessels which visit its ports. Indonesia's natural resources, geography, and prominence on important shipping trade routes allows for various opportunities to be taken advantage of that would aid in Indonesia achieving its decarbonisation goals and catalysing a low carbon economy. In particular, there is the potential to create a wide range of jobs within the supply chains of zero carbon fuels, which can support Indonesia's economy. Moreover, the overall infrastructure and supply chains that would be created could help increase electrification rates in the country and support decarbonisation of energy supply, industry and transport.

There are several zero and low carbon fuels with potential to be used in shipping

The zero and low carbon fuel options available for adoption by the maritime industry include green hydrogen, green ammonia, green methanol, biofuels and battery power. This study investigates the most suitable propulsion solutions for different commercial vessels based on various criteria. It has been identified that the most suitable options are hydrogen and ammonia for large commercial vessels such as tankers, containers, and bulk carriers; small vessels such as port service vessels, ferries and people/vehicle carriers can be supplied through direct and onboard electrification. For Indonesia, the utilization of biofuels in decarbonising shipping comes as a potentially feasible option in cases where there is a sustainable and consistent supply of bioresources. By itself, the utilization of biofuels is not seen as a route that can holistically achieve the decarbonisation of shipping due to supply constraints, the increasing demand for such resources globally and because of the increasing utilization of biofuels in other sectors such as road transport and energy production. However, it can play an important part of the overall solution for Indonesia, aided by the country's limited but diverse renewable energy resource potential, which would allow zero carbon fuels to be derived from renewable electricity generation.

With proper regulations and training, zero carbon shipping fuels are safe to use

Some have raised concerns regarding the health, safety and environmental risks of zero carbon fuels. And while these risks need to be mitigated and managed properly, this should not be perceived as a barrier to adopting zero carbon fuels nor should it keep the industry from moving forward. With the correct standards, codes, training and safety measures, the risks associated with zero carbon fuels can be managed just as the risks associated with other types of fuels are today. Currently used fuels, including biofuels, are also harmful and pose risks, yet the codes, best practices and standards that have been developed over years of expertise have allowed us to use them widely and safely in a variety of applications, environments, and conditions. The same can be achieved for hydrogen and ammonia.

Indonesia has strong trading relationships across Asia and North America, as well as all over the world

Indonesia holds a key position along with two of the most important shipping lanes in the world, the Strait of Malacca and the Sunda Strait, making it a possible hub for international vessels passing between the world's largest economies. Indonesia's largest trading partners are China, Singapore, Japan and the United States. The country is a major exporter of coal and crude oil: fuels are Indonesia's top export commodity by value, with the country previously being a member of the Organization of Petroleum Exporting Countries (OPEC). This highlights the expertise and commercial relationships that Indonesia could leverage for building a strong low carbon fuel industry and helping decarbonise their trading partners' shipping activities, as well as their own.

The best approach for the adoption of zero carbon shipping fuels depends on the global market and requirements of the vessel

In order for a successful adoption of zero carbon shipping fuels, Indonesia should look globally, in particular to the markets connected via trade routes. Vessels adopting zero carbon fuels bunkering (supplying fuel for use by ships) in various ports around the world must have the opportunity to refuel along their journey. Standards set by the maritime industry should be developed to encourage the zero carbon transition not only for vessels but for global ports. Indonesia can be a part of driving these international standards as an important part of the international shipping sector and as a pioneer in zero carbon fuels.

The decarbonisation of the shipping sector is complimentary to Indonesia's ambitions to reduce carbon emissions

Indonesia has set goals to increase electrification as well as increase the renewables contribution to the grid above 20% by 2025. Currently, fossil fuels make up about 84% of energy production in Indonesia. The country has a limited but diverse renewable energy potential - enough to supply its domestic electrical demand as well as production of zero carbon fuels for vessels bunkering in its ports. Adopting zero carbon fuels in its shipping sector could act as a catalyst to achieving the country's overall carbon commitments thanks to the deployment of renewable generation and the development of supply chains, skills and economies of scale which would support wider decarbonisation. Electrofuels produced may also be used in wider activities such as fertiliser, ammonia and steel production industries both for domestic use for and export. With appropriate economy-wide energy, investment and environmental planning, the development of the zero carbon shipping fuel sector and its infrastructure can support Indonesia's decarbonisation goals.

Port Case Studies

This report highlights three different applications for low carbon shipping fuels across Indonesia: supplying busy international shipping lanes with low carbon fuels, fuelling Indonesia's domestic shipping sector and decarbonising small fishing and other off-grid boats. Indonesia serves a large number of international vessels and occupies a key position along busy and important shipping routes. Among these are the Strait of Malacca and the Sunda Strait, which open up even more international opportunities due to proximity to existing ports in Jakarta. As an archipelago, Indonesia has a lot of inhabited islands, and domestic shipping is vital for connecting communities and transporting goods and people. Decarbonising the shipping sector will therefore require a strong focus on implementing solutions that respond to local people and communities' needs and conditions while also addressing emissions and pollution from this segment which consumes 29% of all required shipping energy in Indonesia. For areas that do not currently have access to electrical power, this could mean that small, off-grid renewable energy generation technologies can be deployed and used to power local communities, industries and in parallel charge small battery-powered vessels.

Indonesia has set goals to increase access to electricity as well as increase the renewables contribution to the grid above 20% by 2025

Glossary

AIS	Automatic Identification System
CCS	Carbon Capture and Storage
CSP	Concentrated Solar Power
EDF	Environmental Defense Fund
GHG	Greenhouse Gas
GHGP	Greenhouse Gas Protocol
GtZ	Getting to Zero Coalition
ICE	Internal Combustion Vehicle
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MCA	Multi-Criteria Analysis
$MtCO_2e$	Megatonnes Carbon Dioxide Equivalent
P4G	Partnering for Green Growth and the Global Goals 2030
PPE	Personal Protection Equipment
SOLAS	Safety of Life at Sea
SMR	Steam Methane Reformation
TWh	Terawatt Hours

Introduction

There are several potential pathways for Indonesia to develop new decarbonised fuels to serve its thriving shipping sector

The adoption of zero carbon shipping fuels has significant benefits and synergies for Indonesia far beyond the shipping sector.

The P4G Getting to Zero Coalition Partnership, jointly implemented by the Global Maritime Forum, Friends of Ocean Action, World Economic Forum, Environmental Defense Fund, University College London and International Association of Ports and Harbors, is leveraging the P4G platform to engage stakeholders and companies from three P4G partner countries: Indonesia, Mexico and South Africa. The aim is to make zero emission vessels and fuels a reality and identify concrete and actionable growth and business opportunities that can contribute to sustainable and inclusive economic growth in these target countries.

This report explores the context and potential for the adoption of zero and low carbon shipping fuels through the shipping sector of Indonesia. This work has an important global context as the shipping sector pushes to decarbonise. The International Maritime Organization (IMO), as the regulatory body for international shipping, has set in its Initial Strategy a 'Level of ambition' to cut greenhouse gas emissions by at least 50% on 2008 levels by 2050.

This report is part of a wider project which is investigating the potential adoption of zero emissions shipping fuels in Indonesia, South Africa and Mexico, and builds on the previous work of the Environmental Defense Fund (EDF) in the area of low carbon shipping, including *Sailing on Solar – Could green ammonia decarbonize international shipping?* [1], and *Electrofuels for shipping: How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile* [2].

The analysis in this report takes into consideration Indonesia's unique economic and geographical characteristics to understand the potential scale of the zero and low carbon shipping fuel applications, the applications within and outside of shipping, and the benefits that this might bring to Indonesia. It includes insight and input from a National Committee formed to support the P4G-Getting to Zero Coalition Partnership.

While Indonesia has historically depended significantly on fossil fuels for electricity generation, it has set renewable and decarbonisation targets – to install 45GW of renewables by 2025 and an overall 29-41% GHG emission reduction by 2030 [3]. It is uncertain whether Indonesia will be able to achieve these targets.

About 47% of Indonesia's Gross Domestic Product (GDP) comes from manufacturing [4], which relies on the export of manufactured goods across the world to large economies such as China and the United States. Being able to offer low carbon fuels to shipping vessels will enable Indonesia to serve a future and growing market and facilitate an attractive manufacturing hub to be established as the demand for low carbon goods increases.

Benefits and synergies for Indonesia beyond shipping

The adoption of zero and low carbon shipping fuels is a direct route to decarbonising the shipping sector. It also has significant benefits and synergies for Indonesia beyond shipping, including:

1. **Creation of green jobs** across the whole range of skill and education levels, supporting a just and equitable transition towards a low carbon economy.

2. **Driving investment** in renewable electricity, zero carbon fuels and sustainable infrastructure, which can be supported by reliable demand from the global shipping sector and can be used to support decarbonisation of the wider electricity sector.

3. **Availability of zero carbon fuels** that can be used to decarbonise other sectors, such as heavy transport, mining, agriculture, manufacturing and industry.

The development of the zero carbon fuels sector should be approached with consideration to the synergies beyond the shipping sector to gain full benefit and to avoid potential pitfalls. Further thought is required to investigate these synergies.

Section 1

This report explores various zero and low carbon shipping fuels

There are a variety of potential zero and low carbon shipping fuels that are being considered for applications in the maritime sector. They each have their benefits and downsides that need to be taken into account when selecting a fuel and developing the bunkering infrastructure. This report focuses on zero carbon fuels and propulsion solutions, which use renewable electricity and do not emit carbon dioxide in the supply chain or at the point of use, based on technologies that are likely to be commercially available at scale before 2030. Sustainable biofuels from waste resources are also considered for this report; in order for biofuels to be considered sustainable, there must be considerable care to ensure that the use of these waste products as fuels does not increase lifecycle carbon emissions or other negative environmental or ecological impacts over other methods of disposal. Biofuels are already commercially available in Indonesia, however, the sustainability of these fuels must be ensured to prevent unintended environmental and social consequences.

Exhibit 1: Summary of the zero carbon fuels that are the focus of this report

Renewable Electricity + Battery
Renewable electricity can be used to charge batteries for use in vessels. Vessel batteries have a very high powertrain efficiency and low levels of noise and vibration. However, the energy storage density of existing battery technologies is low compared to fuels, meaning they are currently only suitable for smaller vessels travelling short distances.

Green Hydrogen
Green hydrogen is produced using electrolysers powered by renewable electricity. The production process is energy intensive and requires large volumes of water. Storage of hydrogen can be challenging: it can be stored as a compressed gas in high pressure tanks or as a liquid at around -253°C. Leaks can be challenging to prevent, and hydrogen is an indirect greenhouse gas and any leaks adds inefficiency. Hydrogen can be used in fuel cells or internal combustion engines.

Green Ammonia
Green ammonia is produced by combining green hydrogen with nitrogen separated from air. It is stored as compressed gas at 10 bar or as a liquid at -34°C. It can be used in internal combustion engines or in some fuel cells. Ammonia is more energy dense than hydrogen, though still considerably less energy dense than fossil or biofuels.

Biofuels from waste
Biofuels can be produced from a variety of feedstocks including agricultural and municipal waste. Feedstocks must be reviewed for the sustainability and potential for wider environmental and social impacts. Combustion of these fuels results in carbon dioxide emissions, and lifecycle emissions depend on the supply chain and production process.

PROCESSING

Less processing, resulting in lower losses and costs.

More processes required, requiring additional resources and inputs.

Other candidate fuels that are not a focus of this report

Green methanol
Green hydrogen can be combined with carbon dioxide to produce methanol, which has a higher energy density than ammonia. Green methanol is a liquid at ambient conditions and requires minimal adaptation for vessels designed for fossil fuels.

To be considered zero carbon, the carbon dioxide must be captured directly from air or seawater. This report does not focus on green methanol because direct air carbon capture technologies are assumed to be immature and are unlikely to be viable at industrial scales within the 2030 timescales of this report. However, this may change as the technology matures meaning that green methanol may, in theory, become a viable green fuel option.

Blue Hydrogen and Ammonia
Hydrogen can be produced from fossil fuels, which produces carbon dioxide as a by-product. If the carbon dioxide is captured and stored, the hydrogen is called “blue hydrogen”, which can then be combined with nitrogen to form “blue ammonia”.

Although blue fuels have potential for shipping, this report focuses on zero carbon fuels. This is based on the assumption that carbon capture and storage technologies are immature, and are not likely to be able to achieve the levels of capture needed to ensure that the lifecycle carbon emissions from blue are significantly lower than that of diesel, within the 2030 timescales of this report and at industrial scales. Adoption of blue fuels would also require work to mitigate emissions from extraction and distribution of fossil fuels. See Appendix E for more details.

Biofuels from energy crops
As well as waste products, biofuels can be produced from a variety of energy crops that are cultivated specifically for the purpose of conversion to fuel. As with biofuels from waste, combustion of these fuels results in carbon dioxide emissions, and lifecycle emissions depend on the supply chain and production process.

This report does not focus on the use of biofuels from energy crops for shipping in Indonesia as there is limited land availability, and there is a danger that energy crops might displace food crops or existing forested areas. For this reason, there are limited sustainable and environmentally sensitive feedstocks for biofuels.

Section 2

Low carbon shipping fuels can be used safely with proper regulations and training

As with fossil based marine fuels, the handling of low carbon fuels requires proper industry regulations and training in order to be carried out safely avoiding harm to people and the environment.

Exhibit 2 lays out the main hazards and the implications for handling of low carbon fuels. A full hazard table is included in Appendix B.

Exhibit 2: Summary of main hazards and implications for handling low carbon marine fuels. Marine gas oil and liquified natural gas are included for comparison

	Main hazards	Implications for handling
Renewable Electricity + Battery	• Risk of electricity exposure. • Battery chemicals may be corrosive. • Off-gassing during charging can pose fire risk.	• Safe operation procedures needed to minimize electricity exposure risk. • Ensuring equipment is in good condition should limit risk of fire or exposure to chemicals.
Green Hydrogen (liquid)	• Extremely flammable and explosive. • Risk of cryogenic burns. • Indirect greenhouse gas.	• Ensure that tanks and equipment are in good condition, leaks are prevented, and gas cannot collect in confined spaces. • Safe handling requires appropriate personal protection equipment (PPE).
Green Ammonia (liquid)	• Highly toxic to aquatic environment and humans. • Explosive and flammable. • Corrosive	• As a globally traded commodity there are existing regulations for the storage and handling of ammonia on ships. • Ensure that tanks and equipment are in good condition, leaks are prevented and gas cannot collect in confined spaces. • Safe handling requires appropriate PPE.
Biofuels	• Toxic to environment and humans. • Explosive and flammable. • Formaldehyde can form during combustion.	• Many biofuel types can be stored in tanks similar to a conventional liquid fossil fuel. • Biofuels have similar properties to traditional fossil fuels therefore similar safety and handling rules can be applied.
Marine gas oil	• Flammable and harmful if inhaled or swallowed. • Toxic to aquatic life with long lasting effects.	• Safe handling requires appropriate PPE. • Exposure of water bodies to fuel should be strictly avoided.
Liquified natural gas	• Extremely flammable and explosive. • Risk of cryogenic burns.	• Ensure that tanks are in good condition, leaks are prevented, and gas cannot collect in confined spaces. • Safe handling requires appropriate PPE.

Batteries and charging infrastructure have been proven for road transport and are being deployed rapidly in many countries. Onshore power supply in ports is already being deployed to reduce emissions from auxiliary power systems for vessels when docked. Stakeholders in the steering committee have mentioned pilot projects demonstrating the application of batteries, solar PV and Liquefied Petroleum Gas (LPG) to power small vessels in Indonesia. It is worth considering that the recycling of batteries would require attention given the toxic nature of the remaining materials after use. Without this, there is a risk of accumulating toxic and unusable waste in ecosystems.

Hydrogen and ammonia are well understood in industrial applications with associated regulations, standards and codes of practice. Some modifications to the regulations and codes governing fuel use in maritime applications will be required, but this process is already ongoing [5] [6]. Hydrogen is already consumed in Indonesia for off-grid fuel cell systems with over 800 fuels cells providing power for telecommunications and other critical systems [7]. Hydrogen is particularly difficult to transport and store without the risk of leaks, due to its small molecular size making it able to permeate most materials. Hydrogen leakages should be strictly avoided as it is a secondary greenhouse gas (reducing the removal of methane from the atmosphere). Furthermore, hydrogen is highly explosive and risks detonation in enclosed spaces. For this reason, it may be preferable for hydrogen fuels to be produced close to the port where they will be used to prevent the need for transport and handling, and measures should be put in place for ventilation as well as to detect, measure and reduce slippage.

Ammonia is already used in Indonesia's agriculture sector, which is produced, used domestically, and also exported [8] which means that the handling and transport of ammonia are already well understood. This is demonstrated by Indonesia's ammonia export terminal in North Bontang which includes a 50,000 metric ton double-integrity ammonia storage tank with high-capacity send-out for ships to load. Mitsubishi is also exploring an ammonia manufacturing plant as a fuel source to ship to Japan although this ammonia will be used to supplement coal in coal-fired power stations [9]. Even with these advancements, ammonia's corrosivity, toxicity as well as the production of NO_x gases when it is combusted requires careful attention and mitigation measures during handling and use [5].

Classification Societies around the world have published documents related to the use of hydrogen and ammonia and are developing class rules for the fuels that can be accepted by individual Flag Administrations [10] [11] [12] [13]. It is anticipated that the IMO's International Convention for the Safety of Life at Sea (SOLAS) will be updated in the wake of the rules established by the Classification Societies, which tend to adjust more quickly.

The use of biofuels in road transport, particularly as drop-in fuels, has progressively become more common. Governments such as the Indonesian government have set out policies that aim to utilize bioethanol and biodiesel as blending fuels to decarbonise transport and energy. These fuels are much more similar to established fossil based transport fuels in their storage and handling requirements than hydrogen or ammonia. Throughout the adoption of biofuels, it is imperative that land-use matters along with other sustainability-related issues are considered as this can have significant implications on the reliability of supplying biofuels and the sustainability of the fuels.

Section 3

The best approach for the adoption of zero carbon shipping fuels depends on the availability of natural resources, the global market, and the requirements of the vessels

While decarbonising the shipping sector can be challenging, ambitious goals have been set to achieve this: the IMO has set a target of reducing emissions by at least 50% by 2050 (relative to 2008 levels) and, more recently, John Kerry – the United States' Climate Envoy – called for a more ambitious target of fully decarbonising the sector within that same timeframe. The widespread adoption of electrofuels will likely play a major role in achieving these targets. Yet, to achieve this, two important challenges must be addressed, both on a local and a global scale: their production based on local needs and resources, and safe storing, transport, and use.

The choice of zero carbon shipping fuels for vessels bunkering in Indonesia is dependent on a range of factors, including availability of resources, uptake within the global maritime sector, local context around the port, cost and practical implications of the infrastructure, the characteristics of the fuels and suitability to different shipping applications.

Natural resources and land availability for production of fuels

Adoption of zero carbon fuels relies on the availability of suitable natural resources, and land to produce and store the fuels.

For the production of green hydrogen and ammonia, renewable electricity is required in volume. This can be generated close to fuel production facilities or generated elsewhere and transported to site through electricity networks. The electrolysis process requires water, and since fuel production plants are likely to be near ports, seawater can be used. This will require desalination equipment to be established; the cost of a desalination plant is very small in comparison with the rest of the fuel production infrastructure and establishing a desalination facility could have wider benefits in addressing water shortage issues by creating economies of scale supported by the water demand for fuels. Any leaking of hydrogen is problematic, not only because this reduces process efficiency, but also because hydrogen is an indirect greenhouse gas; this may mean that hydrogen should be produced locally to site and stored for as short a period as possible.

Biofuels from waste must be produced from responsible sources which minimise the ecological and environmental impact. Biofuels, like fossil fuels, release carbon when they are used in combustion engines, however they can be considered net zero if the carbon they emit is offset by the amount of carbon absorbed when they are formed, for example when crops are grown. However, fertilisers, transport and production of biofuels may release additional carbon meaning that biofuels are not truly zero-carbon over their entire lifecycle. It must also be considered if any alternative uses exist for the waste product or residue, utilized as a feedstock, which are of more value, or have lower carbon and environmental impact. These sustainable biomass waste sources are likely to be scarce and are difficult to scale.

Avoiding wider environmental risks

Indonesia has large areas of pristine rainforest and is a biodiversity hotspot. Careful consideration is needed to ensure that the environmental and social impacts of any changes to land use (both direct and indirect) and the use of natural resources are minimised. For example, replacing food producing agriculture, habitat or forest land with fuel infrastructure or renewable generation technologies should be strictly avoided.

Additionally, the development of renewable generation for producing fuels must be in addition to that developed for providing for wider electricity demand and decarbonising the supply of electricity to the communities and industries in Indonesia. Where natural resources are not available in the vicinity of the port, then renewable electricity or the fuels themselves can be imported from elsewhere, or vessels could make separate bunkering stops elsewhere where the resources exist to generate zero carbon fuels sustainably.

Global zero carbon fuel markets

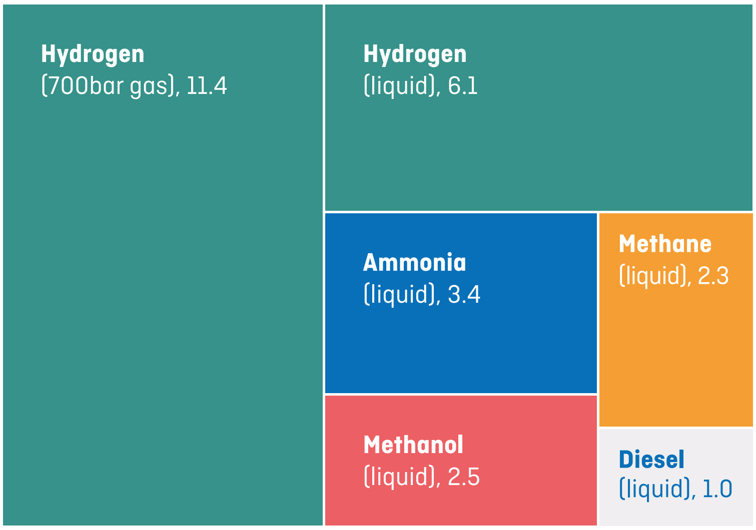
Indonesia is located on busy shipping routes, with international vessel traffic passing through the Archipelago, mainly through the Sunda Strait and Strait of Malacca; connecting the Indian Ocean with the Pacific. As a result, Indonesia has strong trading relationships with Asian markets such as China and Japan as well as the west coast of the American Continents. Additionally, Indonesia is a neighbor to Singapore which is a global maritime hub and a potential zero carbon fuel market.

Globally, green hydrogen and green ammonia have emerged as important fuels for the decarbonisation of shipping. Aligning the fuel selection with the rest of the world would mean that international vessels could bunker in Indonesia and development in vessel and bunkering technology will be available commercially for the global market. For this to occur, adequate market incentives need to be put in place to attract international vessels. While high quality and sustainable biofuels are likely to become an increasingly important commodity in the future, there is limited sustainable feedstocks to produce biofuels across the world, which means that they are not likely to be used for the majority of internationally shipping. Where carefully and sustainably sourced, biofuels could be used to support specific shipping applications or domestic shipping routes.

The suitability of fuels for different applications

A key characteristic of fuels which dictates their suitability for different applications is energy density; the amount of energy they can provide per unit of volume. A lower energy density means that a vessel will not be able to travel as far with a fixed fuel tank size and would need to stop to refuel more often. Exhibit 3 shows a comparison of the energy densities of various fuels relative to diesel, showing that the zero carbon fuels (hydrogen and ammonia) have lower energy densities than the carbon-containing fuels.

Exhibit 3: Relative storage volume needed for various shipping fuels (including tank, relative to diesel) [14]



The energy density of a battery-based propulsion system (not shown in Exhibit 3) is about one quarter that of a gaseous hydrogen system [15]. This means that current battery technologies are only suited to smaller vessels which require less energy, and where onboard volume is less of a constraint. Larger vessels and international ships in particular are more likely to find that green ammonia is the most suitable zero carbon fuel, as it has the higher energy density.

Biofuels are generally in the form of bio-diesel, bioethanol, or biomethane, have high energy densities relative to green fuels or batteries, and would be a more direct replacement to fossil based fuels. Appendix A describes the multi-criteria analysis of various zero and low carbon fuels carried out to support this project.

Shipping patterns

The location of the port and the amount and types of vessels visiting it are important factors in understanding fuel selection and design of the infrastructure solution. Some shipping applications will be more suited to fast uptake of new low carbon fuels.

Vessels that travel regularly between a small number of large ports are well suited for early adoption of low carbon fuels as larger ports are more likely to be able to provide the necessary bunkering arrangements, and the investment will be supported by regular demand. Vessels based out of one or two local ports like tugs, ferries and offshore services may benefit from the availability of zero carbon fuels for larger vessels or may be able to operate based on battery power.

Vessels that visit many more and smaller ports may find it more difficult to find ports that can supply the new fuel, so may be later to adopt zero carbon fuels.

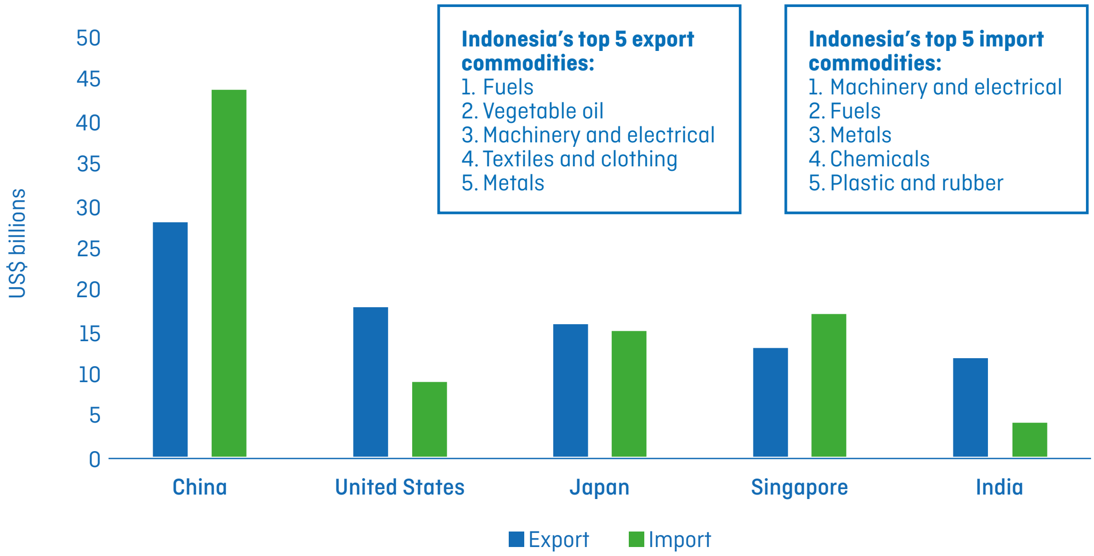
Section 4

Indonesia's shipping sector is significant and diverse; from large international vessels on busy shipping routes to small domestic vessels connecting islands

Indonesia is located along two of the most important shipping lanes in the world, the Strait of Malacca and the Sunda Strait. This position gives it the potential to be a hub for international vessels passing between the world's largest economies. Indonesia's largest trading partners are China, Singapore, Japan and the United States.

Indonesia is a major exporter of coal and crude oil. Together, fuels are Indonesia's top export commodity by value with it previously being a member of the Organization of Petroleum Exporting Countries (OPEC). Indonesia exported US$ 42 billion worth of fossil fuels in 2018 (the latest year that figures are available).

Exhibit 4: Indonesia's largest trading partners by export and import (WITS world bank)

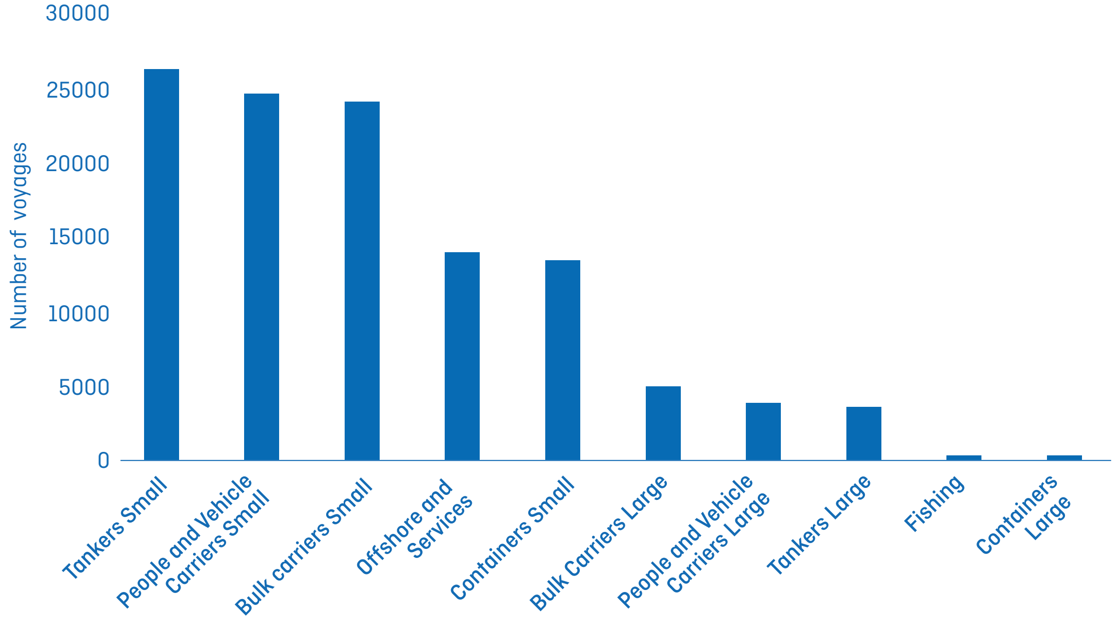


Indonesia's top 5 export commodities:
1. Fuels
2. Vegetable oil
3. Machinery and electrical
4. Textiles and clothing
5. Metals

Indonesia's top 5 import commodities:
1. Machinery and electrical
2. Fuels
3. Metals
4. Chemicals
5. Plastic and rubber

Exhibit 5 shows the number of shipping journeys from Indonesia's ports over a year, based on Automatic Identification System (AIS) vessel tracking data. This data covers only larger vessels that are subject to international tracking. Vessel categories are defined in more detail in Appendix C. There are also large volumes of smaller, untracked vessels (<20 GT) within Indonesia including small fishing, industrial and personal vessels. It is estimated that there are more than 700,000 vessels of this type in Indonesia [16]. There is no tracking data available for these vessels, but they contribute a vital part of Indonesia's shipping sector, and also make up an important part of fuelling demand.

Exhibit 5: Indonesia's International and domestic departures by vessel category (AIS data, capturing large, internationally tracked vessels) see Appendix C for vessel category definitions



Indonesia is an active shipping nation, as illustrated by the number and range of vessel types visiting its ports. The majority of Indonesia's vessel traffic is made up of small people and vehicle carriers, tankers, containers and bulk carriers.

The vessel type with the highest number of journeys leaving ports in Indonesia are small people and vehicle carriers, likely to be significantly made up of vessels transporting people between islands, often frequenting the same ports. This is followed by small tankers delivering fuels across islands and small bulk carriers transporting goods.

Large commercial fishing vessels account for little of Indonesia's total traffic – this is because the majority of Indonesia's fishing is done with small vessels (more than 80% of all fishing vessels) without AIS tracking, and so does not appear in this data [17].

Exhibit 6 shows the amount of fuel, shown in fuel energy (terawatt hours, TWh) used across Indonesia by each vessel category. The top four categories for energy consumption are small tankers, bulk carriers, container vessels and people and vehicle carriers.

Exhibit 6: Fuel energy use of Indonesia's shipping sector, including international and domestic departures by vessel category (AIS data, capturing large, internationally tracked vessels) [16] see Appendix C for vessel category definitions

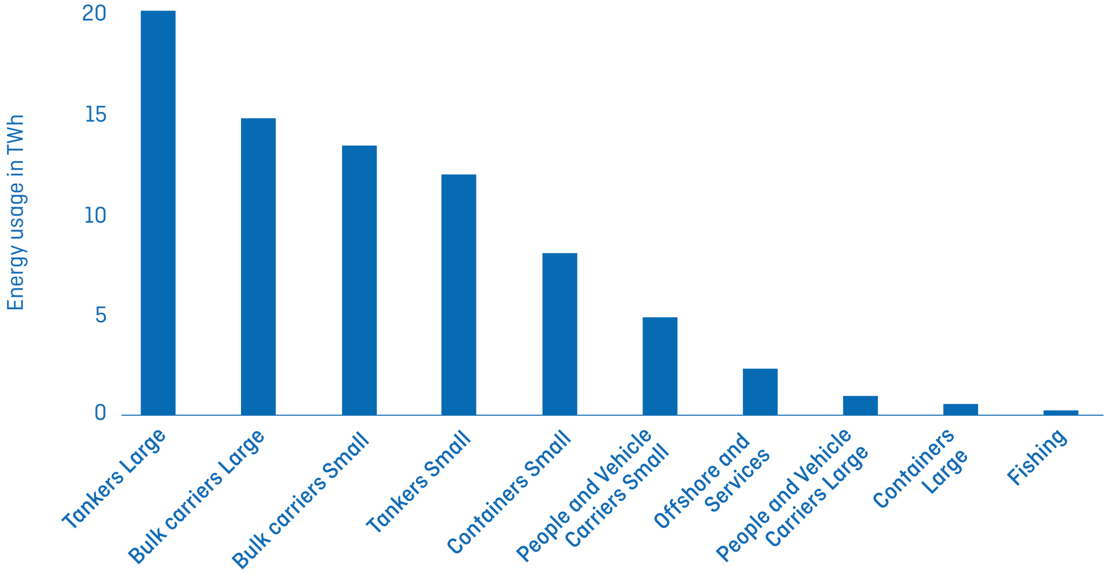


Exhibit 7 and 8 show the fuel energy usage by domestic and international vessels in the busiest 15 ports in Indonesia, again using the AIS tracking data. In total there are over 160 ports in Indonesia. The majority of these ports have very few vessels, requiring very small amounts of fuel compared to the largest few ports shown in Exhibits 7 and 8.

Exhibit 7: Fuel energy usage by vessel category for domestic departures, showing the 15 largest energy users in Indonesia (AIS data, capturing large, internationally tracked vessels) [16]

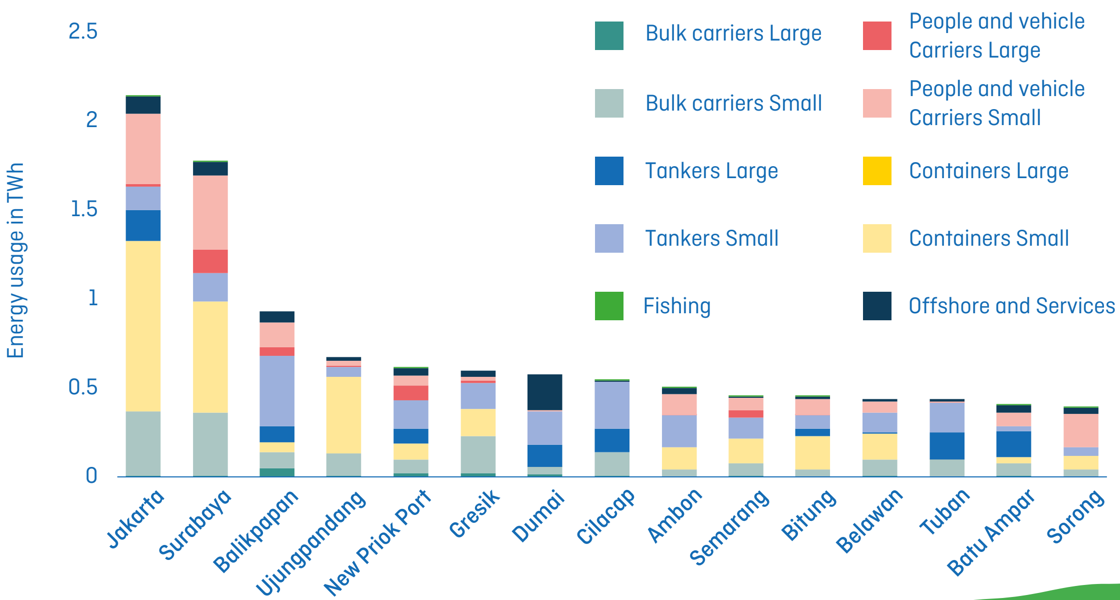
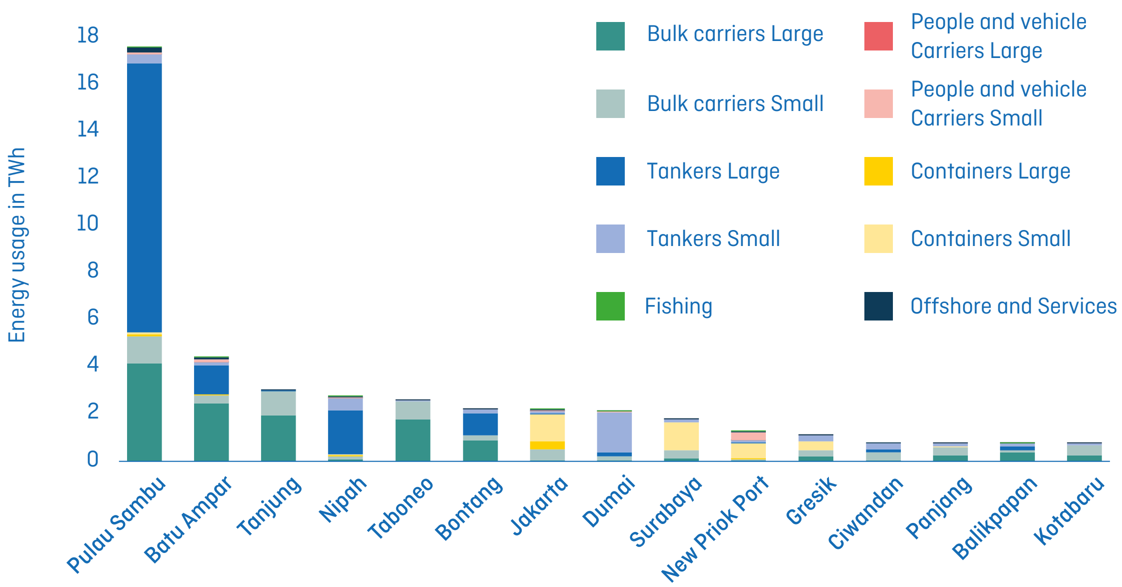


Exhibit 8: Fuel energy usage by vessel category for international departures, showing the 15 largest energy users in Indonesia (AIS data, capturing large, internationally tracked vessels) [16]



Jakarta and Surabaya ports are Indonesia's largest ports in terms of energy consumption and number of voyages for domestic departures, these are primarily made up of containers and people and vehicle carriers. The port of Jakarta is more specialized in containerized cargo, and serves relatively fewer liquid bulk tankers and dry bulk carriers. Surbaya port has a strategic position and surrounding advantageous hinterlands, and is the center of inter island shipping for eastern Indonesia.

Pulau Sambu and Batu Ampar, being located along the international route of the Malacca Strait and close to Singapore, are the top two largest ports in terms of energy usage and number of voyages for international departures, with bulk carriers, containers, and tankers accounting for approximately 95% of total energy demand for international departures from these ports.

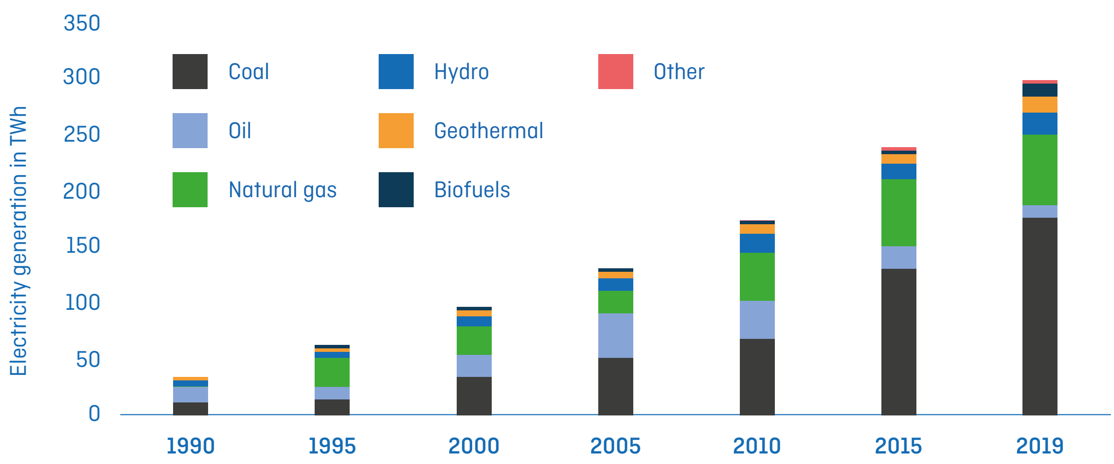
Section 5

Indonesia is largely reliant on coal and natural gas for electricity generation, with moderate recent increases in renewable generation

Fossil fuels remain Indonesia's main source of fuel for energy production (86.7% in 2020). Hydro power has contributed to the energy mix for decades, and there has been more recent development in geothermal and biofuel use. However, coal and natural gas use has also substantially increased to meet Indonesia's growing electrical demand. It is likely that coal is seen as the quickest, easiest and cheapest way to provide millions of people with electricity [18]; Indonesia has a price cap on coal, making generation very attractive economically compared to other sources.

Renewable and low carbon electricity generation has increased moderately from a low base, particularly bioenergy and geothermal production. The increase in bioenergy is attributed to growth in biodiesel (B20, B30) produced from conventional crude palm oil. This reached 16% of total electricity generation in 2019 [19].

Exhibit 9: Indonesia's historical electricity generation mix

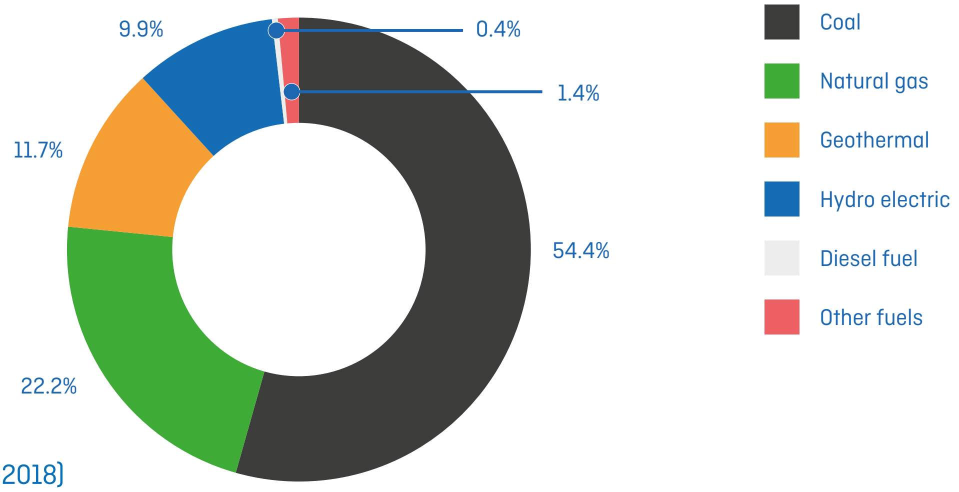


Due to Indonesia's rapid industrialisation and urbanisation, its electrical demand is predicted to treble from 2015 to 2030. The country is already Southeast Asia's largest electricity consumer, and this growth is driven by population growth, an emerging middle-class and electrification of non-electrified households.

For Indonesia to achieve universal electrification by 2026, it is anticipated that 80GW of additional generation will be needed at a cost in the region of US$155 billion. Indonesia's state utility company PLN (Perusahaan Listrik Negara) currently only plans to add 35GW generation capacity to its grid by 2029, 57% of this would come from coal [20].

Indonesia has multiple renewable generation and emission reduction targets. The National General Energy Plan includes ambitious targets to increase the renewable electricity generation capacity from 9GW in 2018 (providing 12.5% of the total generation capacity) to 45GW in 2025 (23% of total generation capacity).

Exhibit 10: Predicted electricity generation mix for Indonesia in 2025



(PwC - 2018)

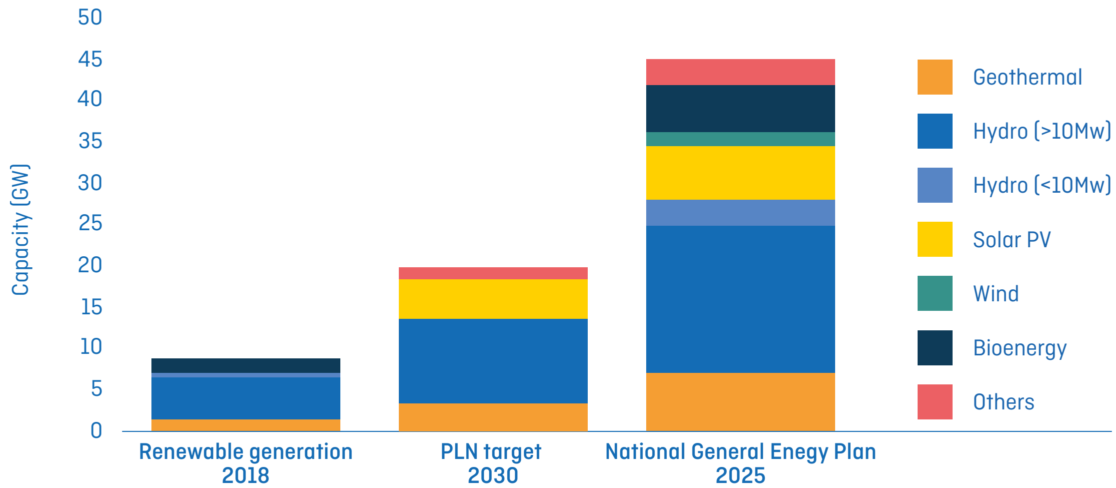
PLN has a more modest ten-year plan which includes an additional 20.9GW of capacity in 2030. Currently Indonesia is not on track to meet its renewable generation targets [19].

Indonesia' geography over many islands has led to more than 600 isolated grid systems, and electricity access is inconsistent between islands and locations [21]. For example, Papua is less than 40% electrified while Jakarta is close to 100%. This means it is difficult to generalise the grid condition and develop policies that are appropriate across the country. There are plans to increase the interconnection between Indonesia's islands, and aims for universal access by 2024. It is likely that increased access will be heavily reliant on "micro-grids", requiring off-grid isolated generation systems rather than through a nationally connected grid [22].

Another barrier to the adoption of renewable generation is land use; there is already tension between a growing population, economic growth, and the natural habitats in Indonesia. It is important that direct and indirect land use change is considered carefully when identifying renewable generation solutions.

Bioenergy is used in some sectors (industry, buildings and transport), including in the form of biofuels for transport and generators. This is principally from palm oil, which itself has environmental implications due to land use change [22].

Exhibit 11: Indonesia's renewable energy capacity targets from PLN and the National General Energy Plan in comparison to actual renewable generation in 2018



Section 6

Indonesia has diverse but limited potential of renewable sources to produce fuels for the shipping sector

Indonesia has limited renewable potential due to land availability, feasibility of site development and its disconnected grid across the country. In total Indonesia has the estimated potential to produce between 830TWh and 1,873TWh of renewable energy annually from exploitable geothermal, hydropower, tidal, wind and solar, as described in Exhibit 12.

Exhibit 12: Indonesia's renewable potential based on various resources

Wind

Indonesia has 9.3GW of onshore wind potential (10TWh/year). The majority of this is located on Indonesia's southern coastline. Indonesia has limited potential for fixed offshore wind potential due to limited wind resource and deep waters off the coast. However, greater potential may be unlocked as floating offshore wind becomes more commercially mature in coming years [36]. Offshore wind technologies are more complex and costly than their onshore counterpart, and any offshore wind development will need to be designed with environmental and weather factors in mind, and be associated with an extensive environmental impact assessment.

Solar

Indonesia has a good solar potential of 4.8kWh/m^2/day due to low seasonal variability. Estimations of solar potential in Indonesia vary. One study by IRENA estimated total potential to be 500GW capacity while another study by IESR estimated a 1,492GW potential capacity [36] [37]. The differences are likely to be due to assumptions on land use considerations and availability as well as progress of solar technologies over the next decade. This translates to between 525TWh [36] to 1,568TWh of energy generation per year [37]. A recent study has highlighted solar resource potentials exceeding those previously mentioned [42]. If this additional resource is accessible, then there would be a significant benefit to decarbonising the energy supply in Indonesia as well as provide opportunities for the generation and creation of zero carbon fuels. However, any renewable energy infrastructure must be developed in an environmentally sensitive way, avoiding land use change from food producing agriculture or forest.

Tidal

While some tidal and wave generation technologies are immature, this resource has the potential to become more reliable in the near future. Indonesia has good tidal potential of 18GW of capacity which can be used close to ports, making it convenient for green fuel production. This translates to 47TWh per year of potential energy [38].

Geothermal

Indonesia holds 40% of the world's geothermal energy reserves due to lively volcanic activity. The known developable potential of geothermal in Indonesia is 133TWh/year from 19GW of capacity [37].

Hydropower

Hydropower is currently Indonesia's largest renewable generation source. Future hydropower developed in Indonesia must be considered where there is low impact on the environment, and it is easily accessible. Based on this and potential sites that are relatively easy to develop there is 105TWh/year of hydro potential in Indonesia [39].

The total renewable energy required to support a 5% adoption of zero carbon green fuels (hydrogen or ammonia) across all of Indonesia's shipping fleet is expected to total approximately 8.3TWh/year. This is a small energy requirement when compared to Indonesia's renewable energy potential, but becomes more significant as adoption rates rise towards full 100% adoption.

This renewable electricity potential should also be used to support decarbonisation of Indonesia's domestic energy supply. The demand for electricity from the grid is expected to be in the region of 500 to 950TWh by 2030. If this demand were to be largely decarbonised, which should be the aim over time, there would be limited renewable energy available for other uses such as shipping, and this availability is expected to be highly localised.

Required renewable electricity generation to support 5% adoption of zero carbon vessel technologies in 2030:
~8.3TWh/year

The investment potential for infrastructure to support 5% adoption of zero carbon vessel technologies by 2030 (see Appendix D):
45.9 – 65.4 trillion rupiah (3.18 – 4.53 billion USD)

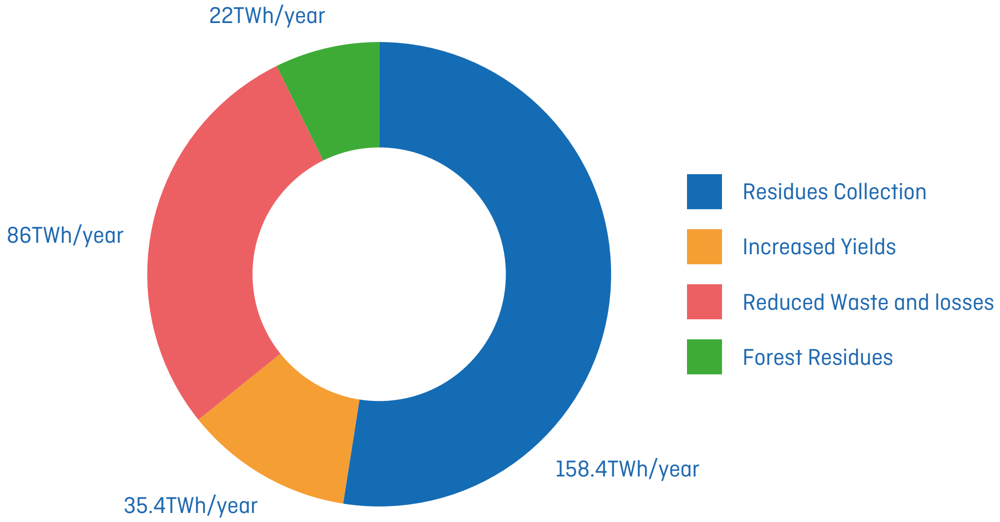
Indonesia's national electricity demand in 2030 is forecast to be:
500 – 950TWh/year

Indonesia's renewable potential:
830 – 1873TWh/year

Indonesia has potential waste biomass streams including from forestry, agriculture, and household waste. The Indonesian Government plans to utilise 22% of this biofuel potential by 2030, with 60% for grid-connected electricity generation and 40% for off-grid captive power generation. Any production of shipping fuels would need to supplement current plans by the Indonesian government, rather than compete or conflict with them, to ensure there is no risk to overarching decarbonisation of Indonesia's domestic energy and transport sectors.

The potential resources from waste streams are estimated at 302TWh/year [23]. This has been calculated from potential sustainable feedstock streams, including the collection of agricultural residues, increasing crop yields through sustainable intensification of agriculture, bioresources from land freed through reducing losses and waste in value chains and residues from productive forests. The actual biofuels potential will depend on which process pathway the feedstocks are put through and the subsequent biofuel produced. For the sake of this calculation a percentage of the theoretical feedstock potential is taken to account for logistical inefficiencies, and thereafter a factor of 40% taken to account for process efficiencies. Appendix F lists the likely feedstocks and processes needed to produce biodiesel, bioethanol, bio-oil, and biomethane.

Exhibit 13: Indonesia's potential generation from advanced biofuels



Section 7

There are multiple options for how Indonesia could supply its maritime industry with low carbon fuels

There are several options and opportunities to fuel vessels visiting Indonesia's ports using zero and low carbon fuels. The eventual solution is likely to be a combination of these options.

High volume renewable uptake

If Indonesia is able to exploit close to the full renewable energy potential of 1,873TWh, then it will be able to fully decarbonise the grid and have around 1,000TWh to use in applications such as industry, land transport and to decarbonise domestic and international shipping through conversion to green hydrogen and ammonia, or where possible, through direct electrification using battery powered vessels. It is unlikely to be possible to reach the full theoretical renewable energy potential, as a proportion of this is likely to be shown to be infeasible due to land and practical constraints or unwanted environmental impacts. The energy available could be augmented with emerging technologies such as floating offshore wind and improvements in existing generation approaches making them more efficient. This option would be desirable as it makes Indonesia energy independent, supports existing decarbonisation efforts, fuels vessels with zero carbon green fuels, as well as fulfilling the ambition to become a bunkering hub for zero cabron international shipping due to Indonesia's geographic location.

Local renewable microgrids

There are significant opportunities for off-grid deployment of renewables in rural areas; over 12,000 villages across Indonesia are currently not electrified (EIC). There is the potential to establish local community energy systems in these areas in order to supply local homes, community buildings and businesses, and further to charge local small scale battery powered vessels for fishing or transport between islands. Direct electricity charging is likely to provide lower cost fuelling for the vessels, further supporting the economies in these remote villages. It is these smaller vessels that are best suited for battery power technologies, which would not be suitable for larger vessels undertaking longer journeys.

Importing green electricity for fuels

If Indonesia was to import electricity from a neighbouring country, this could be used to generate green fuels. This would be a very large project and would take a significant amount of infrastructure. The investment required for an electricity interconnector would be very large, and the economic feasibility should be carefully considered.

Any interconnector would most likely be developed based on a much broader business case than supplying fuels for Indonesia's shipping sector, and will likely be driven by mutual benefits between connecting neighbouring countries. There are feasibility studies ongoing to build the world's first intercontinental power grid, connecting Australia to Singapore to supply renewable energy [24]. This interconnector is planned to go through the Indonesian archipelago, which could provide additional renewable capacity that is needed for Indonesia to fully decarbonise its grid as well as produce zero-carbon fuels for domestic and international vessels.

An interconnector to Jakarta would enable fuels to be produced and shipped around Indonesia. This would mean that Indonesia would not be limited by the modest local renewable energy potential. This option may be particularly advantageous if only the lower renewable potential estimates are achievable, and it would present the opportunity of developing a green shipping fuel production industry within Indonesia without the need to provide all of the green electricity domestically. Due to the difficulties in preventing hydrogen slippage during storage and transport, it might be preferable to convert to green ammonia on the point of production before transport.

Importing green fuels to supply bunkering ports

Indonesia's major bunkering ports could use imported fuel from a growing global zero carbon fuel market. This would enable Indonesia to serve its thriving shipping sector with zero carbon fuels without needing to rely on domestic renewable energy supply or fuel production. This could be used alongside domestic production to supplement fuel supplies for large scale international take up. Due to the difficulties in preventing hydrogen slippage during storage and transport, this approach might be best suited for green ammonia.

Limited use of biofuels from sustainable waste feedstocks

There is an option for Indonesia to use its already established biofuel capability to support the decarbonisation of the maritime industry. This would need to use only sustainable biofuels from waste or other adequate sources and have sustainable supply lines to the end use, accounting for carbon emissions throughout the whole lifecycle. These supplies are not likely to be available at the scale required to supply significant proportions of the shipping fuels required, particularly as the Indonesian government has already begun deploying biofuels for road transport and energy. Furthermore, sustainable biofuels will be a valuable commodity in their own right and may be exported on international markets creating another demand stream for biofuels.

Section 8

Adoption of low carbon fuels can bring wider benefit

The decarbonisation of the shipping sector in Indonesia could have wider co-benefits when considering sustainable development, including creation of green jobs to support a just transition, supporting access to the global demand for green products and commodities, and enabling wider decarbonisation far beyond the shipping sector.

Electrification through renewable generation

It is assumed that, in the future, mini-grids fed by renewable generation mixes will be developed to serve the remote communities over Indonesia. This allows the natural, local resources to be exploited to serve communities and industries, and also provide reliable zero carbon propulsion for its fishing vessels.

On remote islands outside the main islands of Java and Bali expensive diesel is used to generate electricity in a relatively inefficient way. This can be expensive, adding to the subsidy burden of the government to supply diesel, taking resources away from improving infrastructure. The development of isolated mini-grids would empower local communities by supplying their own energy for commercial and domestic vessels as well as homes and businesses; creating additional revenue streams and skilled green jobs. This also supports the Indonesian Government's electrification and decarbonisation goals.

Creation of green jobs across the whole range of skill and education levels

Given that various local economies are expected to transition from a fossil fuel-based economy to a less carbon intense one, it is important to consider the concept of a just transition whereby those who will be affected by the transition are supported. This includes those individuals and communities that rely on these industries for employment and to sustain their economies, as well as local and indigenous communities that could be negatively affected by these developments.

The production of alternative fuels would be accompanied by the creation of a wide range of jobs within the supply chains of zero carbon fuels. As jobs in fossil fuel extraction, transport and electricity generation decrease, the creation of jobs within sustainable supply chains could play a pivotal role in supporting a transition. Indonesia's coal output has been declining in recent years. While this can disrupt local economies, it may open even larger opportunities to create local capacity and future-proof jobs, bringing significant development to the country and fostering green economies around the ports. This has the potential to significantly alleviate poverty and inequality, which have been highlighted as potential barriers for the sustainable development of the country [25].

Benefiting from the global demand for green products and commodities

An early adoption of zero carbon fuels in Indonesia could establish the country as a world leader in bunkering of these fuels. Indonesia could feed into these markets benefitting from its location on major shipping routes as well as diversifying the maritime industry through decarbonisation of cruise vessels.

Being able to offer green hydrogen and ammonia to bunkering vessels would also position Indonesia to feed into a growing global demand for "green" products. As the market for these products and materials sees an increase, Indonesia will be at an advantage of being able to offer these options to vessels.

Similarly, green and low carbon fuels could be adopted in industry to provide industrial heat and combustion, replacing high carbon options. An example of this is the production of green steel, by means of green hydrogen. The consumption of steel in Indonesia has been increasing and is projected to nearly double by 2025 (21.4 million tons) as compared to 2016 consumption levels (12.7 million tons), indicating significant growth opportunities for local steel producers [26]. Products and commodities produced utilizing green hydrogen could feed directly into these growing markets and offer a more sustainable alternative. Steel producers are already actively participating in this dialogue through local hydrogen associations, which could lead to Indonesia successfully leveraging this and other opportunities in related zero carbon fuel technologies and goods.

Attracting foreign and private investment

Deploying renewables at large-scale and building the infrastructure, supply chains and capacities necessary to enable electrofuel economies in the country and reaping the benefits that they would bring will call for significant volumes of investment, 45.9 - 65.4 trillion rupiah (3.18 - 4.53 billion USD) for a 5% adoption of zero carbon vessel technologies in 2030. The nature of these projects and associated co-benefits for industry would mean that international climate funding alongside partnerships with the domestic and international private sector can be leveraged and could play a key role not only in supplying the necessary capital but also in effectively allocating it, helping drive the advancement of sustainability and the local energy sector.

Conclusions

Indonesia could adopt decarbonised shipping fuels through a mix of generation and fuelling options. This would enable Indonesia to offer into the growing and valuable demand for these fuels in the international shipping sector, and also support decarbonisation and economic goals throughout Indonesia.

Indonesia has a diverse but potentially limited renewable energy potential. There is also potential to supply biofuels from sustainable and environmentally sensitive waste sources, though the scalability of these sources is limited. There should be the ambition to use this potential to decarbonise the domestic energy supply, and any remaining can be utilized in decarbonising shipping and other sectors such as land transport. It is uncertain if there are adequate viable and environmentally sensitive renewable energy resources to provide all of these needs. There are also barriers due to the spatial variance of Indonesia's renewable potential and its disconnected grid.

Indonesia can overcome these challenges to provide decarbonised shipping fuel by adopting a mix of generation and fuelling options. These include leveraging renewable energy generation potential where it is available and transporting green electricity to ports for conversion to fuels, importing renewable electricity from neighbouring countries, or importing green fuels to supply ports. Local microgrids, fed from renewable electricity generation, can be leveraged to supply communities as well as directly charge small local vessels which are well suited for direct electrification.

Biofuels from waste should be established only using sustainable and environmentally sensitive feedstocks, ensuring that the lifecycle emissions are zero or very low and that the alternative use or disposal of the waste would not produce lower emissions than its use as a biofuel. Sources for biofuels that meet these criteria are expected to be modest, inconsistent across timescales and they will not be scalable due to the fact that they are waste products and therefore not directly produced. However, their use for specific or very localised applications may be appropriate.

For Indonesia to achieve its decarbonisation goals, it requires key pieces of infrastructure and large investments to come together, this will need coordination and long-term planning. Indonesia will benefit greatly from establishing a comprehensive roadmap and sending clear signals early on. Doing so would allow investments, infrastructure, and markets to grow and evolve to enable local zero carbon electrical economies in time to meet these goals and for Indonesia to capitalize on the upcoming market shift. Indonesia could attract foreign and private investment through international funding, which would present opportunities for local enterprises to grow and develop skills and expertise. The development of the zero-emission fuel infrastructure to supply 5% of the shipping sector with green fuels could attract investment of between 45.9 - 65.4 trillion rupiah (3.18 - 4.53 billion USD).

Port case study

Port case study one: Supplying busy international shipping lanes with low carbon fuels

Indonesia serves a large number of international vessels and is located on many busy and important shipping lanes. This includes the Strait of Malacca and Sunda Strait. The Sunda Strait is situated close to large ports in Jakarta.

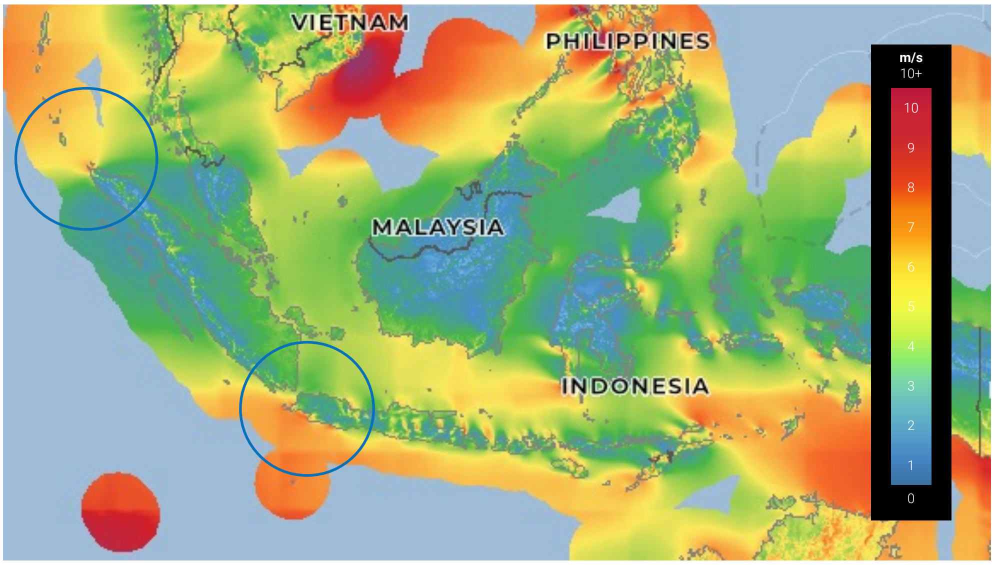
International vessels are likely to require green hydrogen or ammonia as decarbonised bunkering fuels, as these fuels are most likely to be adopted by the international maritime sector. In the long term, the fuel demand will be high, requiring significant secure supplies of shipping fuel. However, it is expected that this demand will be small at first, as the first vessels convert to low carbon fuels, and it will then grow over time, which allows time for planning and adaptation.

Initially, it may be possible to establish bunkering of low carbon fuels based on limited nearby renewable resources such as solar, wind and geothermal. This could be supplemented by imported fuels as required.

By the time that the demand for low carbon fuels ramps up, more advanced renewable generation technologies could be developed, such as offshore energy generation such as wind, tidal and wave power.

While offshore wind has not been explored to a large extent, there are pockets of offshore wind potential that could be further explored to supply the production of zero-carbon fuels to serve decarbonised international vessels. Some of these pockets of slightly higher offshore wind potential can be found in the Strait of Malacca and the Sunda Strait (see Exhibit 14).

Exhibit 14: Wind density map of Indonesia and location of Indonesia's straits [40]



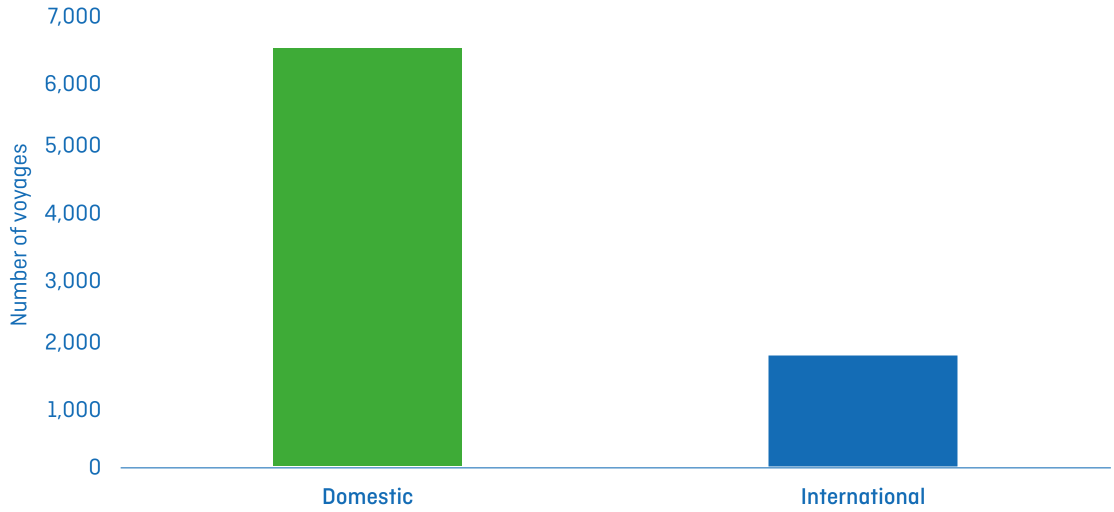
The feasibility of fixed and floating offshore wind could be considered in these areas; the development of these technologies over time would unlock additional renewable energy potential and minimise the land impacts of using onshore renewable infrastructure. Tidal or wave generation could also enable access to additional energy sources to support the generation of shipping fuels; tidal and marine energy may hold more potential in both the Sunda Strait and the Strait of Malacca due to higher tides and faster ocean current, however, this would need to be explored further.

This renewable resource could be further supplemented by an international interconnector if established, which alongside providing renewable electricity for domestic and industrial supplies, could provide energy for green fuel production. The best prospect for an international indicator would be with Australia, where there is a large amount of renewable potential on its northern coast, at its shortest distance between the two countries (i.e. 2,000 miles of ocean). Additionally, green fuels could be imported from other areas to supplement those produced within Indonesia. These options combined could be optimised to provide green shipping fuels to international vessels visiting Indonesia's ports while maximising benefits to Indonesia's economy and environmental goals.

Port Example: Tanjung Priok (Jakarta)

Jakarta, on the island of Java, contains Indonesia's largest port in terms of domestic voyages and domestic energy usage. Tanjung Priok is frequented by a mix of many small vessel types; in particular, small container vessels followed by small bulk carriers and small people and vehicle carriers. While most vessels departing Jakarta are domestic voyages, Indonesia has a significant energy demand from vessels on international voyages (see Exhibit 15). Jakarta's location close to the Sunda Strait presents it with one of the busiest shipping lanes passing close by but also one of Indonesia's largest wind resources (see Exhibit 14). Establishing a mix of renewable generation including exploiting the wind power in the region would enable Jakarta to become a zero-carbon fuel stakeholder.

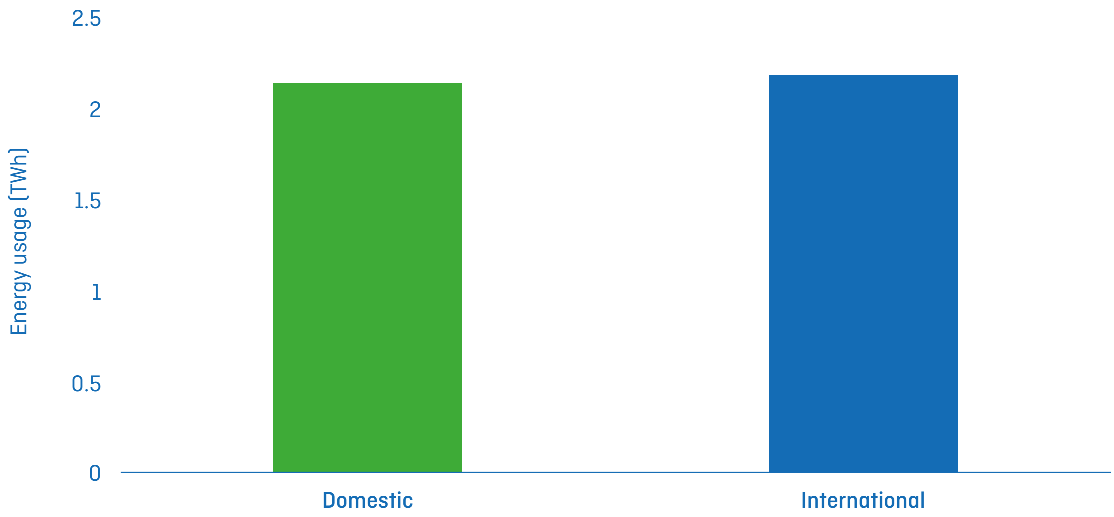
Exhibit 15: Tanjung Priok domestic and international voyages



With a reliable source of renewable electricity, Jakarta could produce zero-carbon fuels to supply the domestic and international vessels bunkering at the port but also act as a hub to export zero-carbon fuels to other ports in Indonesia through its well-established domestic shipping lanes. This will enable ports that have a large number of international vessels bunkering at the port to be supplied by zero-carbon fuels, if the port does not necessarily have a large amount of renewable potential close to it.

Jakarta may have enough renewable potential to cover the initial energy demand to supply international and domestic vessels; 5% by 2030 [27]. However, as demand for these fuels increases at the port and for Jakarta to establish itself as an export hub for other ports then this demand may need to be supplemented by additional renewable capacity. This could potentially be achieved through international interconnectors, with neighbouring countries such as Australia and Singapore, to supply enough energy to produce fuels while also providing renewable capacity for domestic and commercial industries on Java.

Exhibit 16: Tanjung Priok energy usage by international and domestic energy use (TWh)



Port case study

Port case study two: Fuelling Indonesia's domestic shipping sector

As an archipelago, Indonesia has a lot of inhabited islands, and domestic shipping is vital for connecting communities and transporting goods and people. From the vessels with AIS tracking, Indonesia's domestic vessels are mainly small containers, bulk carriers and people and vehicle carriers taking people and goods between the islands of Indonesia. However, there are also large volumes of smaller, untracked vessels (<20 GT) within Indonesia including small fishing, industrial and personal vessels.

An important part of decarbonising Indonesia's shipping industry will be to decarbonise domestic vessels. The most appropriate approach to this will depend on the application and the resources available:

Very small vessels: The smallest fishing boats, container vessels and people carriers may be suitable for adoption of battery fuelling technologies. This is the most efficient way of using renewable generation to fuel vessels and is based on proven battery and charging technologies. Electricity can be supplied from the grid, or using community scale microgrids.

Vessels based on green hydrogen and ammonia: In areas where green hydrogen and ammonia bunkering capability is being established, for example for use by international vessels, it is likely to be feasible and advantageous for larger domestic vessels to take advantage of this availability. Green fuels may be generated through use of domestic renewable electricity generation, or through established routes to import fuels or green electricity. Fuels can also be supplied from larger port hubs if fuel production is established at scale. These fuels could then supply smaller ports to serve domestic vessels through ship-to-ship (STS) bunkering for example. It would also be possible to establish local fuel production near to domestic ports, if the demand is large enough to make this feasible and if there was suitable renewable energy resource in proximity to fulfil demand.

The use of sustainable biofuels from waste: There may be some applications that are particularly suitable for the use of sustainable biofuels. This includes areas where there is a local waste stream suitable for biofuels production that is sustainable and available in adequate volumes. Vessels being fuelled in this way would most likely need to have limited or predictable shipping patterns which relied on this fuel being available at only a small number of suitable ports. The option to utilize STS refuelling, given high resource availability in a low demand area, could also aid in meeting biofuel demand at ports that require such fuels but contain little resource potential. A key advantage of using these fuels for these vessels is the relative ease of converting vessel technologies to operate on biofuels. A full lifecycle analysis should be done for all biofuel options in Indonesia to check whether they would be an improvement over other options considering land uses, sustainability and efficiency.

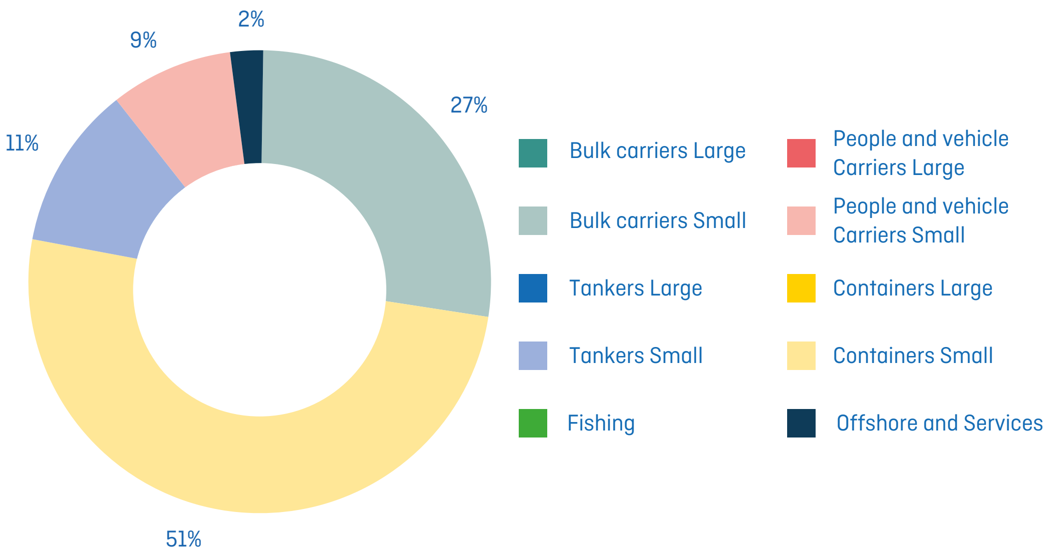
Indonesia could by establishing various alternative fuels and approaches for domestic shipping set an example for other south-east Asian countries relying on domestic vessels for transport and trade. The most suitable approach will vary from island to island, from port to port, and between shipping applications. The combination of solutions selected can be optimised to provide greatest value to the local communities and industries that the vessels serve. This could include the potential to create local jobs throughout Indonesia's domestic ports and fuelling supply chains, supporting Indonesia in its decarbonisation aims and enabling a green future economy.

Port example: Ujungpandang

Ujungpandang is a port located in the city of Makassar the capital of province South Sulawesi. 90% of vessels departing from Ujungpandang are domestic vessels, primarily comprised of small containers, small bulk carriers and small people and vehicle carriers – See Appendix C for vessel category descriptions.

These vessel types are suited to being powered by on-board batteries. The region of South Sulawesi is geographically well positioned to establish local renewable power, particularly wind power, to supply these vessels with electricity as well as meet other energy demands on the island such as domestic electricification. Establishing local generation can be replicated to other ports around Indonesia and where this is feasible this could come from a mix of generation including wind, solar, geothermal and hydro. The exhibit below highlights the wind potential that exists on the Island based on wind speeds.

Exhibit 17: Ujungpandang domestic departures by vessel category

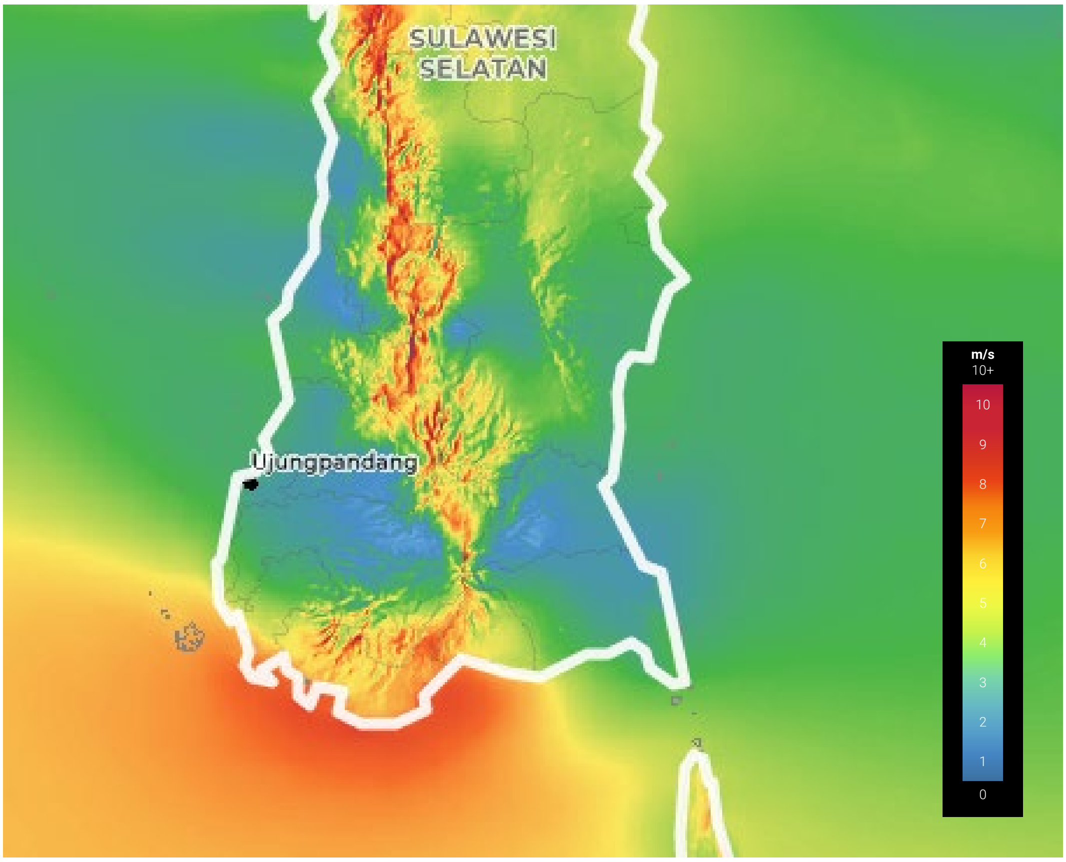


Port example: Balikpapan

Balikpapan is a tanker heavy port located in East Kalimantan, located on the western shore of the Makasar Strait. Tanker vessels are more suited for using combustible fuels. Therefore, powering domestic departures from green hydrogen and green ammonia would be the preferred solution. As the renewable potential around the port of Balikpapan may be limited, the port would benefit from importing electricity or fuels directly from other ports.

This approach could be replicated at other ports in Indonesia that have limited local renewable potential and that focus on domestic travel – and therefore serve smaller ships that are better suited for direct electrification. If supplies of domestically produced green fuels are not feasible, then Balikpapan could, alternatively (or complementarily), establish a supply of sustainable biofuels from waste to supply the demand from vessels departing the port to domestic ports.

Exhibit 18: Wind energy potential on the island of South Sulawesi [40]



Port case study

Port case study three: Decarbonising small fishing and other off-grid boats

While the main populated islands of Indonesia are electrified, islands in the archipelago are unelectrified, particularly in some of the islands distant from Jakarta. Small vessels in these areas, generally made up of small fishing and people carriers, are fuelled using diesel which has to be brought in from elsewhere, impacting costs and increasing emissions.

For small vessels such as these, it is likely that electrification through batteries and motors is the most efficient fuelling approach. For areas that do not currently have access to power, there is the potential to establish small, off-grid renewable energy generation technologies which can be used to power local communities and industries and can also be used to charge small vessels using batteries. This is the most efficient way of powering vessels using renewable electricity and is well suited to small vessels travelling shorter distances.

The two islands with the greatest density of fishing vessels are Sumatra (34.2%) and Java (39.76%) [28]. Many of these vessels – estimated to be more than 700,000 across Indonesia – are not tracked through AIS systems. There is therefore little accurate data for them. However, these vessels contribute a vital role in connecting communities, distributing goods and small scale fishing, so should be considered when designing solutions for these ports and islands.

For small vessels such as these, and those in Sumatra and Java, it is likely that electrification through batteries and motors is the most efficient fuelling approach. For areas that do not currently have access to power, there is the potential to establish small, off-grid renewable energy generation technologies which can be used to not only charge small vessels using batteries, but also to power local communities and industries. This is an efficient and suitable way of powering small vessels which tend to travel shorter distances. The use of off-grid renewables will help reduce the reliance on diesel for off-grid generation and bring electricity to local communities. This approach as well can provide synergies and economies of scale to help communities with access to clean electricity.

There is solar and wind potential in many of Indonesia's coastal locations where generation infrastructure could be installed on a small-scale with minimal environmental impact. Electricity generated from renewables can be fed directly into battery chargers – making the coupling of renewable generation and vessels utilising batteries a favourable combination. The design of the off-grid system will need to take into account increased domestic electricicification and shipping patterns to ensure that power is available at the times when vessels need to be charged without hindering overall electricity access. For example, during the day, vessels are in use and power demand is low, then a solar-based charging infrastructure may not be appropriate, as more fixed power storage could be necessary. It is also possible for vessel batteries to be used as storage for domestic use and charging times could be relatively flexible meaning that generation can be exploited when available.

People-vehicle carriers, fishing, and offshore services account for nearly 42% of total domestic departures but only 28% of total energy demand, indicating that the majority of these journeys are short distances. As Indonesia has a large number of small ports scattered throughout the country, using microgrids to decarbonise small vessels can be trialled first at ports that are co-located with under-electrified remote coastal villages or whose geographical location makes them act as a gateway to multiple locations.

The solution to electrify small vessels across Indonesia will vary between locations and ports. Two example applications are provided below.

Example 1: Ports that are co-located with under-electrified remote coastal villages
The Indonesian government has already announced plans to use mini grids and renewable energy to illuminate eastern provinces such as Papua, West Papua, Maluku, North Maluku, and east and west Nusa Tenggara [29]. Small electrical grids planned for these areas could be designed and located in a way that they could be used for both supplying electricity to local villages and for electrification of small vessels at the port. This could aid in the decarbonisation of shipping while also improving people's access to energy and, therefore, their quality of life.

A similar strategy could then be replicated wherever there is a plan to install a small electrical grid for electrification and a port is nearby. Electrification can also benefit remote coastal villages without ports: if they are on a busy shipping route, a small electrical grid and charging infrastructure can be set up to provide charging services to other ships passing by. It would be a win-win situation for all, as villages will get energy security, vessels will not have to carry large batteries, and it will aid in the development of business models that will allow remote regions to have new sources of income which will incentivise the development of various regions.

Example 2: Islands with a favourable geographical location
Kalimantan province, being located near the centre of Indonesia's islands, serves as a gateway to almost all of the country's other major islands, including Sumatra, Java, and Sulawesi, as well as international destinations such as Singapore. Initially, it makes more sense practically and technically to identify the ports that are relatively close to each other (they could be on the same island or another island), and then identify the ports between which ships make a large number of to-and-fro journeys. With enough land and renewable resource potential to establish a mini grid near these ports, the necessary charging infrastructure can be built on these ports to support the electrification of small shipping vessels. Given the success of this approach, a similar model could be replicated in many other ports and could be scaled up to supply vessels taking long-distance journeys.

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Appendices

Appendix A: Presentation of the assumptions and results of the multi-criteria analysis of zero and low carbon shipping fuels

As part of this project, a multi-criteria analysis was carried out to compare the strengths and weaknesses of various zero and low carbon fuels. This analysis was carried out at a high level to inform the development of the material in the main body of the report, and is not intended to represent a detailed numerical assessment of the fuels. The tables below include the scoring for each criterion and their weighting for each fuel, and lays out the numerical results.

Scores: Criterion 1

Criterion 1: Change to fuel storage volume in comparison with fossil fuels												
Fuels	Bulk carriers large	Bulk carriers small	Tankers large	Tankers small	Containers large	Containers small	People & Veh. Carr. large	People & Veh. Carr. Small	Offshore and Services	Fishing offshore	Small industrial	Small fishing
Green Hydrogen	3	4	3	3	0	4	3	3	3	0	3	3
Green Ammonia	3	3	4	4	4	4	4	0	4	3	0	0
Green Methanol	0	3	4	4	4	4	4	0	4	3	4	4
Blue Hydrogen	3	3	3	3	4	4	4	0	4	0	3	3
Blue Ammonia	3	3	4	4	4	4	4	0	4	3	0	0
Waste-derived Biomethane	3	3	4	4	4	4	4	0	4	3	3	3
Waste-derived Biomethanol	0	3	4	4	4	4	4	0	4	3	3	3
Waste-derived Biodiesel	4	3	4	4	4	4	4	4	4	4	4	4
Batteries	0	0	0	0	0	3	0	0	0	0	4	4

Rating definition

Score	Criterion 1
0	Fuel density is not sufficient (eliminated from analysis)
1	Not used
2	Not used
3	Increase in storage / change to fuelling strategy needed
4	No change required to fuel tanks

Scores: Criteria 2 to 8

	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8
Fuels	Compatibility with existing fuel storage infrastructure	Current state of vessel technologies: Powertrains	Well-to-tank energy efficiency	Environmental accidental release risk	Handling risk: NFPA704	Climate change: Zero carbon	Levelised cost in 2030 accounting for powertrain efficiency
Green Hydrogen	1	2	2	4	1	4	2
Green Ammonia	2	1	2	2	2	4	2
Green Methanol	3	3	1	3	3	4	1
Blue Hydrogen	1	2	3	4	1	0	3
Blue Ammonia	2	1	2	2	2	0	3
Waste-derived Biomethane	3	4	3	3	2	2	3
Waste-derived Biomethanol	3	3	3	3	3	2	2
Waste-derived Biodiesel	4	4	3	1	3	2	2
Batteries	3	3	4	4	4	4	4

Rating definition: Criteria 2 to 8

Score	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8
0	Not used	Not used	Not used	Not used	Not used	Lifecycle emissions > 50% diesel emissions	Not used
1	Needs technology development	Technology is in R&D phase	X <= 50%	Harm is severe and long lasting	NFPA704 health rating 3; flammability rating 4	Not used	X > 100 $/MWh
2	Needs significant changes. Technology is established	Technology is in demonstration phase	50% < X <= 70%	Harm is long lasting	NFPA704 health rating 3; flammability rating ≤3	Lifecycle emissions < 50% diesel emissions; emissions at point of use	60 $/MWh < X <= 100 $/MWh
3	Needs changes. Established technology already in use	Technology is commercially available	70% < X <= 90%	Harm is limited in time or severity	NFPA704 health rating ≤2; flammability rating ≤3	Not used	30 $/MWh < X <= 60 $/MWh
4	Compatible - No changes needed	Technology is widely adopted	X > 90%	Low risk to marine or human life	NFPA704 health rating = 0; flammability rating ≤1	Lifecycle emissions < 50% diesel emissions; no emissions at point of use	X <= 30 $/MWh

Weighting factors

	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8
	Energy density of stored fuel (GJ/m3) including cylindrical tank + insulation for H2 & CH4 insul + equipment for NH3	Compatibility of fuel to existing bunkering infrastructure	Current state of vessel technologies: Powertrains	Well-to-tank energy efficiency	Environmental accidental release risk	Handling risk: NFPA704	Climate change: Zero carbon	Levelised Cost - 2030 prices $/GJ prop (inc. PT efficiency)
Bulk carriers: Large	0.6	0.5	0.7	0.5	0.1	0.1	1	1
Bulk carriers: Small	0.6	0.3	0.5	0.5	0.1	0.2	1	1
Tankers: Large	0.6	0.5	0.7	0.5	0.1	0.1	1	1
Tankers: Small	0.6	0.3	0.5	0.5	0.1	0.2	1	1
Containers: Large	0.6	0.8	0.7	0.5	0.1	0.1	1	1
Containers: Small	0.6	0.8	0.7	0.5	0.1	0.1	1	1
People & Vehicle Carriers: Large	0.6	0.3	0.7	0.5	0.1	0.2	1	1
People & Vehicle Carriers: Small	0.6	0.3	0.5	0.5	0.1	0.5	1	1
Offshore and Services	0.6	0.3	0.3	0.5	0.1	0.5	1	0.5
Fishing	0.6	0.5	0.5	0.5	0.1	0.5	1	0.8
Small boats: Industrial	0.6	1	1	0.5	0.1	1	1	0.8
Small boats: Fishing / Small	0.6	1	1	0.5	0.1	1	1	0.8

Scores were calculated as the product of the rating and the weighting factors for each technology and type of vessel. Rankings were then assigned to each one in descending order according to these final scores (with highest scores coming in first in the ranking order). This way, the analysis prioritises the technologies that impact the most important criterion for each type of vessel.

Ranking outcome (Bulk carriers, Tankers and Containers)

	Bulk carriers		Tankers		Containers	
Fuels	**Large**	**Small**	**Large**	**Small**	**Large**	**Small**
Green/Blue Hydrogen	3	4	5	5	N/A	5
Green/Blue Ammonia	4	5	4	4	4	5
Green Methanol	N/A	6	6	6	5	7
Waste-derived Biomethane	1	1	1	1	1	2
Waste-derived Biomethanol	N/A	3	3	3	3	4
Waste-derived Biodiesel	1	2	2	2	2	3
Batteries	N/A	N/A	N/A	N/A	N/A	1

Ranking outcome (People & Vehicle Carriers, Offshore and Services, Fishing and Small boats)

	People & Vehicle Carriers		Offshore and Services	Fishing	Small boats	
Fuels	**Large**	**Small**			**Industrial**	**Fishing/Small**
Green/Blue Hydrogen	5	2	6	N/A	6	6
Green/Blue Ammonia	4	N/A	4	4	N/A	N/A
Green Methanol	6	N/A	5	5	5	5
Waste-derived Biomethane	1	N/A	2	2	3	3
Waste-derived Biomethanol	3	N/A	3	3	4	4
Waste-derived Biodiesel	2	1	1	1	2	2
Batteries	N/A	N/A	N/A	N/A	1	1

The multi-criteria analysis shows that batteries are the preferred zero carbon propulsion technology for applications that are feasible given the low energy density (infeasible options are marked with N/A). This is due to high efficiencies in using renewable energy in batteries and motors. The analysis also shows that all vessels applications could adopt either green hydrogen or ammonia, with some being suited to both. Due to their high energy density and technological maturity, biofuels from waste generally score well. As described in the main body of this report, biofuels must use feedstocks that are sustainable and environmentally sensitive, and such sources are generally constrained and difficult to scale. Therefore, it is not expected that biofuels will form a significant part of low carbon fuel provision for the shipping sector.

As detailed in Section 1 of this report, methanol and blue fuels were removed from the rest of the project for broader reasons, but are shown here for comparison.

Appendix B: Comparison of safety and environmental hazards for selected marine fuels

	Marine Gas Oil	Liquefied Natural Gas	Methanol	Hydrogen (Liquid)	Ammonia (Liquid)
Physical Hazards					
Flammability	Cat. 3 H226 Flammable liquid and vapour	Cat. 1 H220 Extremely flammable gas	Cat. 2 H225 Highly flammable liquid and gas	Cat. 1 H220 Extremely flammable gas	Cat. 2 H221 Flammable gas
Gas under pressure	Not classified	H281 Contains refrigerated gas; may cause cryogenic burns or injury	Not classified	H281 Contains refrigerated gas; may cause cryogenic burns or injury	H280 Contains gas under pressure; may explode if heated
Health Hazards					
Acute toxicity	Cat. 4 H332 Harmful if inhaled	Not classified	Cat. 3 H301 H311 H331 Toxic if swallowed, in contact with skin, or inhaled	Not classified	Cat. 3 H331 Toxic if inhaled
Aspiration hazard	Cat. 1 H304 May be fatal if swallowed and enters airways	Not classified	Not classified	Not classified	Not classified
Skin corrosion	Cat. 2 H315 Causes skin irritation	Not classified	Not classified	Not classified	Cat 1/1B H314 H318 Causes severe skin burns and serious eye damage
Carcinogenicity	Cat. 2 H350 May cause cancer	Not classified	Not classified	Not classified	Not classified
Specific target organ toxicity	Cat. 2 H373 May cause damage to organs through prolonged or repeated exposure	Not classified	Cat. 1 H370 Causes damage to organs (single exposure)	Not classified	Not classified
Environmental Hazards					
Hazards to the aquatic environment	Category 2 (chronic): Toxic to aquatic life with long lasting effect (H411)	Not classified	Not classified	Not classified	Category 1 (Acute): Very toxic to aquatic life with long lasting effects (H400)
Summary					
Summary (US NFPA704)	2, 1, 0	4, 3, 0	3, 1, 0	4, 3, 0, CRYO	1, 3, 0

Source: Sailing on Solar [1]

Biofuels are assumed to have similar properties to conventional liquid and gaseous fossil fuel based marine fuels.

Appendix C: Vessel category definitions

Category	Size	Length (m)	Number of vessels globally	Capacity	IMO ship types
Bulk carriers	Large	195+	5308	>60,000DWT	Bulk carrier (such as grains, coal, ore, steel coils and cement), Refrigerated bulk and General cargo
	Small	75-195	15410	<60,000DWT	
Tankers	Large	195+	3571	>60,000DWT	Liquefied gas tanker, Oil tanker, Other liquids tankers and Chemical tanker
	Small	75-195	9312	>60,000DWT	
Containers	Large	260+	1554	>5,000TEU	Container ships: Small feeder and river vessels through to Panamax and Ultra Large Container Vessel.
	Small	125-260	3604	<5,000TEU	
People and Vehicle Carriers	Large	120-360	1306	Varies by type	Cruise, Ferry: Roll-on-Roll-off (passenger), Roll-on-Roll-off (cargo), Yacht, Vehicle and passenger-only ferry
	Small	30-205	5725	Varies by type	
Offshore and Services	–	30-290	14264	Varies by type	Offshore (oil/gas and windfarm service & supply), Service, Tug, Bunker, Miscellaneous
Fishing	–	5-145	8220	Varies by type	Fishing: Inshore to ocean

Source: Ricardo analysis and discussions with University College London [41]

Appendix D: Electricity demand for zero carbon propulsion in 2030

Input assumptions - Demand

Description	Value
Shipping demand growth 2018 - 2030	2%
Energy efficiency improvement 2018 - 2030	1.2%
Uptake of zero/low carbon fuels in 2030	5%
IDR/USD exchange rate	14,418
Costs indexed to this year	2020

Input assumptions - Renewables supply

Technology	Assumed contribution	Capacity factor	Installed cost USDm/MW in 2030 low case	high case
Solar PV	23%	0.23	0.40	0.60
CSP	12%	0.39	1.89	2.84
Onshore wind	50%	0.3	0.93	1.40
Offshore wind	15%	0.45	1.53	2.30
References			IRENA (2021) Global Trends for 2018 costs, reduction to 2030 as per IRENA (2020) "Global Renewables Outlook" (p60)	

Fuel/storage data from MCA

Fuel type	Powertrain tech	Powertrain efficiency	Well-to-tank efficiency	Production plant annual operating hours	Notes
Battery	Electric motor	90%	95%	8,760	
Biodiesel (Waste-derived)	ICE - Compression	50%	80%	7,446	
Biomethane (Waste-derived)	ICE - Spark	40%	100%	7,446	
Biomethanol (Waste-derived)	ICE - Spark	40%	77%	7,446	
Fossil fuel	ICE - Compression	50%	N/A	8,000	
Green Ammonia	ICE - Compression	50%	56%	8,000	
Green Hydrogen	ICE - Compression	50%	56%	8,000	Incl. liquefication
Green Methanol	ICE - Spark	40%	43%	8,000	

Calculated energy requirements

Vessel category	Preferred fuel/ storage from MCA	Powertrain tech	Fossil fuel energy demand 2018	Fossil fuel energy demand 2030	Zero/low carbon fuel energy demand 2030, 100% uptake	Zero/low carbon fuel energy demand 2030, 1% assumed uptake	Zero/low carbon fuel energy demand 2030, 5% assumed uptake	Renewable electricity requirement 2030, 100% assumed uptake	Renewable electricity requirement 2030, 1% assumed uptake	Renewable electricity requirement 2030, 5% assumed uptake
			GWh/y	GWh/y	GWh/y	GWh/y	GWh/y	GWh/y	GWh/y	GWh/y
Bulk carriers: Large	Green Ammonia	ICE - Compression	14,770	16,288	16,288	163	814	29,086	291	1,454
Bulk carriers: Small	Green Hydrogen	ICE - Compression	13,405	14,782	14,782	148	739	26,397	264	1,320
Tankers: Large	Green Ammonia	ICE - Compression	20,079	22,143	22,143	221	1,107	39,540	395	1,977
Tankers: Small	Green Ammonia	ICE - Compression	11,977	13,207	13,207	132	660	23,585	236	1,179
Containers: Large	Green Ammonia	ICE - Compression	572	630	630	6	32	1,126	11	56
Containers: Small	Battery	Electric motor	8,060	8,888	4,938	49	247	5,198	52	260
People & Veh. Carr: Large	Green Ammonia	ICE - Compression	959	1,057	1,057	11	53	1,888	19	94
People & Veh. Carr: Small	Green Hydrogen	ICE - Compression	4,838	5,336	5,336	53	267	9,528	95	476
Offshore and Services	Green Ammonia	ICE - Compression	2,300	2,536	2,536	25	127	4,529	45	226
Fishing	Green Ammonia	ICE - Compression	216	238	238	2	12	426	4	21
Small boats: Industrial	Battery	Electric motor	31,192	34,397	19,110	191	955	20,115	201	1,006
Small boats: Fishing / Small	Battery	Electric motor	6,364	7,018	3,899	39	195	4,104	41	205
Grand total			**114,731**	**126,521**	**104,164**	**1,042**	**5,208**	**165,520**	**1,655**	**8,276**
Total - Battery					**27,946**	**279**	**1,397**	**29,417**	**294**	**1,471**
Total - Green Ammonia					**56,100**	**561**	**2,805**	**100,179**	**1,002**	**5,009**
Total - Green Hydrogen					**20,118**	**201**	**1,006**	**35,925**	**359**	**1,796**

Inputs for calculation of investment potential - Fuel production & delivery (Low case in 2030)

Fuel type	Annual electricity requirement	Production plant operational hours per year	Aggregate electrical capacity requirement	Fuel production & delivery infrastructure investment cost per MW capacity	Fuel production & delivery infrastructure investment cost	Fuel production & delivery infrastructure investment cost
	GWh/y	hours/y	MW	USDm/MW capacity	USDm	IDRm
Battery	1,471	8760	168	0.15	25	363,130
Green Ammonia	5,009	8000	626	1.58	989	14,263,191
Green Hydrogen	1,796	8000	225	1.61	361	5,211,975
Total	**8,276**		**1,019**		**1,376**	**19,838,296**

Inputs for calculation of investment potential - Renewable plants (Low case in 2030)

Fuel type	Annual electricity produced	Installed capacity	Investment cost - Renewables plants	Investment cost - Renewables plants
	GWh/y	MW	USDm	IDRm
Solar PV	5,379	2,670	1,077	15,521,295
Hydropower	1,241	363	316	4,557,932
Onshore wind	414	157	146	2,111,318
Geothermal	1,241	177	266	3,834,085
Total	**8,276**	**3,368**	**1,805**	**26,024,630**

Inputs for calculation of investment potential - Fuel production & delivery (High case in 2030)

Fuel type	Annual electricity requirement	Production plant operational hours per year	Aggregate electrical capacity requirement	Fuel production & delivery infrastructure investment cost per MW capacity	Fuel production & delivery infrastructure investment cost	Fuel production & delivery infrastructure investment cost
	GWh/y	hours/y	MW	USDm/MW capacity	USDm	IDRm
Battery	1,471	8760	168	0.28	47	677,843
Green Ammonia	5,009	8000	626	2.10	1,315	18,957,405
Green Hydrogen	1,796	8000	225	2.07	465	6,701,111
Total	**8,276**		**1,019**		**1,827**	**26,336,360**

Inputs for calculation of investment potential - Renewable plants (High case in 2030)

Fuel type	Annual electricity produced	Installed capacity	Investment cost - Renewables plants	Investment cost - Renewables plants
	GWh/y	MW	USDm	IDRm
Solar PV	5,379	2,670	1,615	23,281,943
Hydropower	1,241	363	474	6,836,898
Onshore wind	414	157	220	3,166,977
Geothermal	1,241	177	399	5,751,128
Total	**8,276**	**3,368**	**2,708**	**39,036,945**

Summary of investment potential

	Low case	High case
	IDRm	IDRm
Fuel production & delivery	19,838,296	26,336,360
Renewable plants	26,024,630	39,036,945
Total	**45,862,927**	**65,373,305**

Appendix E: Lifecycle greenhouse gas emissions of blue fuels

As described in Section 1, blue hydrogen is a commonly accepted term for the production of hydrogen using the steam methane reforming (SMR) process where some of the carbon dioxide emissions are captured and prevented from going to atmosphere. Blue hydrogen and its derivative, blue ammonia, could play an important role in the decarbonisation of shipping. It has the advantage of being cheaper to produce than green hydrogen in most jurisdictions based on current costs of natural gas (for blue hydrogen) and renewables (for green hydrogen) [30].

The lifecycle greenhouse gas (GHG) emissions of blue hydrogen are an important consideration when assessing its potential as a low carbon shipping fuel.
Current carbon capture technologies do not capture 100% of the carbon dioxide emitted from the SMR plant. In addition, there are GHG emissions to consider in the natural gas supply chain as well as the process where the captured carbon dioxide is transported and stored. EDF and UMAS [31] have suggested that the lifecycle GHG emissions of alternative shipping fuels should be at least 50% less than the lifecycle of emissions of conventional fuels. Therefore, a minimum reduction of 50% compared to diesel is a useful yardstick for assessing the suitability of blue fuels as low carbon options for the shipping sector.

The Greenhouse Gas Protocol (GHGP) is used by some governments (including the UK government) and companies as an independent standard for reporting GHG emissions. It will be used in this appendix for the assessment of the lifecycle GHG emissions of blue hydrogen and diesel. The GHGP divides emissions into 3 separate scopes, where each scope considers a different aspect of the supply chain. These have been applied for the analysis of blue hydrogen and diesel below.

	Description	Diesel	Blue hydrogen
Scope 1	Direct emissions at point of use	GHG emissions from ship's engine	GHG emissions from the SMR plant There are no GHG emissions when blue hydrogen is used for vessel propulsion)
Scope 2	Indirect emissions from purchased electricity or heat	Not applicable	GHG emissions associated with electricity consumed by the SMR plant
Scope 3	Value chain emissions including feedstocks	GHG emissions in the diesel supply chain	GHG emissions in the natural gas supply chain and the process of transporting and storing captured carbon dioxide

The Scope 1 emissions for diesel are given in the UK Government GHG Conversion Factors for Company Reporting 2020 [32] as 0.27 kg CO_2e/kWh[1].The scope 1 emissions for blue hydrogen are calculated based on the amount of natural gas consumed by the SMR plant, which depends on the design of the plant (i.e. its conversion efficiency).

1 In this appendix, unless otherwise indicated, all units referring to fuel energy content are quoted on the basis of lower heating value (net calorific value)

A report by IEAGHG [33] provides a useful overview of different plant designs and will be used as the basis for the analysis here. The conversion efficiency of the plant is dependent on the carbon capture technology because it generally requires more energy to increase the proportion of carbon dioxide that is captured.

There are currently a small number of carbon capture projects around the world that have been demonstrated at industrial scale. Most of these have been used in the fossil power generation sector. Projects have generally struggled to achieve the capture rates that were intended in the design phase, with a notable example in Canada reducing its target capture rate to 65% after a few years of operation, having aimed for 90% when the plant was designed and built [34]. Thus, the cases analysed for SMR will assume capture rates of about 60% as this is representative of the current state of technology. Design cases 1A and 1B in the IEAGHG report have capture rates of 55.7% and 66.9% respectively, which will be used as low and high cases. Based on these capture rates, the carbon emissions were calculated as 4.41 and 3.47 kg CO_2e/kg hydrogen for case 1A and 1B respectively. Based on energy content8 these are equal to 0.13 and 0.10 kg CO_2e/kWh hydrogen.

Scope 2 emissions are not applicable to either of the IEAGHG cases because the plants would export electricity rather than import it.

According to SimaPro lifecycle analysis software, the global average scope 3 emissions for diesel are 0.49 kg CO_2e/kg, which is equivalent to 0.041 kg CO_2e/kWh[2].

There is a wide range of estimates for the scope 3 emissions from natural gas, reflecting a variety of extraction methods and jurisdictions (some with stringent regulations regarding emissions and others with laxer regulations). Balcombe et. al. [35] conducted a wide review of the emissions factors from the natural gas supply chain published in a range of literature from around the world. Based on their review of the evidence, they proposed a representative range of 0.0031 to 0.038 kg CO_2e/MJ HHV10 without liquefication, increasing to 0.007 to 0.058 kg CO_2e/MJ HHV if liquefication was involved. Conversion of these figures gives a range of scope 3 emissions of 0.013 to 0.16 kg CO_2e/kWh natural gas (0.03 to 0.25 kg CO_2e/kWh if the natural gas is liquefied and regasified).

For case 1A where the thermal efficiency is 73.5%, this results in a scope 3 range for hydrogen of 0.017 to 0.21 kg CO_2e/kWh; whereas for case 1B where the thermal efficiency is 69.7%, the scope 3 range is 0.018 to 0.22 kg CO_2e/kWh hydrogen. These ranges assume that the natural gas is not liquefied; if it is, then the scope 3 emissions increase accordingly.

The table below summarises these results where the natural gas is not liquefied for transport and regasified for use.

Blue hydrogen low emissions case (1B)	Diesel	Blue hydrogen low emissions case (1B)	Blue hydrogen high emissions case (1A)
Scope 1	0.27	0.10	0.13
Scope 3	0.041	0.018	0.21
Total	0.31	0.12	0.34

2 Lower heating value of hydrogen = 33.3 kWh/kg

The table below summarises the equivalent results but for the case where the natural gas is liquefied for transport and regasified for use.

kg CO_2e/kWh hydrogen	Diesel	Blue hydrogen low emissions case (1B)	Blue hydrogen high emissions case (1A)
Scope 1	0.27	0.10	0.13
Scope 3	0.041	0.04	0.32
Total	0.31	0.14	0.45

Therefore, based on the analysis above, the lifecycle emissions of blue hydrogen are between 39% and 110% of the lifecycle emissions of diesel, depending on the design of the SMR plant and the natural gas supply chain. This rises to 45% to 145% if the natural gas supply chain involves liquefication and regasification, which is typical if it is imported.

These ranges are mostly in excess of the emissions reduction threshold of 50% mentioned above. Furthermore, it should be noted that the analysis above does not include the GHG emissions associated with the compression, transport and storage of the captured carbon dioxide to ensure that it does not eventually escape to the atmosphere.

If the capture technology was improved and demonstrated to achieve capture rates of 90% at industrial scale, then the scope 1 emissions would be in the order of 0.03 kg CO_2e/kWh (Case 3 in [33]). Assuming the median scope 3 emissions excluding natural gas liquefaction from [35] (0.015 kg CO_2e/MJ HHV), the total lifecycle emissions for the 90% capture case would be 0.12 kg CO_2e/kWh hydrogen. This is 39% of the diesel lifecycle emissions. For the equivalent case where liquefied natural gas is used with a capture rate of 90%, the lifecycle emissions are 0.17 kg CO_2e/kWh hydrogen (55% of diesel). Again, these estimates exclude the emissions associated with compressing, transporting and storing the captured carbon dioxide.

For comparison in the UK context, the UK's Committee for Climate Change [30] provides a range of 0.05 to 0.12 kg CO_2e/kWh hydrogen assuming capture rate of 95% and Sadler et al [31] calculates a median value of 0.13 kg CO_2e/kWh based on a 90% capture rate.

This analysis indicates that with improvements in technology, it is possible for blue hydrogen to meet the emissions reduction threshold of 50% in the future, provided the following conditions are met:

i. Consistently high capture rates in the order of 90% have been demonstrated in practice at industrial scale;
ii. Effective regulations and monitoring are in place to ensure that emissions from the natural gas supply chain are within acceptable limits; and
iii. The emissions associated with the handling, transport and storage of the captured carbon dioxide are included in the accounting.

The multicriteria analysis in Appendix A reflects the reality that these preconditions have not yet been met.

Appendix F: Process summaries for various biofuel production processes

Biodiesel	Bioethanol	Bio-oil	Bio-methane
Predominant point of emissions occurs when fuel is burnt. Biodiesel can include FAME, syn-diesel and HVO if combined with hydrogen	Predominant point of emissions occurs when fuel is burnt, however, CO_2 is a by-product of fermentation, with significant energy required for distillation	Predominant point of emissions occurs when fuel is burnt. If pyrogas is emitted to atmosphere it could contribute to life-cycle emissions.	LNG from digestion would mainly emit at combustion, however, emissions during digestion and supply chain could contribute to life cycle emissions.
Feedstock	**Feedstock**	**Feedstock**	**Feedstock**
Palm oil, oil crops, cooking oil	Crops and crop residues (novel)	Various types	High moisture content biomass
Process Transesterification TRL9	**Process** Fermentation TRL8	**Process** Flash pyrolysis TRL9	**Process** Anaerobic digestion TRL9
Oil is mixed with alcohol (methanol) and a strong base (e.g. NaOH) to form a mixture which is purified to biodiesel. Glycerol is a by-product of the process.	The feedstock is milled and processed, requiring a significant amount of water. The broth is fermented using yeast and bacteria. The fermented solution is distilled to produce bioethanol.	Biomass is pre-treated with steam and thereafter reacted in an endothermic environment with minimal oxygen. The product is quenched to form prygas and bio-oil, char is also recovered.	Biomass is produced in a pH controlled biodigester, containing bacteria. The produced methane from the reaction is stored for use.Alernatively syngas can be produced from woody biomass.
Biodiesel	**Bioethanol**	**Bio-oil**	**Bio-methane**
Similar characteristics to conventional diesel - suitable as a "drop-in" shipping fuel for small diesel engine.	Could be used as a replacement for gasoline, for power generation or cooking. Limited applications for the shipping sector.	Requires further processing to produce bio-crude, which can be used for power generation or processed to produce other synthetic hydrocarbons .	Bio-methane can be stored as compressed natural gas or liquefied natural gas and used for shipping in suitable engines.

About the Getting to Zero Coalition

The Getting to Zero Coalition is an industry-led platform for collaboration that brings together leading stakeholders from across the maritime and fuels value chains, financial sector and others committed to making commercially viable zero emission vessels a scalable reality by 2030.

Learn more at:
www.globalmaritimeforum.org/getting-to-zero-coalition