Mexico: fuelling the future of shipping

Mexico's role in the transformation of global shipping through green hydrogen-derived fuels

Revised

By Ricardo
& Environmental Defense Fund

For the
P4G Getting to Zero Coalition Partnership

Table of Contents

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 decarbonization 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.

About the Global Maritime Forum

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.

About Friends of Ocean Action

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.

About Environmental Defense Fund

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.

About University College London

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 Harbours

The International Association of Ports and Habours (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).

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. It was commissioned by Aoife O'Leary, Marie Cabbia Hubatova and Panos Spiliotis of EDF Europe and the authors are grateful for their input through the course of its production. The authors and EDF would like to thank 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), Ingrid Sidenvall Jegou (Global Maritime Forum), Emma Skov Christiansen (World Economic Forum), Ned Molloy (Global Strategic Communications Council).

The Steering Committee also provided valuable contributions through the course of the project: Abel Lopez Dodero (World Bank), Adela Olano Roche (CEMEX), Ana Lepure (Mexico Consultant, Energy Efficiency), Edna Rosas Huerta (Universidad Veracruzana, campus Veracruz, Marine Engineering Department), Erick Rosas Lopez and Claudia Alejandra Octaviano Villasana (Instituto Nacional de Ecología y Cambio Climático (INECC)), Gildardo Alarcón Daowz (Secretaría de Marina; Unidad de Capitanías de Puerto y Asuntos Marítimos (UNICAPAM-SEMAR)), Heberto Barrios Castillo (Dirección General de Asuntos Internacionales de la Secretaría de Energía (SENER)), Israel Hurtado (Mexican Hydrogen Association), Jacobo Mekler Waisburd (Mexican Hydro Power Association (AMEXHIDRO)), José Manuel Becerra Pérez (Comisión de Energía del Consejo Coordinador Empresarial), Lucia Shaw (Asuntos Internacionales y Relaciones Institucionales (Consejo Coordinador Empresarial)), Luis A. Sarrás (AES South America Luisa Sierra Iniciativa Climatica de Mexico), Marco Jano Ito (Mario Molina Center for Strategic Studies on Energy and the Environment), Nelson Mojarro (Government Clean Energy R&D), Norma Patricia Muñoz Sevilla (Interdisciplinary Center for Research and Studies in Environment and Development), Ricardo Sanchez (UN Economic Commission for Latin America and the Caribbean (ECLAC)), Sergio Silva Castañeda (Secretaría de Economía), Sheila Guadalupe Cadena Nieto and David Mora Fonz (Ministry of Energy Development Tabasco), Tomas Baeza and Antoine Millet (ENGIE)

Disclaimer

This report is based on analysis by Ricardo Energy and 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

With abundant renewable energy potential and access to busy shipping routes, Mexico is perfectly placed to build a valuable zero carbon shipping fuels sector. This includes production of zero carbon fuels from renewable electricity, supplying shipping vessels that visit Mexican ports, and potentially exporting the fuels as a valuable commodity on the global market. This new zero carbon fuels sector would have benefits far beyond shipping; it could also improve energy security by harnessing local resources, help catalyse the low carbon economy in Mexico by supporting decarbonization of other sectors and creating a wide range of jobs.

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 and blue hydrogen, green and blue ammonia, green methanol, biofuels and battery power. This study investigates the most suitable propulsion solutions for different commercial vessels based on a number of criteria. The abundance of renewable energy resources in Mexico means that shipping fuels can be derived from renewable electricity generation. This study has identified that the most suitable options for the ports assessed in Mexico are hydrogen and ammonia for large commercial vessels such as tankers, containers and bulk carriers (and even tugboats); while small vessels such as port service vessels can be supplied through electrification.

The decarbonization of the shipping sector is complimentary to Mexico's ambitions to reduce carbon emissions

Mexico has an abundance of renewable energy potential - enough to supply its domestic electrical demand as well as production of zero carbon fuels to supply commercial vessels bunkering in its ports. Mexico has committed to reduce GHG emissions by 22% below business as usual by 2030 and by 50% (relative to 2000) by 2050. Adopting zero carbon fuels in its shipping sector could act as a catalyst to achieving the country's overall carbon commitments; developing renewable generation supply chains, skills and economies of scale which support wider adoption of the technologies. Fuels may also be used in wider industries such as in the production of fertiliser, ammonia and steel production for domestic use and export. With appropriate economy-wide energy, investment and environmental planning, development of the zero carbon shipping fuel sector and its infrastructure can support wider decarbonization goals and alleviate local pain points such as energy security. Areas with low energy security and a high dependency on imports of either fossil fuels or electricity can benefit greatly from locally-deployed renewables that reduce this reliance on outside sources, and from locally producing electrofuels that could be stored for later use, increasing security of supply. In the future, benefits like these could be harnessed in areas such as Baja California, with potential spill-over benefits for the good of the environment and local economies and communities.

It's safe to use zero carbon shipping fuels with proper regulations and training

Some have raised concerns regarding the health, safety and environmental risks of zero carbon fuels. However, this should not be seen as a major barrier for adoption of these fuels; fuels used today have significant associated risks, so codes, best practices and standards have been developed over years of expertise allowing us to use them widely and safely in a variety of applications, environments, and conditions. Recent developments and projects involving their transport and storage also paint an optimistic picture on the possibility of safely handling large volumes of hydrogen, potentially even leveraging on the extensive pipeline infrastructure present in the country [1] [2]. The same can be done for green hydrogen and ammonia. These fuels have a different set of risks that can be mitigated and managed properly, and there is already handling and storage experience in Mexico and globally. This challenge will need to be addressed by the industry moving forward.

Mexico has strong trading relationships across South America and North America, as well as all over the world

Mexico has established itself as a major trading hub between North and South America and has capitalised on its access to the Pacific and Atlantic Oceans, which gives it access to Asian markets as well as access into Europe and Africa. Mexico is the second largest economy in Latin America and 15th largest in the world. Its participation in the U.S.-Mexico-Canada Agreement (USMCA) and the Southern Common Market (MERCOSUR) further strengthens its market opportunities and trading relationships. These factors mean that Mexico is in a good position to drive the zero carbon fuel market and supply a growing global demand.

By moving early, Mexico can set the trend for electrofuel adoption and position itself as a key part of global zero carbon shipping routes

International vessels adopting zero carbon fuel bunkering (supplying of fuel for use by ships) must have the opportunity to refuel along their journey, using fuels and the appropriate bunkering technologies that are compatible with the requirements of the vessel. Therefore, to an extent, there must be coordination with the global shipping sector so as to ensure the availability of both fuels and infrastructure, and standards must be set by the maritime industry to encourage the zero carbon transition of both vessels and ports. Mexico 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, given the crucial location of its ports.

Port Case Studies

This report highlights the Ports of Manzanillo, Cozumel and Coatzacoalcos, three great examples of how different types of ports in Mexico could capitalise on a zero carbon transition: large commercial ports handling a significant amount of Mexico's import and export goods (Manzanillo), Mexico's smaller ports with less traffic and smaller vessels (Cozumel), and ports with existing production industries and exporting capabilities (Coatzacoalcos). These port profiles exemplify a significant number of ports across Mexico, and cover a range of potential use cases and benefits, allowing Mexico to meet its decarbonization targets as well as diversifying existing port activities such as industry and tourism and creating a hub for producing and exporting zero carbon fuels.

Adoption of zero carbon propulsion technologies at Mexico's ports could attract investment of 36.7 - 52.8 billion pesos in onshore infrastructure by 2030.

Glossary

AIS	Automatic Identification System
CCS	Carbon Capture and Storage
CFE	Federal Electricity Commission
CSP	Concentrated Solar Power
EDF	Environmental Defense Fund
GHG	Greenhouse Gas
GHGP	Greenhouse Gas Protocol
GtZ	Getting to Zero Coalition
ICE	Internal Combustion Engine
IGF	International Code of Safety for Ships using Gases
IMO	International Maritime Organization
MARPOL	International Convention for the Prevention of Pollution from Ships
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
UNFCCC	United Nations Framework Convention on Climate Change

Introduction

Decarbonization of shipping could catalyse investment and wider climate action in Mexico

The adoption of zero carbon shipping fuels has significant benefits and synergies for Mexico 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 carbon shipping fuels through the shipping sector of Mexico. This work has an important global relevance, as the shipping sector pushes to decarbonize. The International Maritime Organization (IMO), as the regulatory body for international shipping, has a target to cut GHG emissions by 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? [3], and Electrofuels for shipping: How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile [4].

The analysis in this report takes into consideration Mexico'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 Mexico. It has included insight and input from a Steering Committee formed to support the P4G-Getting to Zero Coalition Partnership.

Mexico has historically depended on fossil fuels as primary sources of energy for the country. Natural gas alone accounted for nearly 40% of the national energy supply mix in 2019, while solar PV and wind combined contributed only 3% [5]. Moving forward, however, the picture might change as Mexico has legally set renewable and decarbonization targets that it is well-equipped to achieve. These include reducing GHG emissions by 22% below business as usual by 2030, 35% renewables by 2024 and an overall 50% GHG emission reduction by 2050 [7].

The country has a wealth of available natural resources [8] that can be channelled to not only decarbonize electricity generation, but also to produce electrofuels such as hydrogen and ammonia that could help decarbonize other sectors and applications such as industry, which makes up over 30% of the country's Gross Domestic Product (GDP) [9]. Hydrogen is already consumed in Mexico in oil refining and the iron and steel industries. With the decline of oil reserves and onshore wells, alongside the high cost of offshore extraction, Mexico has already began looking at new sources of primary energy sources. The Mexican hydrogen group Asociación Mexicana de Hidrógeno (AMH), formed in 2021, brings together energy companies, energy trade groups and agencies. Their aim is to develop a national hydrogen plan [10].

Benefits and synergies for Mexico beyond shipping

The adoption of zero carbon shipping fuels is a direct route to decarbonizing the shipping sector. However, it also has significant benefits and synergies for Mexico 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. **Development of a new export commodity** which would position Mexico to feed into a growing global demand for "green" products.

3. **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 decarbonization of the wider electricity sector.

4. **Increase energy security and independency** by harnessing local renewable resources for both electricity and synthetic fuel production.

5. **Availability of zero carbon fuels** that can be used to decarbonize other sectors in Mexico, such as heavy transport, mining, agriculture, manufacturing and the country's extensive iron ore industries.

6. **Reducing air pollution**, especially around port-centred cities that are often highly urbanised or experience high levels of tourism.

7. **Preservation of local ecosystems** that are not only essential in themselves but that are also often at the heart of tourism-centred local economies across the country.

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 concentrates on zero 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, downsides and considerations that need to be considered when selecting a fuel and when developing the bunkering infrastructure. This report focuses on zero carbon fuels and propulsion solutions that 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. Locally producing these fuels can be a key element in ensuring these conditions, as it would help prevent losses and leakage, as well as any adverse health or climate effects associated with them.

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

	PROCESSING	ENERGY DENSITY
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 other fuels, meaning they are currently only suitable for smaller vessels travelling short distances.	Less processing, resulting in lower losses and costs.	Less energy dense; not suited to large ships undertaking long journeys.
Green Hydrogen Green hydrogen is produced using electrolysers powered by renewable electricity. The production process is energy intensive. Storage of hydrogen can be challenging due to its low density: it can be stored as a compressed gas in high pressure tanks or as a liquid at around -253°C. 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.	More processes required, requiring additional resources and inputs.	More energy dense; able to support larger ships undertaking longer journeys.

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, as results from the multi-criteria analysis outlined in more detail in Appendix A indicate.

Biofuels

Biofuels can be produced from a variety of feedstocks including energy crops or agricultural and municipal 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 their use for shipping as there are limited sustainable and environmentally sensitive feedstocks. Furthermore, the abundance of renewable resources in Mexico indicates that hydrogen-derived fuels would be better suited.

Blue Hydrogen and Ammonia

Hydrogen can be produced from fossil fuels, which includes 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 green fuels as 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.

Section 2

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

As with fossil based marine fuels, the handling of zero carbon fuels, including green hydrogen and ammonia, requires proper industry regulations and training in order to be carried out safely avoiding harm to people and the environment. While this area is still in development, extending codes as the IMO's IGF (International Code of Safety for Ships using Gases) can prove crucial in enabling the secure adoption of these fuels in the marine industry. A full hazard table is included in Appendix B.

Exhibit 2: Summary of main hazards and implications for handling zero emission marine fuels.

	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.	• Ensure that tanks 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.	• As a globally traded commodity there are existing regulations for the storage and handling of ammonia on ships. • Ensure that tanks are in good condition, leaks are prevented, and gas cannot collect in confined spaces. • Safe handling requires appropriate PPE.
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.

Battery and charging infrastructure have been proven for road transport and they are being deployed rapidly in many countries. Onshore power supply in ports is already being deployed to reduce emissions from auxiliary power systems for some vessels.

Hydrogen and ammonia are well understood in industrial applications with associated regulations, standards and codes of practice. Special attention should also be given to prevent leakage along the hydrogen supply chain, yet this and other concerns can be addressed through regulation and the building of best practices. Modifications to the regulations and codes governing fuel use in maritime applications will be required and are already in development. Furthermore, hydrogen is already consumed in Mexico in oil refining, iron and steel industries. The largest consumer of hydrogen in Mexico is Petróleos Mexicanos (PEMEX) which is produced by third parties as a secondary product of other chemicals and in dedicated facilities as well [11] [12].

Ammonia is already used in Mexico's agriculture sector, which is mainly imported to the country, which means that the handling and transport of ammonia is already well understood. PEMEX is looking at developing strong domestic nitrogen production for agriculture from natural gas [13], which might create important expertise and know-how around the handling of ammonia, although at a high environmental cost due to high emissions. This could, however, open the door for local green fertiliser production using green hydrogen and green ammonia, and for the safe handling of them for other purposes.

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 [14, 15, 16, 17]. 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. International collaboration and commitments such as the IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) can also become great opportunities for Mexico to propel the adoption of new low-carbon fuels in both a clean and safe manner.

Section 3

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

While decarbonizing the shipping sector can be challenging, ambitious goals have been set towards this goal: the IMO has set a target of reducing emissions by at least 50% by 2050 (relative to 2008 levels) and, more recently, it was announced that the IMO will start working with governments towards a more ambitious target of fully decarbonizing the sector within that same timeframe. The widespread adoption of electrofuels will likely play a major role in achieving these targets. To achieve this, two important challenges will require addressing, both on a local and a global scale: their production based on local needs and resources, and their safe storing, transport and use, so as to prevent leakage and minimise risks.

The choice of zero carbon shipping fuels for vessels bunkering in Mexico is dependent on a range of factors, including 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.

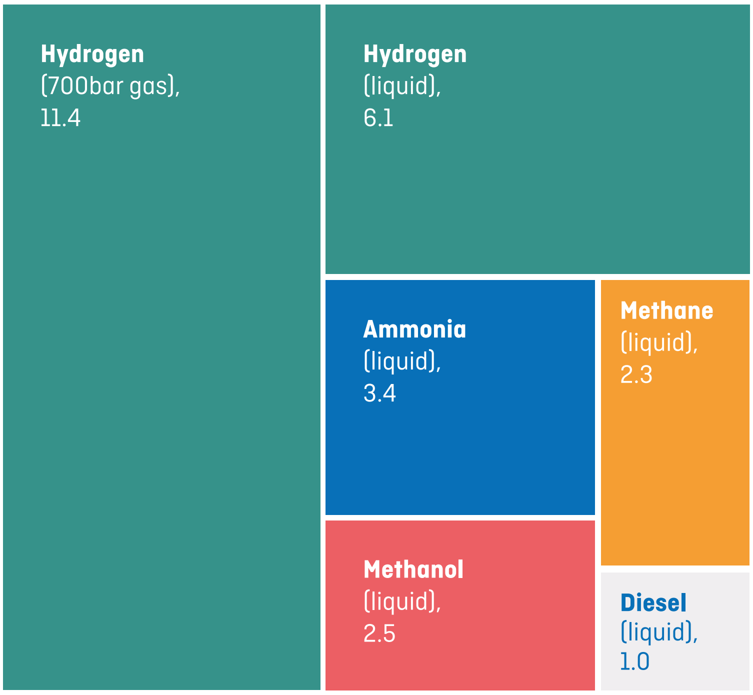
Global zero carbon fuel markets

Mexico is placed in an advantageous position geographically; between the large economies of North and South America, in proximity of the Panama Canal, with access to both the Atlantic and Pacific Oceans and its Caribbean coast with dense cruise traffic. Globally, green hydrogen and green ammonia have emerged as important fuels for the decarbonization of shipping. Mexico has already expressed interest in adopting these fuels, however, it is still in the early stages of development. Aligning the fuel selection with the rest of the world would mean that international vessels could bunker in Mexico. Development in vessel and bunkering technology will be available commercially for the global market, including the United States, who are already looking at adopting these fuels for commercial vessels. This could enable Mexico to become a zero carbon bunkering hub providing international vessels zero carbon fuel as well as producing a new commodity that can be exported globally. This could set an example of how zero carbon fuels can be successfully integrated in the maritime industry as well as for use in other activities around Mexico's ports.

The suitability of fuels for different applications

The energy density of a fuel is the amount of energy it 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 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: Energy densities of various shipping fuels (storage volume including tank relative to diesel) [19]



Fuel costs and energy security

Relying on foreign fuels to supply the shipping sector adds the risk of price shocks (given the interlinked nature of global commodity markets) and hinders security of supply. Producing these fuels from local renewable resource greatly reduces both risks. In the future, using them can even become cost competitive when compared to fossil fuels due to taxation – both at a national and international level – and due to learning rates and cost reductions from industry maturity as the transition progresses. It is estimated that Mexico can produce green hydrogen at costs up to 64% lower than other countries with less favourable renewable resource [18], and costs will be further reduced as key components such as electrolysers and renewables progress through their technology cost reduction curves.

The energy density of a battery-based propulsion system is about one quarter that of a gaseous hydrogen system [20]. This means that current battery technologies are only suited to smaller vessels 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 highest energy density.

The choice of fuels might also be dependent on the handling requirements and safety implications of the fuel; for example, some applications may be less suited to using ammonia due to the risk to public health in the event of a leak. This may be a consideration on ferries, for example. 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 number 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 zero carbon fuels.

Large vessels, such as bulk carriers, that travel regularly between a small number of large ports, are well suited for early adoption of zero 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 from the same large vessels. 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 ports or smaller ports may find it more difficult to find ports that can supply the new fuels, so may be later to adopt zero carbon fuels.

Natural resources and land available local to the port

Adoption of zero carbon fuels relies on the availability of suitable natural resources (e.g. renewable electricity generation potential and water for electrolysis), and land to produce and store the fuels. Since fuel production plants are likely to be near ports, seawater can be used for electrolysis, which would require desalination equipment to be incorporated. The cost of a desalination plant is very small in comparison with the rest of the infrastructure and establishing this infrastructure could have wider benefits in addressing water shortage issues by creating economies of scale supported by the water demand for fuel production.

Careful consideration is needed to ensure that the environmental and social impacts of any changes to infrastructure and land use (both direct and indirect) are minimised. For example, replacing food producing agriculture, habitat or forest land with fuel infrastructure.

Additionally, the development of renewable generation for producing fuels must be in addition to that developed for providing for wider electricity demand and decarbonizing the grid in Mexico. If natural resources are not available near the port, fuel can be imported from elsewhere, or vessels stopping at the port may need to make separate bunkering stops elsewhere where the resources exist to generate zero carbon fuels sustainably. Local solutions, however, would be beneficial whenever feasible, as they would not only reduce infrastructure and transport costs but also any potential emissions associated with them or with the storing of these fuels.

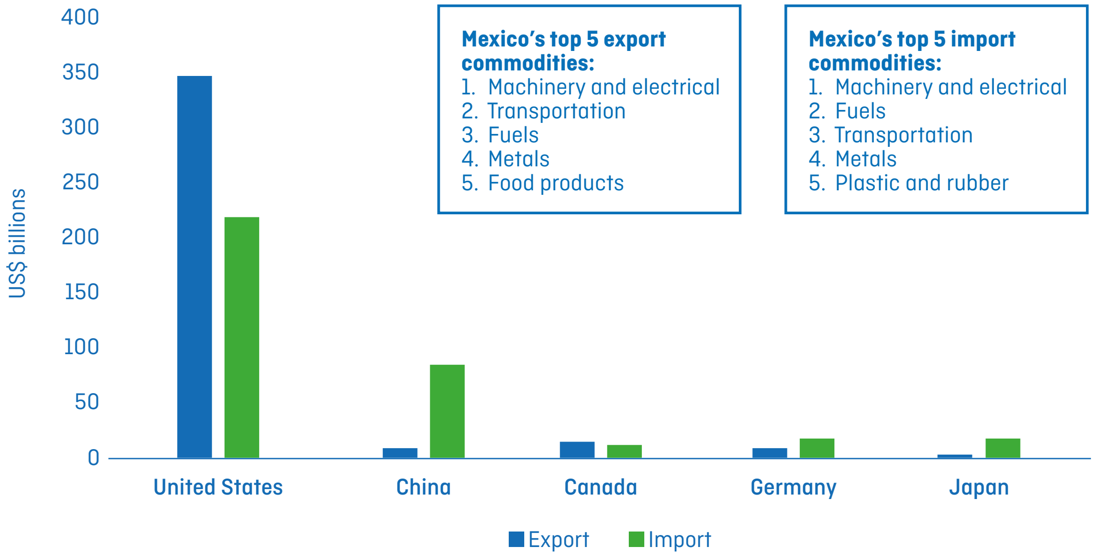
Section 4

Mexico is well placed as a major trading hub between North and South America

Mexico is the second largest economy in Latin America and 15th largest in the world [21]. The country has a diversified market and strong trading relationships with its neighbouring countries. It is part of the U.S.-Mexico-Canada Agreement (USMCA) replacing the North American Free Trade Agreement and MERCOSUR, where Mexico acts as an observer member.

Mexico's geographic position on both the Pacific and Atlantic Oceans gives it access to Asian markets as well as access into Europe and Africa. The top trading partners include the United States, China and Canada. Mexico is a major exporter of automobiles and their related parts, along with petroleum oils and other fuels [22].

Exhibit 4: Mexico's largest trading partners by export and import



Mexico's position as a major trade hub is illustrated by the range of vessel types visiting its ports. The majority of Mexican maritime vessel traffic is dominated by offshore service vessels, but these are not the vessels that consume most of the fuel energy. The largest proportion of fuel usage[1] (35%) is attributed to container vessels, which are generally larger and have longer journeys than offshore sevice vessels.

1 Throughout this report, vessel energy demand is the calculated energy demand of departing journeys from Mexican ports based on data from 2018 [17, 16]

Manzanillo is Mexico's largest port in terms of energy usage. This port is responsible for the Pacific cargo for Mexico City; the capital and largest city in North America, and handles a large portion of manufactured products from industrial facilities in north-western Mexico and other regions [23]. The next largest ports in Mexico are located across Mexico on both Pacific and Atlantic seaboards, as shown in Exhibit 5 (below).

Exhibit 5: Map of Mexico illustrating vessel traffic and Mexico's busiest sea ports. Vessel traffic data from Marine Traffic.com used with permission.

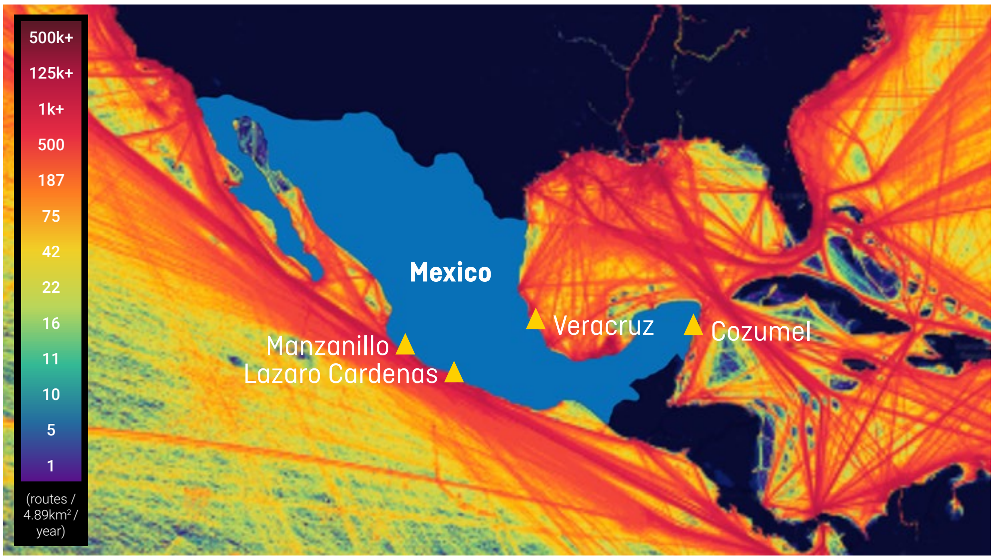
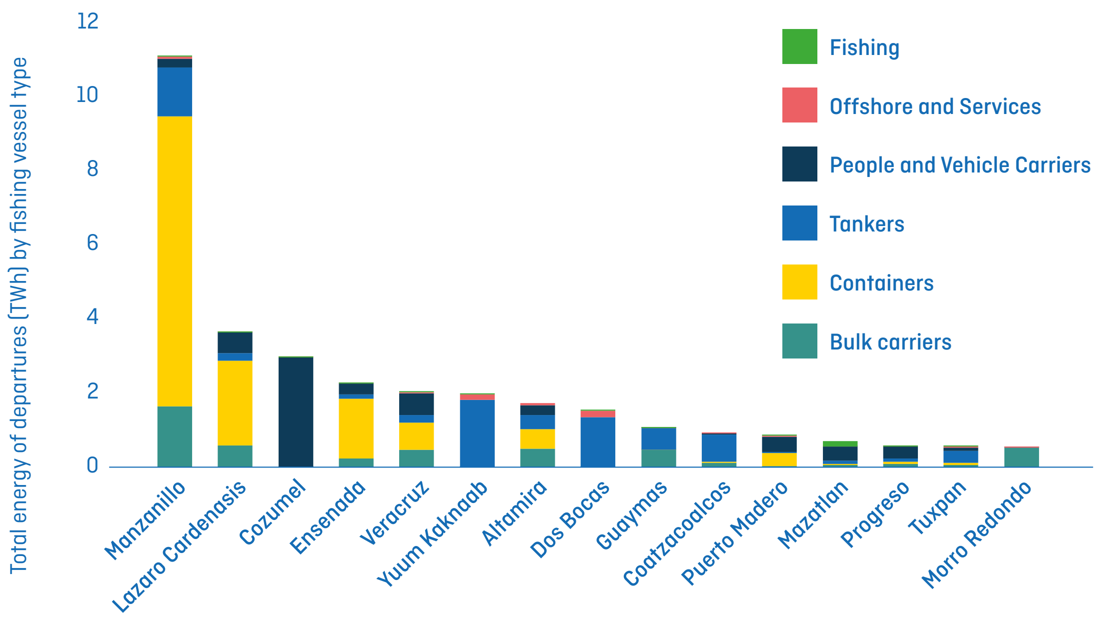


Exhibit 6 shows that these large ports are dominated by container traffic. However, other ports show a diversity of vessels and, in particular, how ports are particularly suited to a singular vessel type. Cozumel for example, located in the Yucatan peninsula, serves mainly people and vehicle carriers, likely for its tourism industry and proximity to Caribbean islands. Similarly, the port of Dos Bocas, in the south east, serves mainly tankers bringing gulf oil to the port to be refined.

Exhibit 6: Energy usage by departing vessels, showing the 15 largest ports in Mexico



Section 5

Mexico currently relies on imported gas from North America to produce electricity but has ambitious targets to reduce carbon emissions

Mexico's power sector has recently undergone change, moving from a traditional model run by the state-owned Federal Electricity Commission (CFE) to a new market structure, triggered by the Energy Reform. Post Energy Reform, privately owned generators, as well as the CFE, can supply users, although the electricity transmission and distribution services are still owned by the Mexican State. However, the Mexican State can enter contracts with the private sector for the operation of transmission and distribution grids.

In 2019, natural gas made up 60% of Mexico's total electricity generation. Natural gas is largely imported to Mexico from the United States and benefits from low North American gas prices.

The Mexican Energy Secretariat expects considerable growth of generation and transmission capacity in coming years. For 2024, they forecast that over 19 GW of new and replacement generation capacity will be added – half of it corresponding to solar PV – and that over 3,300 km of new transmission and distribution lines will be energised. Distributed generation is also expected to grow, with the forecast indicating that close to 6 GW are likely to come online by 2025, growing to almost 14 GW by 2035 [24].

Exhibit 7: Mexico's historical electricity generation mix [42]

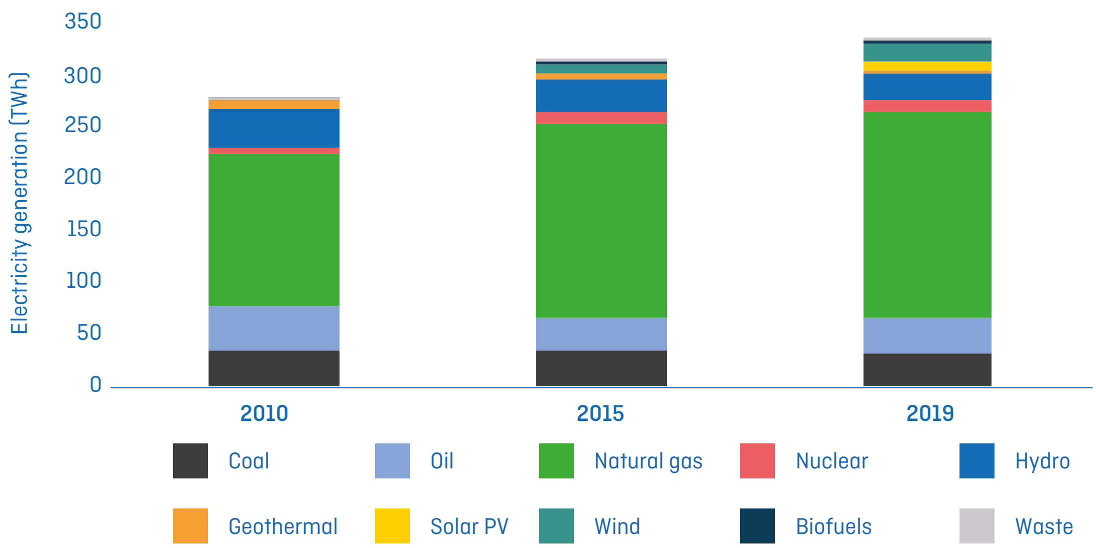
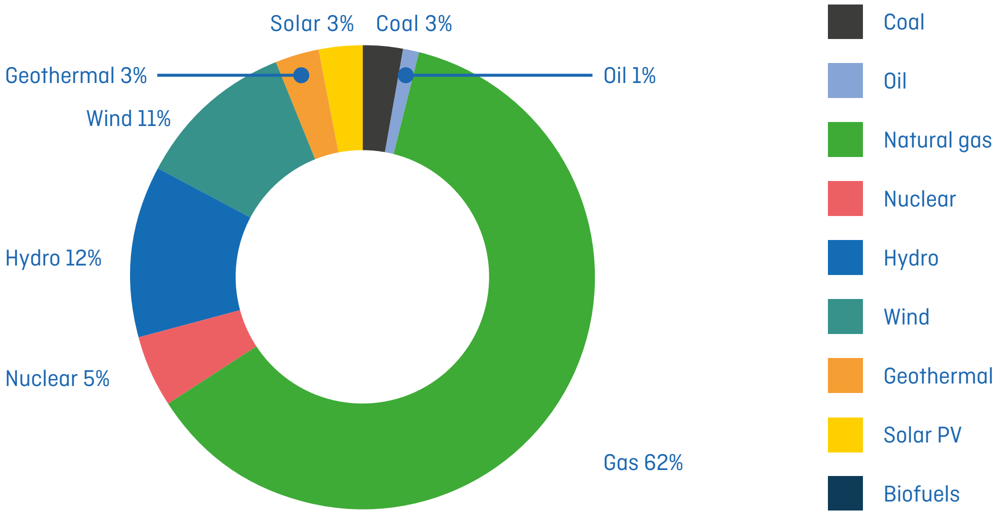


Exhibit 8: Predicted electricity generation mix for Mexico in 2030 [27]



Mexico has committed to reduce GHG emissions by 22% and black carbon emissions by 51% below business as usual by 2030, implying that emissions would peak by 2026 and that the intensity of GHG emissions per unit of GDP will be reduced by about 40% between 2013 and 2030 [25]. There is a conditional target to further reduce GHG emissions by 36% and black carbon by 70% below business as usual by 2030, subject to international support.

Under the Copenhagen Accord, Mexico aimed to "reduce its GHG emissions up to 30% with respect to the business as usual (BAU) scenario by 2020, subject to the provision of adequate financial and technological support from developed countries as part of a global agreement." Policies and efforts did not meet this target [26].

In November 2016, Mexico submitted its "Climate Change Mid-Century Strategy" to the UNFCCC in accordance with the Paris Agreement (Government of Mexico, 2016). With this strategy, Mexico pledges to reduce its GHG emissions to 50% below 2000 levels by 2050, while the Nationally Determined Contributions (NDC) Mexico states an interim target of a 22% reduction compared to a business as usual by 2030. The potential to support decarbonization of the international maritime industry and Mexico establishing itself as a first mover to produce zero carbon fuels will require the Mexican government to establish policies that actively supports the development of renewable energy to supply its domestic demand and also to generate shipping fuels.

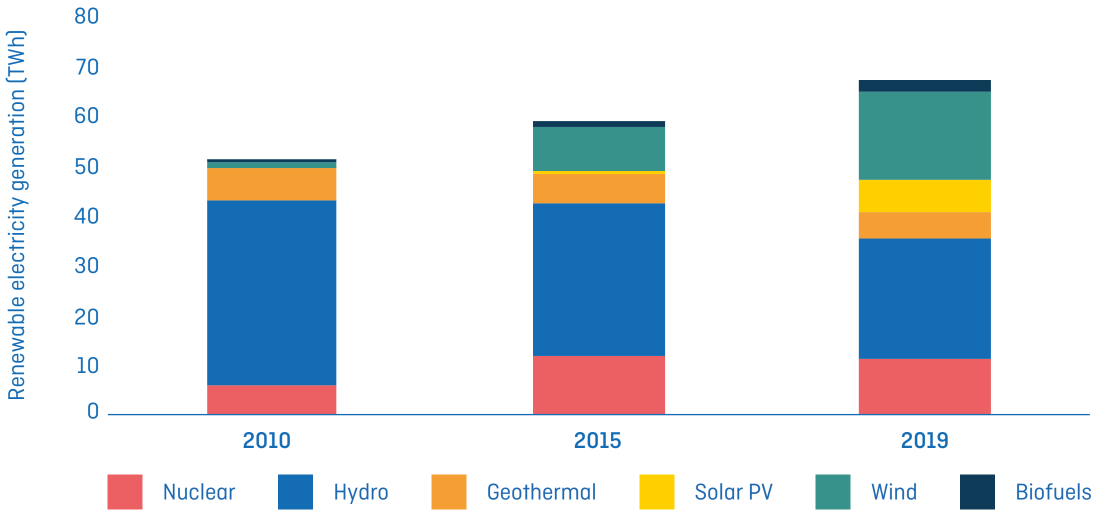
Section 6

Mexico has significant renewable potential that could supply its electricity demand and more

Clean generation accounted for 23% of total power generation in 2019, primarily from hydropower and wind. The share of generation from wind and solar sources has increased between 2010 and 2019, largely due to the country's energy reform referred to in section 5 above. Wind generation is mainly located in Oaxaca in the south, and Solar PV generation in the north-western states.

The Mexican government has considered various scenarios in quantifying the renewable potential of the country. These scenarios take into consideration aspects such as the proximity of renewable resources to existing grid infrastructure. Based on the information gathered by the government it is projected that there are thousands of unexplored terawatt hour (TWh) of solar and wind energy which could contribute to Mexico's grid and the production of low carbon fuels.

Exhibit 9: Mexico's historical renewable and low carbon generation [42]



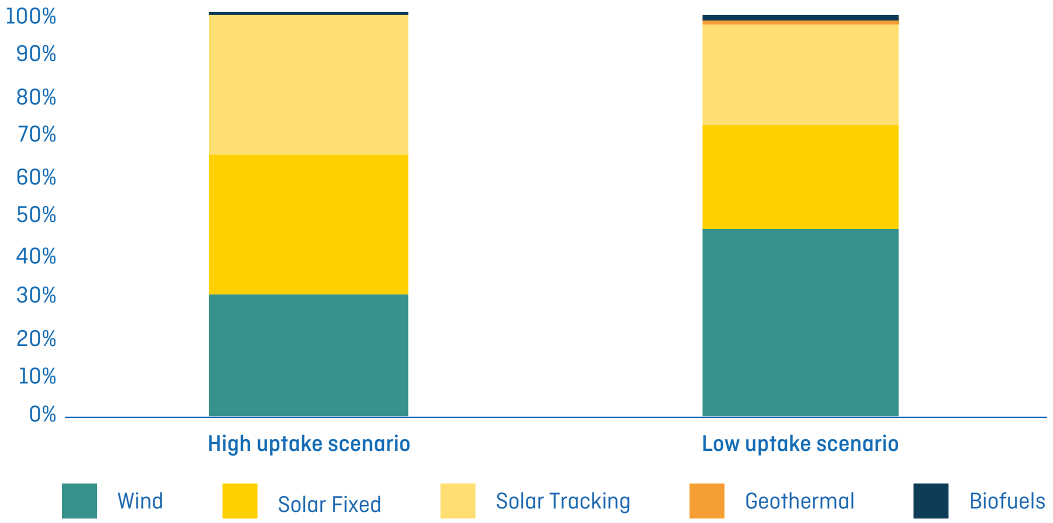
This report analyses two of four different scenarios of solar and wind power adoption in the country [27]. While four scenarios were analysed, this report considers only the highest and lowest ones, these being the high uptake and moderate uptake scenarios, respectively:

High uptake scenario identifies areas of high potential for the development of solar & wind electricity generation projects without considering the proximity to the general transmission networks. This scenario throws a probable installable capacity of 2,472 GW and a probable generation potential of 4,904 TWh per year.

Moderate uptake scenario, similarly, to the high uptake scenario, this scenario identifies areas of high potential for project development of solar and wind generation taking into consideration the proximity to the general transmission networks. This scenario, whose criterion is a distance less than or equal to 10 km, yields a probable installable capacity of 378 GW and a generation potential of 864 TWh per year. While this is a ten-fold increase on 2019, exporting zero carbon electrofuels would trigger additional renewable demand, in which case less-favourable sites would need to be exploited, resulting in higher prices.

These scenarios do not include additional hydropower development beyond existing capacity, as the technology is already well established in Mexico. Renewable (or, at least, low carbon) adoption could therefore be even higher than assumed in the scenarios if additional hydro developments, both at small and large scale – for which there is further potential – were to be considered. The Ministry of Energy has stated in the Renewable Energy Prospective (2016-2030) that Mexico has the proven potential to generate close to 4.7 TWh/year from hydropower plants [27]. There are also opportunities in smaller-scale plants, according to the National Renewable Energy Inventory (INERE) there are 16 TWh/year of additional potential of small hydro in Mexico between now and 2030.

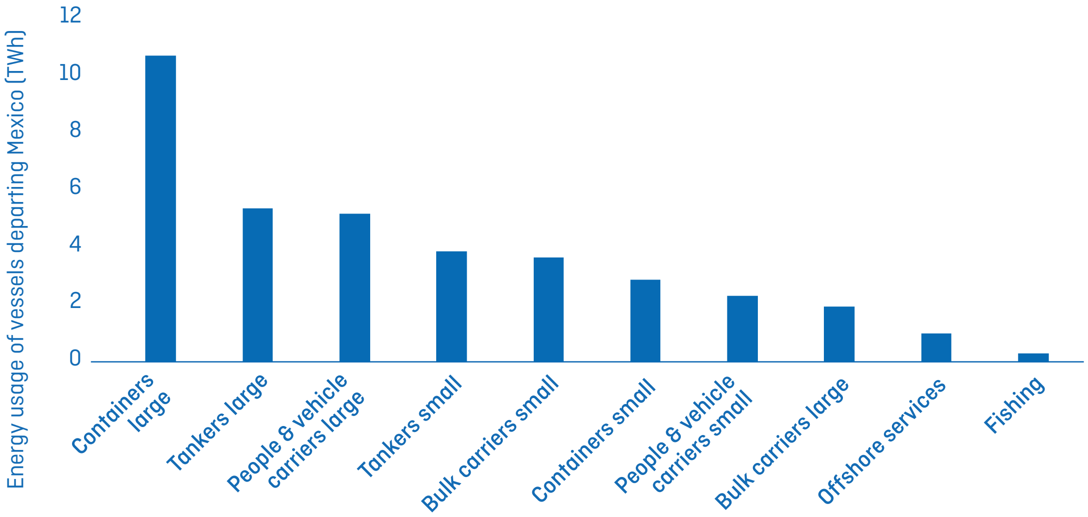
Exhibit 10: The renewable potential for solar, wind, geothermal and biomass based on the scenarios produced by the Mexican Energy Secretariat [27].



Section 7

Mexico's abundance of renewable potential puts it in a strong position to produce zero carbon fuels

Exhibit 11: Energy usage by vessel category in Mexico, based on energy required at departure



The largest energy demand from vessels departing Mexico's ports is large container vessels, carrying goods produced in Mexico across the world to its trading partners. In total, the fuel energy demand from all domestic and international commercial vessels providing Automatic Identification System (AIS) data departing Mexican ports was approximately 37 TWh/year in 2018 [28]. In addition to this, there are smaller commercial, industrial and private vessels which do not have AIS, with an estimated fuel energy demand of around 2 TWh/year, giving a total energy demand of approximately 39 TWh/year.

In order to determine the amount of renewable electricity it would take to supply this energy through zero carbon propulsion technologies (batteries, green hydrogen and green ammonia), the efficiencies of the processes required to create the fuels and use them in the vessels need to be taken into account. The methodologies used to do this are described in Appendix D.

Assuming an extreme scenario of full adoption of zero carbon vessel technologies by 2030, Mexico would require approximately 69 TWh/year of renewable electricity to satisfy demand. This is a significant requirement. However, a paper by Global Maritime Forum estimated that a 5% uptake of zero carbon fuels by 2030 is required to put the industry on course for its decarbonization targets, and this has even now become the target Mission Innovation's Zero-Emission Shipping Mission [29]. While this number is not meant to reflect targets for each individual country, it is used here as a reasonable scale of uptake of zero carbon fuels to produce example results.

Assuming a 5% uptake of zero carbon fuels by vessels visiting Mexico's ports and that all these vessels refuelled during their visits, about 3.47 TWh/year of renewable generation would be required in 2030 (see appendix D) and increase after that. This can be considered as a highly achievable target given the country's extensive renewable potential.

Even the most conservative estimations of Mexico's renewable potential indicate that local resources can meet both the power grid's requirements and additional demand from electrofuel production, even under a 100% adoption scenario. The transition to zero carbon shipping, however, is expected to happen over a longer horizon beyond 2030. By then, technological advancements in renewable energy – like solar PV, onshore and offshore wind, and potentially others like wave and marine energy – coupled with the expansion of power networks in the country are likely to enable significantly more renewable potential to be economically accessible. By providing a source of demand for renewable power, adopting electrofuels can help lay the groundwork for decarbonization by increasing renewable capacity and infrastructure, decarbonizing applications and creating local expertise. Meanwhile, the grid would have time to expand and become more robust, preparing for a more widespread integration of renewable energy sources into the power network, which can be crucial for enabling Mexico's energy transition.

In monetary terms, there is a possibility to attract investment of between 36.7 - 52.8 billion pesos to build the infrastructure required by 2030 to provide renewable electricity and zero carbon fuels to decarbonize 5% of the vessels visiting Mexico's ports. Of these 23.8 - 35.8 billion Mexican pesos would be for solar and wind farms, with the balance required for green hydrogen and green ammonia plants as well as related infrastructure. More details are provided in Appendix D.

Required renewable electricity generation to support 5% adoption of zero carbon vessel technologies in 2030:
~ 3.47 TWh/year

The investment potential for infrastructure to support 5% adoption of zero carbon vessel technologies by 2030:
36.7 – 52.8 billion pesos

Mexico's national electricity demand in 2030 is forecast to be:
600 TWh/year

Mexico's renewable potential:
864 – 4,094 TWh/year

Section 8

Adoption of zero carbon fuels can bring wider benefit

The decarbonization of the shipping sector in Mexico 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 decarbonization far beyond the shipping sector.

Energy security

As traditional fuels such as gas, coal and oil are phased out, Mexico has the opportunity to become more energy independent; relying less on imported energy and developing its own domestic production and consumption. This has the benefits of protecting the economy from price shocks from fossil-fuels and also more stability in energy supply throughout the country. Coupled with further health, economic and decarbonization benefits, this can become a strong argument for government support and incentives towards increasing renewable energy capacity and other key elements needed to enable electrofuel economies.

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 fossil fuel-based 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 in construction and operation. 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, helping local economies to not only adapt, but also potentially grow. Mexico's oil and gas output has been declining in recent years, going from representing over 7% of the national GDP in 2007 to roughly 2% in 2020. While this can temporarily disrupt local economies, it may open even larger opportunities to locally create the capacities that new and future-proof jobs will demand, bringing significant development to the country and fostering green economies around the ports and beyond. This development and resources inflow has the potential to both significantly alleviate or aggravate some of the country's main existing problems – including poverty and inequality, which have also been highlighted as potential barriers for the sustainable development of the country [30] – stressing the need to implement guidelines to assure a just transition for the benefit of all.

This includes a range of job roles, skill levels and education requirements, and includes roles in renewable generation and transport, fuel generation, storage and handling, research and manufacturing into related technology solutions such as fuel cells.

Benefiting from the global demand for green products and commodities

Green hydrogen could be a valuable export commodity that the country could supply to various global markets, for example to the United States, Japan and Western Europe [31]. Other countries in South America could also become off-takers for either meeting their internal demand or for re-distributing and exporting in the future, which could be the case of Panama [32]. An early adoption of zero carbon fuels in Mexico could establish the country as a world leader in their production and could feed into these markets benefitting from its location on major shipping routes as well as diversifying the maritime industry through decarbonization of cruise vessels.

Production of green hydrogen and ammonia would also position Mexico to feed into a growing global demand for "green" products. As the market for the products and materials sees an increasing demand for zero carbon options, Mexico will be at an advantage being able to offer these to international markets.

Similarly, the production of green steel and cement, by means of green hydrogen, could provide a commodity that would feed directly into these growing green markets. Cement producers have done significant advances towards adopting hydrogen in their operations [33], and steel producers are already actively participating in this dialogue through local hydrogen associations, which could lead to Mexico successfully leveraging this and other opportunities in zero carbon fuel technologies and goods.

A catalyst for decarbonization of Mexico's Economy

Investment in renewable electricity, zero carbon fuels and sustainable infrastructure can support the decarbonization of Mexico's economy far beyond shipping. Establishing renewable generation for shipping fuels at scale within Mexico will help establish strong supply chains, developing skills and experience with these technologies, and generating economies of scale which will support wider adoption of renewable technologies for domestic energy supply. Energy demand from generation of zero carbon fuels is well suited to support investment in renewable generation without curtailment, as the fuel production can provide flexibility for grid balancing directly from the renewable infrastructure.

In addition, the availability of zero carbon fuels can be used to decarbonize other sectors; green hydrogen and ammonia can be used to replace fossil fuels and high carbon materials in heavy transport, mining, agriculture, manufacturing and industry. This can be achieved with collaboration with the Asociación Mexicana de Hidrógeno, the Mexican hydrogen group formed in 2021, which brings together energy companies, energy trade groups and agencies with the aim of promoting a hydrogen industry in Mexico by articulating strategies and actions [10].

Attracting foreign and private investment

Deploying renewables at large scale and building the infrastructure, supply chains and capacities necessary to enable electrofuel economies in Mexico and reaping the benefits that they would bring will call for significant volumes of investment. Between 36.7 and 52.8 billion pesos of investments for onshore infrastructure can be attracted if electrofuel propulsion systems were to be adopted in Mexico's ports. 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 can play a key role not only in supplying the necessary capital but also in effectively allocating it, helping to drive the advancement of sustainability and the local energy sector.

This study emphasizes the potential investment opportunity that Mexico has in the production of zero carbon shipping fuels. It is currently not certain what impacts the recent Energy Reform will have in terms of developing Mexico as a hub for zero-carbon fuels [34]. However, implementing the right policies, incentives and market design, coupled with additional backing from public funding, can create a sound environment where projects in Mexico can thrive early on. Shipping's future demand for zero carbon fuels will allow for increasing export and can provide a constant long-term revenue stream, which is an attractive feature for investment and can help Mexico reach its emission targets as well as create new green jobs.

Mexico becoming a first mover in the generation and supply of zero carbon fuels on a global market will mean that it becomes attractive for foreign investment. The ability to supply zero carbon fuels will make Mexico well positioned for trade and cooperation with other countries who are also establishing zero carbon fuels, potentially in Asia, Africa, South, North and Central America and Europe, which plays to Mexico's geographical advantage.

Hydrogen prices

While the price of green hydrogen remains high, it is expected to drop significantly over time thanks to the lowering cost of renewables, the industry's learning curves, and reduction of hydrogen production technologies' prices, reaching $1.40 US Dollars per kg HHV in 2030 [35]. There are concerns that existing subsidies for fossil fuels in Mexico are making investments in renewable power appear artificially unattractive. G20 countries, including Mexico, have agreed to phase out fossil fuel subsidies.

This situation may therefore cause the retail prices of electricity to increase considerably for certain consumer segments once subsidies are phased out, at which point the country could find itself in a position of high energy dependency and high prices, having insufficient local renewable capacity that would have been built over time if it were not for fossil fuel subsidies.

Environment preservation

Technologies and fuels currently used for marine transport are damaging for the climate and environments at a large scale, but they also have important local impacts that can often be overlooked. Impact on air pollution, which in turn impacts the health of flora, fauna and people, can be significant. This carries great importance in itself but becomes especially crucial in various locations across Mexico where local economies, often centred around tourism and related services, can be additionally affected through the loss of biodiversity and ecosystems which are at the centre of their economy. Furthermore, the discomfort and potential health concerns related to air pollution may drive away visitors, further adding to the problem. Tackling the emissions and pollution of marine transport becomes then not only a matter of preventing climate change and reducing environmental impacts, but also of health and of preventing the disruption of local economies.

Conclusions

With its excellent renewable potential, its key position along major shipping routes and its extensive trading relationships, Mexico could capitalise on the impetus to decarbonize international shipping to be able to offer zero carbon fuel bunkering for vessels visiting the country's ports, potentially creating a new export commodity and developing its own hydrogen economy. This would result in significant benefits for the economy and society as this new sustainable industry emerges, creating jobs and developing supply chains.

As the world takes action against climate change, Mexico 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-emissions fuel infrastructure could attract investment of between 36.7 and 52.8 billion pesos.

This expansion could be sustained by demand from international shipping companies as adoption of zero carbon fuels increases over the coming years. This is contingent on the Mexican government putting the right policies in place nationally and supporting ambitious global policy at the International Maritime Organization.

The production of zero carbon fuels requires significant amounts of renewable electricity. The renewable electricity infrastructure to supply shipping fuel should be developed over and above that developed to meet the requirements of the grid to ensure that the decarbonization goals of Mexico are supported. This demand, especially for wind and solar power, will drive the development of supply chains and enable economies of scale, supporting wider adoption of renewable infrastructure, and allowing Mexico to capitalise on its excellent renewable potential.

With such crucial and ambitious goals and considering the key pieces – and large volumes of investment – that must come together to reach them, coordination and long term planning will be crucial. Mexico could therefore greatly benefit from establishing a comprehensive roadmap and sending clear signals early on. Doing so would allow investments, infrastructure and markets to grow and evolve apace to enable local zero carbon electrofuel economies in time to meet these goals and for Mexico to capitalise on this upcoming market shift.

Even as Mexico has great prospects to benefit in this way, there are similar opportunities for other nations in South and Central America and around the world. Early movers will establish themselves early as zero carbon bunkering hubs and position themselves as leaders in the new world of decarbonized shipping.

Potential for synergies and cooperation with surrounding countries

The benefits described in this report are not limited to Mexico, and a wider, regional adoption of zero carbon fuels would support trade routes and regional co-benefits, as well as support and help accelerate the country's transition towards low carbon. The map below provides some further examples of ports that have potential to benefit from decarbonization of shipping activity. There are many more ports in the region that could benefit in similar ways.

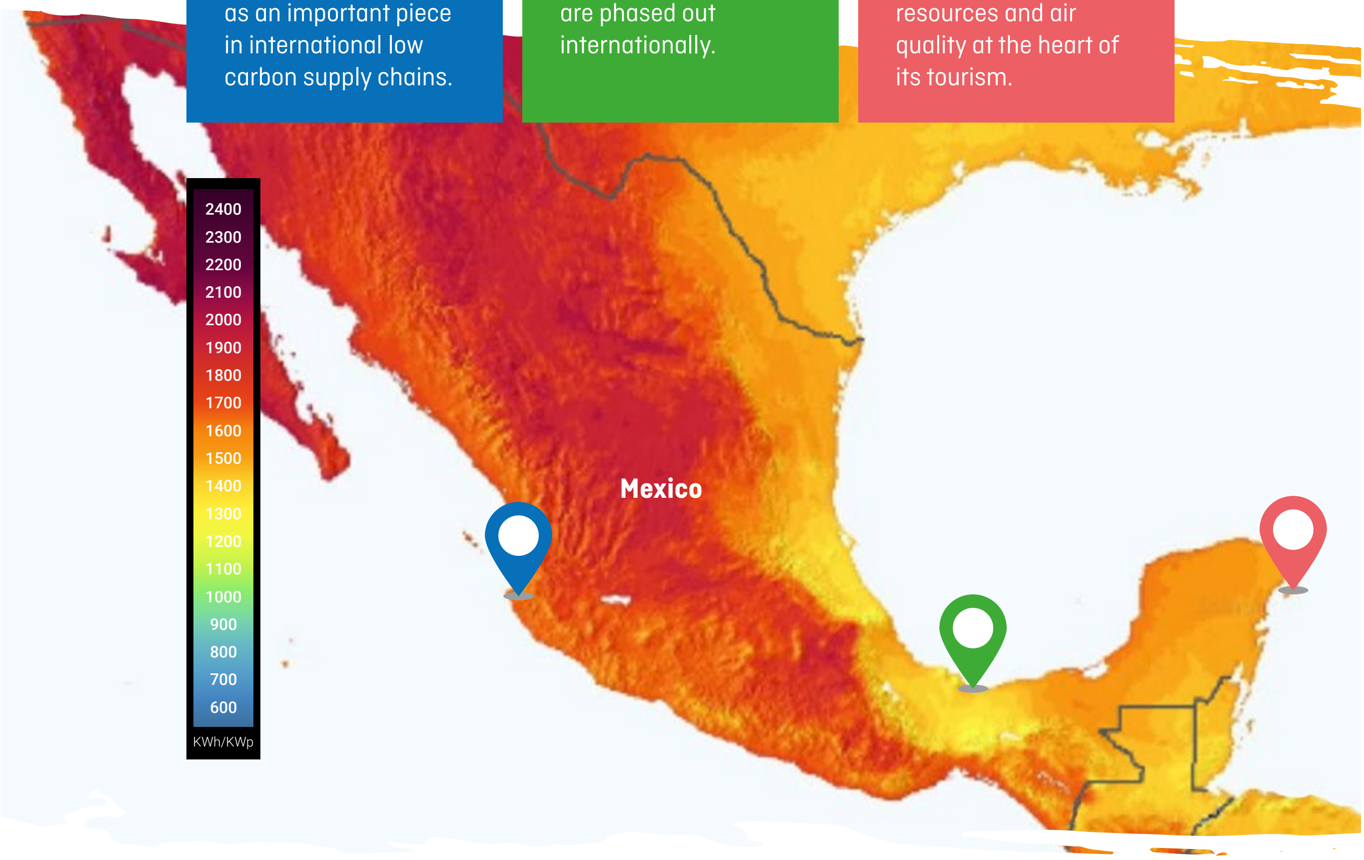
Port case studies in Mexico

This section dives into three port categories representative of the type of ports that can be found in other locations across Mexico: large and busy ports, smaller ports along shipping routes and export-focused ports along the Gulf of Mexico. The section investigates case studies for each of these port categories, showing they are well suited for enabling local electrofuel markets and that other similar ports in Mexico that could potentially follow their lead.

Manzanillo:
Busiest port in Mexico. This landmark port handles large amounts of imports and exports and has significant renewable potential. Locally produced electrofuels could be exported to other linked ports and establish Manzanillo as an important piece in international low carbon supply chains.

Coatzacoalcos:
One of the central pieces in oil logistics in Mexico. Equipped with considerable local resource, it can become a future-proof source of income and create considerable local capacity, even as fossil fuel commodities are phased out internationally.

Cozumel:
This famous touristic destination is globally recognised for its beaches and biodiversity. Locally enabling electrofuels here can be a solid business case thanks to dense and constant traffic and help preserve the precious resources and air quality at the heart of its tourism.



Port case study

Busy ports handling import and export of goods have an opportunity to be able to offer zero carbon fuels to a growing market for decarbonized products

An increasing demand is anticipated for low carbon and environmentally friendly shipping services as goods manufacturers want to offer their customers green options. Being able to offer zero carbon fuels as a bunkering option for early adopters will put container and carrier ports, dealing with goods and materials, at an advantageous market position.

Port category narrative

There will be an increasing demand for low carbon and environmentally friendly shipping services as goods manufacturers want to offer their customers environmentally friendly options. Shipping is part of this story as lifecycle environmental impacts become increasingly discussed, and greater expectations are placed on product suppliers on the ethical sourcing and transport of goods and materials. Being able to offer zero carbon fuels as a bunkering option for early adopters will put container and carrier ports, dealing with goods and materials, at an advantageous market position.

Ports that develop zero carbon fuel production and bunkering capability could also offer bunkering for international vessels which are travelling long distances, and for those visiting ports which do not offer the zero emission fuels that the vessels need, thus increasing demand and generating additional revenue. Other vessels that use these ports, including the smaller vessels, offshore services and vehicle and people carriers (ferries), could benefit from the zero carbon fuels infrastructure being developed at the port by operating on these fuels. Furthermore, if the vessels are suited, they could adopt battery and charging systems to run alongside the hydrogen and ammonia vessels.

The approach and strategy for developing zero emissions fuelling capability for a particular port will depend on the renewable potential in the area, including onshore and offshore options. These renewable energy generation technologies could either directly feed into zero carbon fuel production or could be connected to the wider electricity grid with a separate supply and transmission agreement in place for the supply of the production facility. This means that the generation infrastructure does not need to be co-located with the production infrastructure and the port which is a useful option for ports located in urban areas, or with little renewable potential nearby. While this approach is possible, local production should be favoured whenever feasible as it would result in fewer losses, reduced leakage risk and lower emissions and costs associated with transport and storage.

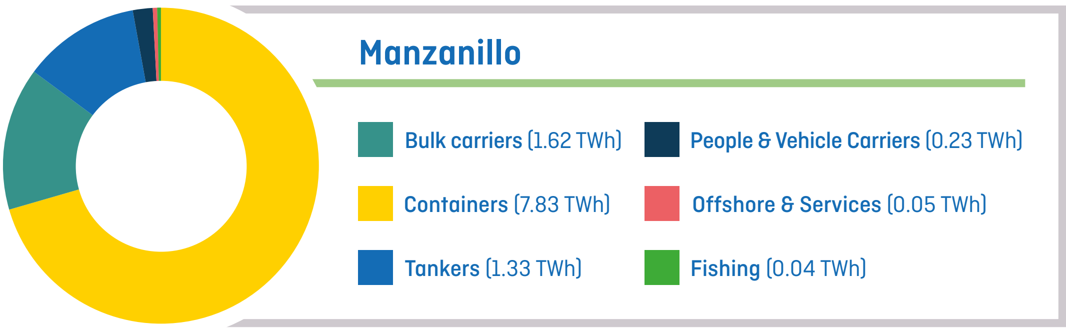
Port example: Port of Manzanillo

The Port of Manzanillo is one of the busiest ports in Mexico handling Pacific Ocean cargo. It is located on the west coast of Mexico and contains connections to 74 international ports in Asia, Eastern Europe, Australia, North America and South America. These destinations could become targets for exporting locally produced electrofuels and could play a role in enabling zero carbon shipping between these destinations. This port handles significant amounts of general and consumer goods, a market which is expected to increasingly demand decarbonized solutions.

The main traffic at this port includes bulk carriers, tankers and container vessels. With regards to fuel requirement, 70% of the energy required for the port is attributed to containers, with bulk carriers and tankers making up a further 27% of the required energy. The annual energy usage of vessels visiting the Port of Manzanillo is 11.1 TWh/yr. A future local electrofuel economy could leverage on the vast solar resource that the port and its surrounding regions enjoy, harnessing it to supply the zero carbon fleet of the future. This could unlock tremendous benefits for the region and local economies and significantly help advance the decarbonization of the shipping sector and, by supporting renewable deployment, of the power grid as well.

The production of zero carbon fuels could become a pathway to exporting these fuels to the international ports associated with the Port of Manzanillo, alongside opportunities for the port to become a bunkering port for various routes.

Exhibit 12: Energy demand from departing vessels in Manzanillo (TWh)



Port case study

Mexico's smaller ports could have a considerable opportunity to develop as zero carbon fuels are implemented

Smaller ports near busy shipping lanes could develop the capability to provide zero carbon fuelling opportunities for larger vessels passing by. This may be a vital enabler to the adoption of fuels that are less energy dense and thus requiring vessels to make more bunkering stops. The smaller vessels that these ports serve may be suited to adopting battery technologies charged with renewable energy.

Port category narrative

Many of the vessels visiting smaller ports in Mexico may be suited for adopting battery technologies (smaller fishing vessels, ferries and individually owned vessels). Adoption of these technologies may be gradual, with new battery vessels being bought as older vessels become expensive to repair and are replaced. Therefore, the onshore charging infrastructure will be needed early, but can be ramped up over time.

Larger vessels travelling longer distances are more likely to be suited to a zero carbon fuel in the form of green hydrogen and ammonia. These fuels have a lower energy density than fossil shipping fuels, and it is likely that more frequent bunkering stops will be needed.

Ports could benefit from being part of a wider network of ports supplying zero emission fuels, enabling vessels that make many stops in their journey to adopt them. Some of these ports may also have the potential to expand, providing bunkering for larger ports, or even producing zero carbon fuels as an export to the global market. This could represent a significant economic benefit to the port and its surrounding area. There could be a potential pathway towards adoption of zero carbon fuels, which could be produced locally, or transported from other locations in Mexico or beyond.

Port example: The Port of Cozumel

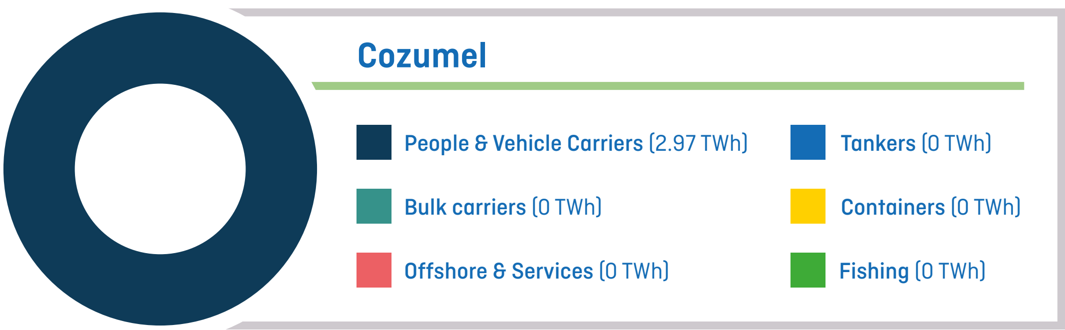
The Port of Cozumel serves the largest island in Mexico. Cozumel is located on the South-eastern coast of Mexico, in close proximity to Cuba, Guatemala and Honduras.

People and vehicle carriers make up a large amount of the port traffic, with these largely being cruise ships and ferries. In terms of vessel energy requirement for the port, almost 99% of this is attributed to people and vehicle carriers (mostly cruise ships), with offshore services, small bulk carriers and fishing vessels accounting for the remaining ~2%. The overall energy requirement for the port is around 2.97 TWh/year, which could represent a vast opportunity if vessels were to start switching to electrofuels: the considerable solar PV potential present in the area and the favourable wind speeds experienced around the coast could be harnessed to locally produce electrofuels, enabling considerable decarbonization, a new local economy and a future-proof source of income.

Meanwhile, any renewable capacity installed on site can be used to supply short-haul, smaller vessels such as ferries that move between the island and mainland and that are better suited for electrification. This overall decarbonization can substantially help preserve local economies and ecosystems – classified as a biosphere reserve by UNESCO [36] – by reducing air pollution and ocean acidification. Quieter operation from electrified ships would also reduce noise, providing further relief for local fauna. These local ecosystems are at the heart of the highly touristic local economy and failing to act could prove detrimental not only for them, but for the local economy as well.

While batteries are likely to be suitable for fuelling the smaller vessels that visit this port, larger fishing and offshore services vessels supplying the island could be a potential pathway towards utilizing zero carbon fuels. Bunkering facilities could be established for zero carbon fuels at the Port of Cozumel to fuel cruise ships travelling along this route.

Exhibit 13: Energy demand from departing vessels in Cozumel (TWh)



Port case study

Zero carbon fuels could facilitate the transition to green export opportunities in the Gulf of Mexico and beyond

There are several ports in Mexico, particularly in the Gulf of Mexico, which have significant exports over the world. This includes exports of fossil fuels like oil, which are expected to decline with the global move towards low carbon options. Zero carbon fuels signal a significant opportunity to transition towards green, future-proofed economies.

Port category narrative

There are several ports in Mexico, particularly in the Gulf of Mexico, which have significant exports over the world, including exports of fossil fuels like oil and gas. As the global demand for lower carbon options increases, fossil and high carbon exports are expected to decline, putting these ports and the communities and economies that rely on them at risk.

The production and supply of zero carbon fuels could be a significant opportunity to transition towards green, future-proofed economies. Offering zero carbon bunkering opportunities or exporting zero carbon fuels to growing global markets could bring vital revenue into the local area, while supporting the decarbonization of Mexico's shipping sector.

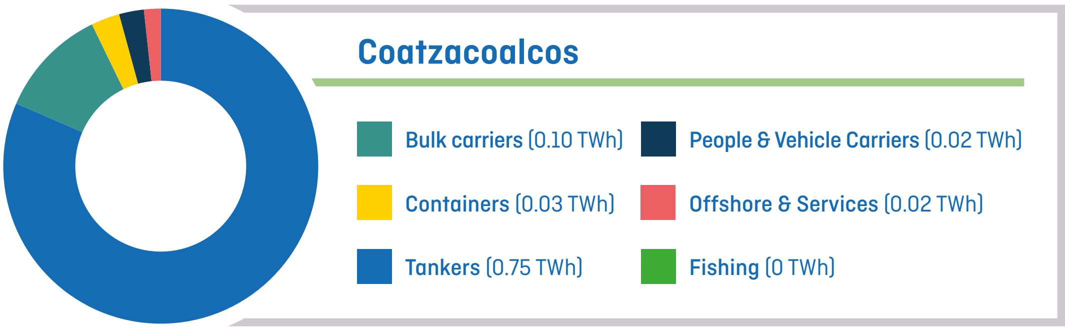
The development of zero carbon fuels infrastructure could also be an opportunity to develop other low carbon commodities and goods – the renewable electricity infrastructure could power local industry, and the zero emissions fuels themselves could be leveraged to decarbonize industrial processes such as steel making, provide fertiliser for agriculture, or fuel for heavy machinery. The ports could also serve to export other decarbonized goods beyond the fuel itself, providing further economic opportunities.

Port example: Port of Coatzacoalcos

Coatzacoalcos is a petroleum product exporting port which is well connected by rail and road to central Mexico and the Pacific coast. Other export products from this port include agricultural, forestry and manufactured products. The port is located in the Gulf of Mexico on the East Coast. A major focus on oil exploration is present in this region with large oil exports at neighbouring ports.

The vessel traffic in Coatzacoalcos is dominated by tankers and bulk carriers, which together consume over 90% of the total energy requirement for departing vessels at the port, which stands at a total of around 0.857 TWh/yr. While solar resource around the port is not the highest in the country – although still considerable at ~1,580 kWh/kWp, compared to ~1,750 kWh/kWp around Manzanillo [37]– the surrounding areas present high wind potential which could be harnessed to not only produce electrofuels to meet this fuel demand from ships, but also to potentially export them. Tankers make up most of the port energy requirement at about 82% of total energy.

Exhibit 14: Energy demand from departing vessels in Coatzacoalcos (TWh)



Zero carbon fuels could become an export commodity at Coatzacoalcos, along with the potential for bunkering to occur. Offshore wind potential would need to be explored to allow for zero carbon bunkering facilities to be established in the region. Local infrastructure could also be leveraged on, helping not only strengthen the business case for zero carbon electrofuel investments, but also potentially salvaging a portion of existing assets. Gas pipelines, for example, could be used as a way to transport and even export hydrogen through blending, and generation capacity could be retrofitted for power generation and security of supply purposes.

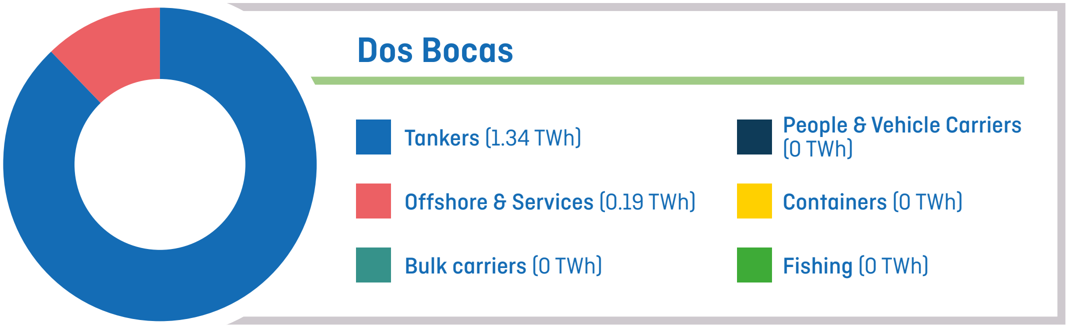
Port example: Port of Dos Bocas

The Port of Dos Bocas focuses mostly on oil, handling over 85% of the country's production [38]. A variety of food products – including various fruits, sugar cane and coffee – are also exported through this port, which serves the Mexican states closer to Guatemala (Tabasco, Chiapas and Campeche). The port itself is located in the southern shore of the Gulf of Mexico in the State of Tabasco.

Given the high oil-related activity, much of energy demand from vessels (over 85% of the 1.53 TWh yearly energy demand) corresponds to tankers and the offshore services ships that support oil operations in the region, while bulk carriers and ships make up a small share of local energy demand.

Local solar resource is relatively high, yielding ~1,650 kWh/kWp of solar PV [39], and wind speeds are promising, standing at over 7 m/s (yearly average) at the coast and beyond it [40]. As the world moves away from fossil fuels, operations and traffic at the port are expected to diminish, yet the considerable renewable potential found in the region presents an opportunity for local electrofuel production which can be used to supply ships, or even for exporting, given the port's location and the established trading routes that rely on it. This can provide significant initial momentum towards establishing zero carbon shipping routes and lay the foundation to get local economies ready for the more accelerated stages of the transition expected after 2030.

Exhibit 15: Energy demand from departing vessels in Dos Bocas (TWh)



References

[1] SGN, "Aberdeen Vision," 2021. [Online]. Available: https://sgn.co.uk/about-us/future-of-gas/hydrogen/aberdeen-vision. [Accessed 2021 July 17].

[2] Networks, "Could hydrogen piggyback on natural gas infrastructure?," 17 March 2016. [Online]. Available: https://networks.online/gas/could-hydrogen-piggyback-on-natural-gas-infrastructure/. [Accessed 2021 July 17].

[3] N. Ash and T. Scarbrough, "Sailing on Solar - Could green ammonia decarbonise international shipping?," Environmental Defense Fund, London, 2019.

[4] N. Ash, I. Sikora and B. Richelle, "Electrofuels for shipping: How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile" Environmental Defense Fund, London, 2019.

[5] IEA, "Mexico Country Profile," 2019. [Online]. Available: https://www.iea.org/countries/mexico. [Accessed 27 June 2021].

[6] Forbes, "Political Risk Analysis: Is Mexico Declaring War Against Clean Energy?," 2021 April 22.

[7] Secretaría de la Gobernación, "DOF: 24/03/2021," 2021 March 22. [Online]. Available: https://www.dof.gob.mx/nota_detalle.php?codigo=5614425&fecha=24%2F03%2F2021. [Accessed 30 July 2021].

[8] IRENA, "Renewable Energy Prospects: Mexico," May 2015. [Online]. Available: https://www.irena.org/publications/2015/May/Renewable-Energy-Prospects-Mexico. [Accessed 27 June 2021].

[9] Statista, "Mexico: Distribution of the gross domestic product (GDP) across economic sectors from 2009 to 2019," [Online]. Available: https://www.statista.com/statistics/275420/distribution-of-gross-domestic-product-gdp-across-economic-sectors-in-mexico/. [Accessed 27 June 2021].

[10] C. Lenton, "Mexico seeking to join Latin American peers in hydrogen push," Natural Gas Intelligence, 2021.

[11] Business Wire, "Air Liquide Signs a Long Term Contract with PEMEX for the Supply of Hydrogen to the Tula Refinery in Mexico," 6 September 2017. [Online]. Available: https://www.businesswire.com/news/home/20170906006265/en/Air%C2%A0Liquide-Signs-a-Long-Term-Contract-with-PEMEX-for-the-Supply-of-Hydrogen-to-the-Tula-Refinery-in-Mexico. [Accessed 11 July 2021].

[12] CMS, "Hydrogen law and regulation in Mexico," CMS, 7 October 2020. [Online]. Available: https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/mexico. [Accessed June 2021].

[13] A. Duhalt, "The Urea Value Chain in Mexico: From Natural Gas Supply to Imports of Basic Food Staples," Baker Institute, 2018.

[14] ABS, “Ammonia as Marine Fuel,” American Bureau of Shipping, Spring, Texas, 2020.

[15] Korean Register, “Forecasting the Alternative Marine Fuel - Ammonia,” Korean Register, Busan, 2020.

[16] DNV, “Ammonia as a Marine Fuel: Safety Handbook,” DNV, Bærum, 2021.

[17] Lloyd’s Register, “First LR classed hydrogen-powered vessel launched,” Lloyd’s Register, 20 December 2017. [Online]. Available: https://www.lr.org/en-gb/latest-news/first-lr-classed-hydrogen-powered-vessel-launched/. [Accessed 16 April 2021].

[18] H2 Mexico, “Impulsamos la Industria del Hidrógeno en México,” 2021. [Online]. Available: https://h2mex.org/en/. [Accessed 30 July 2021].

[19] A. Trevistan and B. Rogers, “Fuel Focus - Ammonia,” in Ship.Energy Summit 2021, Online, 2021.

[20] J. J. Minnehan and J. W. Pratt, “Practical application limits of fuel cells and batteries for zero emission vessels,” SANDIA Report: SAND2017-12665., Albuquerque, NM, 2017.

[21] The World Bank, “Mexico Overview,” 2021. [Online]. Available: https://www.worldbank.org/en/country/mexico/overview. [Accessed May 2021].

[22] World Bank, “Mexico Trade Statistics,” 2018. [Online]. Available: https://wits.worldbank.org/CountryProfile/en/Country/MEX/Year/2018/TradeFlow/EXPIMP/Partner/WLD/Product/All-Groups.

[23] World Ports Source, “Puerto de Manzanillo,” 2021. [Online]. Available: http://www.worldportsource.com/ports/commerce/MEX_Puerto_de_Manzanillo_234.php. [Accessed 14 July 2021].

[24] Secretaría de Energía, “Programa para el Desarrollo del Sistema Eléctrico Nacional,” Mexico, 2021.

[25] Ministry of the Environment and Natural Resources, Mexican Government, “Nationally Determined Contributions (Update),” 2020.

[26] Climate Action Tracker, “Climate Action Tracker (Mexico),” [Online]. Available: https://climateactiontracker.org/countries/mexico/pledges-and-targets/. [Accessed May 2021].

[27] Secretaría Nacional de Energía, “Prospectiva de Energías Renovables,” Ciudad de México, 2016.

[28] University College London, 2018.

[29] Mission Innovation, “Zero-Emission Shipping,” 2021. [Online]. Available: http://www.mission-innovation.net/missions/shipping/. [Accessed 17 July 2021].

[30] M. M. D. J. F. (. THOMAS HIRSCH, "Guiding Principles & Lessons Learnt For a Just Energy Transition in the Global South," Friedrich Ebert Stiftung, Germany, 2017.

[31] T. Roos and J. Wright, "Powerfuels and Green Hydrogen (public version)," EU-South Africa (EU-SA) Partners for Growth, EuropeAid/139363/DH/SER/MULTI, 2021.

[32] Secretaría Nacional de Energía de Panamá, "PANAMÁ PROMUEVE CENTRO DE DISTRIBUCIÓN DE HIDRÓGENO PARA LA REGIÓN," 2021. [Online]. Available: https://www.energia.gob.pa/panama-promueve-centro-de-distribucion-de-hidrogeno-para-la-region/. [Accessed 1 July 2021].

[33] CEMEX, "CEMEX successfully deploys hydrogen-based ground-breaking technology," 22 February 2021. [Online]. Available: https://www.cemex.com/-/cemex-successfully-deploys-hydrogen-based-ground-breaking-technology. [Accessed 17 July 2021].

[34] S&P Global Platts, "Mexico's energy sector stagnates as AMLO's counter-reform plays out," 24 March 2021.

[35] Bloomberg New Energy Finance, "Hydrogen's Plunging Price Boosts Role as Climate Solution," 2021. [Online]. Available: https://www.bloomberg.com/news/articles/2019-08-21/cost-of-hydrogen-from-renewables-to-plummet-next-decade-bnef. [Accessed 17 July 2021].

[36] UNESCO, "Sila Cozumel," 2021. [Online]. Available: http://www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/biosphere-reserves/latin-america-and-the-caribbean/mexico/isla-cozumel/#:~:text=The%20Isla%20Cozumel%20Biosphere%20Reserve,the%20city%20of%20San%20Miguel. [Accessed 2021 July 15].

[37] World Bank Group, "Solar GIS," [Online]. Available: https://solargis.com/maps-and-gis-data/overview. [Accessed 2021 July 1].

[38] World Ports Source, "Puerto de Dos Bocas," 2021. [Online]. Available: http://www.worldportsource.com/ports/review/MEX_Puerto_de_Dos_Bocas_1510.php. [Accessed 17 July 2021].

[39] World Bank Group, "Global Solar Atlas," 2021. [Online]. Available: https://globalsolaratlas.info/map. [Accessed 17 July 2021].

[40] World Bank Group, "Global Wind Atlas," 2021. [Online]. Available: https://globalwindatlas.info/. [Accessed 17 7 2021].

[41] Secretaría de Energía, "Prospectiva deEnergías Renovables 2016 -2030," SENER, Mexico, 2016.

[42] https://www.iea.org/data-and-statistics?country=MEXICO&fuel=Energy%20supply&indicator=ElecGenByFuel

[43] UCL Energy Institute and UMAS, "Private Conversations with UCL and UMAS International around South Africa's maritime activities and emissions," London, 2021.

[44] IEA, "The Future of Hydrogen," International Energy Agency, Paris, 2019.

[45] N. Rehmatulla, P. Piris-Cabezas, D. Baresic, M. Fricaudet, C. Raucci, M. Cabbia Hubatova, A. O'Leary, N. Stamatiou and A. Stratton, "Exploring the relevance of ICAO's Sustainable Aviation Fuels framework for the IMO," Environmental Defense Fund, London, 2020.

[46] BEIS, "Greenhouse gas reporting: conversion factors 2020," Department for Business, Energy and Industrial Strategy, 9 June 2020. [Online]. Available:https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020.

[47] IEAGHG, "Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS," IEA Environmental Projects Ltd, Cheltenham, 2017.

[48] D. Schlissel, "Boundary Dam 3 Coal Plant Achieves Goal of Capturing 4 Million Metric Tons of CO2 But Reaches the Goal Two Years Late," Institute for Energy Economics and Financial Analysis, Lakewood, 2021.

[49] P. Balcombe, K. Anderson, J. Speirs, N. Brandon and A. Hawkes, "Methane and CO2 emissions from the natural gas supply chain," Imperial College London, London, 2015.

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
Fuels	Change to fuel storage volume in comparison with fossil fuels	Compatability 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	0.6	0.5	0.7	0.5	0.1	0.1	1	1
Green Ammonia	0.6	0.3	0.5	0.5	0.1	0.2	1	1
Green Methanol	0.6	0.5	0.7	0.5	0.1	0.1	1	1
Blue Hydrogen	0.6	0.3	0.5	0.5	0.1	0.2	1	1
Blue Ammonia	0.6	0.8	0.7	0.5	0.1	0.1	1	1
Waste-derived Biomethane	0.6	0.8	0.7	0.5	0.1	0.1	1	1
Waste-derived Biomethanol	0.6	0.3	0.7	0.5	0.1	0.2	1	1
Waste-derived Biodiesel	0.6	0.3	0.5	0.5	0.1	0.5	1	1
Batteries	0.6	0.3	0.3	0.5	0.1	0.5	1	0.5

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		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

	People & Vehicle Carriers				Small boats	
Fuels	**Large**	**Small**	**Offshore and Services**	**Fishing**	**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.

As detailed in Section 1 of this report, biofuels, methanol and blue fuels were removed from the rest of the project for other reasons, but are shown here for comparison. Biofuels and methanol score well in the analysis due to the high fuel density and ease of handling.

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 [3]

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 [43]

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%
MEX/USD exchange rate	19.77
Costs indexed to this year	2020

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	

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)	

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	1,922	2,119	2,119	21	106	3,785	38	189
Bulk carriers: Small	Green Hydrogen	ICE - Compression	3,643	4,017	4,017	40	201	7,173	72	359
Tankers: Large	Green Ammonia	ICE - Compression	10,708	11,808	11,808	118	590	21,085	211	1,054
Tankers: Small	Green Ammonia	ICE - Compression	2,861	3,155	3,155	32	158	5,634	56	282
Containers: Large	Green Ammonia	ICE - Compression	5,370	5,922	5,922	59	296	10,575	106	529
Containers: Small	Battery	Electric motor	3,849	4,244	2,358	24	118	2,482	25	124
People & Veh. Carr: Large	Green Ammonia	ICE - Compression	5,186	5,719	5,719	57	286	10,213	102	511
People & Veh. Carr: Small	Green Hydrogen	ICE - Compression	2,303	2,540	2,540	25	127	4,536	45	227
Offshore and Services	Green Ammonia	ICE - Compression	987	1,088	1,088	11	54	1,944	19	97
Fishing	Green Ammonia	ICE - Compression	284	313	313	3	16	559	6	28
Small boats: Industrial	Battery	Electric motor	1,460	1,610	894	9	45	942	9	47
Small boats: Fishing / Small	Battery	Electric motor	720	794	441	4	22	464	5	23
Grand total			**39,292**	**43,330**	**40,375**	**404**	**2,019**	**69,391**	**694**	**3,470**
Total - Battery					**3,693**	**37**	**185**	**3,888**	**39**	**194**
Total - Green Ammonia					**30,125**	**301**	**1,506**	**53,794**	**538**	**2,690**
Total - Green Hydrogen					**6,557**	**66**	**328**	**11,709**	**117**	**585**

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	MXNm
Battery	194	8760	22	0.15	3	66
Green Ammonia	2,690	8000	336	1.58	531	10,503
Green Hydrogen	585	8000	73	1.61	118	2,330
Total	**3,470**		**432**		**652**	**12,899**

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	MXNm
Solar PV	798	396	160	3,157
CSP	416	122	230	4,554
Onshore wind	1,735	660	614	12,138
Offshore wind	520	132	202	3,994
Total	**3,470**	**1,310**	**1,206**	**23,843**

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	MXNm
Battery	194	8760	22	0.28	6	123
Green Ammonia	2,690	8000	336	2.10	706	13,960
Green Hydrogen	585	8000	73	2.07	151	2,995
Total	**3,470**		**432**		**864**	**17,078**

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	MXNm
Solar PV	798	396	240	4,736
CSP	416	122	345	6,831
Onshore wind	1,735	660	921	18,207
Offshore wind	520	132	303	5,991
Total	**3,470**	**1,310**	**1,809**	**35,765**

Summary of investment potential

	Low case	High case
	MXNm	MXNm
Fuel production & delivery	12,899	17,078
Renewable plants	23,843	35,765
Total	**36,742**	**52,843**

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 decarbonization 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) [44].

The lifecycle 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 [45] 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 [46] as 0.27 kg CO_2e/kWh[2].

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).

2 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 [47] 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 [48]. 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 content these are equal to 0.13 and 0.10 kg CO_2e/kWh hydrogen.

Scope 2 emissions are not applicable to either of the IEAHG 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[3].

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. [49] 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

3 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 [47]). Assuming the median scope 3 emissions excluding natural gas liquefaction from [49] (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 [44] provides a range of 0.05 to 0.12 kg CO_2e/kWh hydrogen assuming capture rate of 95% and Sadler et al [45] 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.

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 with the financial sector and other committed to making commercially viable zero emission vessels a scalable reality by 2030.

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