South Africa: fueling the future of shipping

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

By Ricardo
& Environmental Defense Fund

For the
P4G Getting to Zero Coalition Partnership

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The Getting to Zero Coalition

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

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

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

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

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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.

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Disclaimer

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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.

Executive Summary

There is a fantastic opportunity for South Africa to produce zero carbon fuels for adoption by the South African shipping sector, and export to other markets. South Africa has the natural resources, geography, and prominence on important shipping trade routes to take advantage of this opportunity, and this in turn can help South Africa achieve its decarbonisation goals and catalyse a low carbon economy. There is the potential to create a wide range of jobs within the supply chains of zero carbon fuels, which can support South Africa's just and equitable transition as jobs in coal mining and coal-based electricity generation decrease.

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. It has identified that the most suitable options are hydrogen and ammonia for large commercial vessels such as tankers, containers and bulk carriers; small vessels such as port service vessels can be supplied through direct electrification and onboard electrification. The abundance of renewable energy resource in South Africa means that shipping fuels can be derived from renewable electricity generation.

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. Rightly so, these risks do need to be mitigated and managed properly. This challenge will need to be addressed by the industry moving forward, since the fuels could otherwise be harmful for both people and the environment. However, this should not be seen as a major barrier for adoption of these fuels. Currently used fuels are also harmful and pose risks, yet the codes, best practices and standards that have been developed over years of expertise have allowed us to use them widely and safely in a variety of applications, environments, and conditions. The same can be done for hydrogen and ammonia.

Development of zero carbon fuels infrastructure to serve South Africa's shipping sector could attract investment of between 122 and 175 billion Rand in onshore infrastructure by 2030.

South Africa's economic development and geography make it a major trading centre on the African continent

South Africa is situated on one of the busiest international sea routes, a passing point between Asia and South America and Europe; boasting strong trade links with China, Germany, United States, United Kingdom and India. As the second largest economy in Africa, South Africa is rich in natural resources, precious stones, metals, and minerals; with mining, manufacturing, textiles and chemicals as major industries.

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

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

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

South Africa has a commitment to reach net zero carbon by 2050, however it is currently reliant upon coal to supply almost 90% of electrical demand. South Africa 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. 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 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 decarbonisation goals.

Port Case Studies

This report highlights three ports which are great examples of how South African ports could capitalise on a zero carbon fuel transition: Saldanha Bay, Port of Ngqura (Coega) and Richards Bay. Saldanha Bay is one of the largest ore exporting ports in Africa and has already established shipping routes to Asian, South American and European markets. The Port of Ngqura (Coega) is located as an Industrial Development Zone (IDZ), which aims to provide industrial infrastructure linked to international sea or airports for fixed direct investment into value-added and export-oriented manufacturing industries. Currently Richards Bay is South Africa's main coal export hub, with bulk carriers as the dominant vessel category.

This report shows South Africa is presented with a great opportunity to decarbonise its maritime industry, and to supply the international market with zero carbon fuels. The transition can act as a catalyst for the country's economy: opening a new export markets, meeting decarbonisation targets and creating a range of new jobs for South Africa.

Glossary

AIS	Automatic Identification System
CCS	Carbon Capture and Storage
EDF	Environmental Defense Fund
GHG	Greenhouse Gas
GHGP	Greenhouse Gas Protocol
GtZ	Getting to Zero Coalition
IDZ	Industrial Development Zone
IMO	International Maritime Organization
INEP	Integrated National Energy Programme
IRP	Integrated Resource Plan
$MtCO_2e$	Megatonnes Carbon Dioxide Equivalent
Nersa	National Energy Regulator of South Africa
P4G	Partnering for Green Growth and the Global Goals 2030
PPE	Personal Protection Equipment
REIPP	Renewable Energy Independent Power Producers
SEZ	Special Economic Zone
SOLAS	Safety of Life at Sea
SMR	Steam Methane Reformation
TWh	Terawatt Hours

Introduction

Decarbonisation of shipping could catalyse investment and wider climate action in South Africa

The adoption of zero carbon shipping fuels has significant benefits and synergies for South Africa 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 Harbours, 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 South Africa. This work has important global context, as the shipping sector pushes to decarbonise. The International Maritime Organization (IMO), as the regulatory body for international shipping, has a target to cut greenhouse gas emissions by at least 50% of 2008 levels by 2050.

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

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

South Africa is already engaging in a number of initiatives related to zero carbon fuels and vehicle propulsion, and in particular, green hydrogen. The Government's Hydrogen Society Roadmap is under development [3] and aims to integrate hydrogen into the economy by capitalising on the country's mineral resources and renewable energy potential to revitalise and decarbonise key industrial sectors. Activities currently underway include exploration of the potential of synthetic fuels by the European Union – South Africa Partners for Growth programme [4], the Boegoebaai Hydrogen Export Port project [5], and the Hydrogen Valley project [6]. This positions South Africa to capitalise on the opportunities that the transition to zero carbon shipping fuels could bring.

Benefits and synergies for South Africa beyond shipping

The adoption of zero carbon shipping fuels is a direct route to decarbonising the shipping sector. However, it also has significant benefits and synergies for South Africa 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 South Africa 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 decarbonisation of the wider electricity sector.

4. **Availability of zero carbon fuels** that can be used to decarbonise other sectors, such as heavy transport, mining, agriculture, manufacturing and industry. This has significant potential in South Africa, with projects already investigating decarbonising heavy mining trucks and land freight.

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

Zero carbon shipping powered by renewable electricity

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 taken into account when selecting a fuel and developing the bunkering infrastructure. This report focuses on zero carbon fuels and propulsion solutions, which use renewable electricity and do not emit carbon dioxide in the supply chain or at the point of use, based on technologies that are likely to be commercially available at scale before 2030.

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

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

Green Hydrogen
Green hydrogen is produced using electrolysers powered by renewable electricity. The production process is energy intensive. 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.

	PROCESSING	ENERGY DENSITY
Renewable Electricity + Battery	Less processing, resulting in lower losses and costs.	Less energy dense; not suited to large ships undertaking long journeys.
Green Ammonia	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 in 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.

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 in renewable resources in South Africa indicates that hydrogen-derived fuels would be better suited for the context.

Blue Hydrogen and Ammonia

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

Although blue fuels have potential for shipping, this report focuses on 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. As a result, it is assumed that the lifecycle carbon emissions for producing blue fuels at industrial scales are not significantly lower than that of diesel, within the 2030 timescales of this report. 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.

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

Exhibit 2: summary of main hazards and implications for handling zero emission marine fuels. Marine gas oil and liquified natural gas are included for comparrision.

	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 has been proven for road transport and is deploying 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. New regulations and codes governing fuel in maritime applications will be required, but this process is already underway. Additionally, battery and charging technology is well establised for road transport applications. This could be expanded and developed in South Africa which would subsequently promote the application of these technologies as a marine fuel. 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 [7, 8, 9, 10]. 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.

South Africa is already a large producer of ammonia for use in agriculture and industry. It is produced and handled within South African industries, predominantly supplied by Sasol [11], and has an export value of approximately US$ 4 million per year [12]. It is therefore likely that the safety and handling of zero carbon fuels can be coordinated with reasonable ease in South Africa given the existing markets for these commodities.

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

The choice of zero carbon shipping fuels for vessels bunkering in South Africa 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.

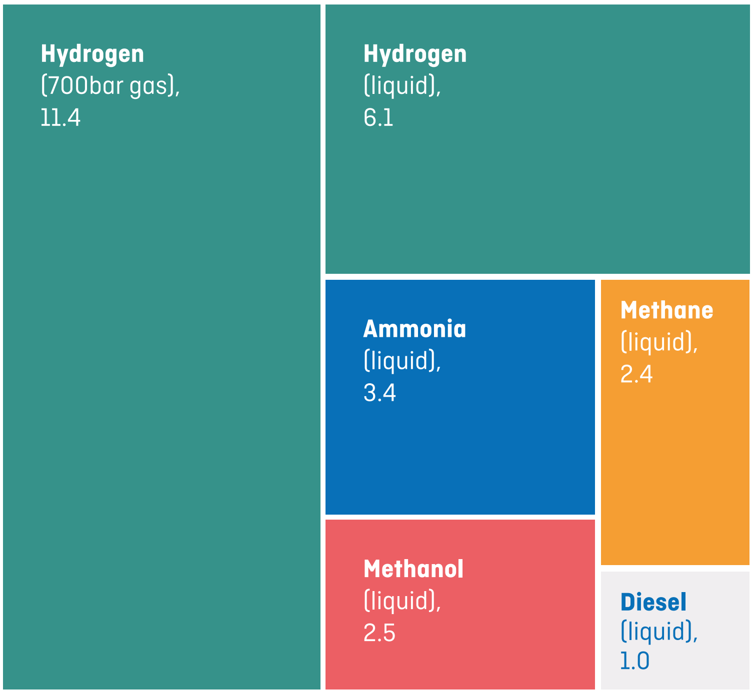
Global zero carbon fuel markets

As South Africa plays a prominent role in the global shipping sector (see section 4), the adoption of zero carbon shipping fuels in South Africa should be influenced by wider, global trends. Globally, green hydrogen and green ammonia have emerged as important fuels for the decarbonisation of shipping, with significant activity being undertaken to develop low carbon fuelling hubs and vessel technologies. Aligning the fuel selection with the rest of the world would mean that international vessels could refuel in South Africa as well as other ports over the world, and developments in vessel and bunkering technology will be available commercially for the global market. This could enable South Africa to become a zero carbon bunkering hub for the significant vessel traffic passing through its waters and to export zero carbon fuels as commodities, setting an example of how these fuels can be successfully integrated in the maritime industry as well as supporting the wider economy around the port.

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 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:Relative fuel storage volume for various shipping fuels (storage volume including tank relative to diesel) [13].



The energy density of a battery-based propulsion system is about one quarter that of a gaseous hydrogen system [14]. This means that current battery technologies are only suited to vessels where onboard volume is less of a constraint; generally smaller vessels that visit port often. 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 amount and types of vessels visiting it are important factors in understanding fuel selection and design of the infrastructure solution. Some shipping applications will be more suited to fast uptake of new, zero carbon fuels.

Large vessels, such as bulk carriers, 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 and smaller ports may find it more difficult to find ports that can supply the new fuel, so may be later to adopt zero carbon fuels.

Natural resources and land availability 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 fuels.

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 decarbonising the grid. Where natural resources are not available in the vicinity of the port, then fuels can be produced elsewhere in S Africa , imported by sea, or vessels stopping at the port may need to make separate bunkering stops elsewhere where the resources exist to generate zero carbon fuels sustainably.

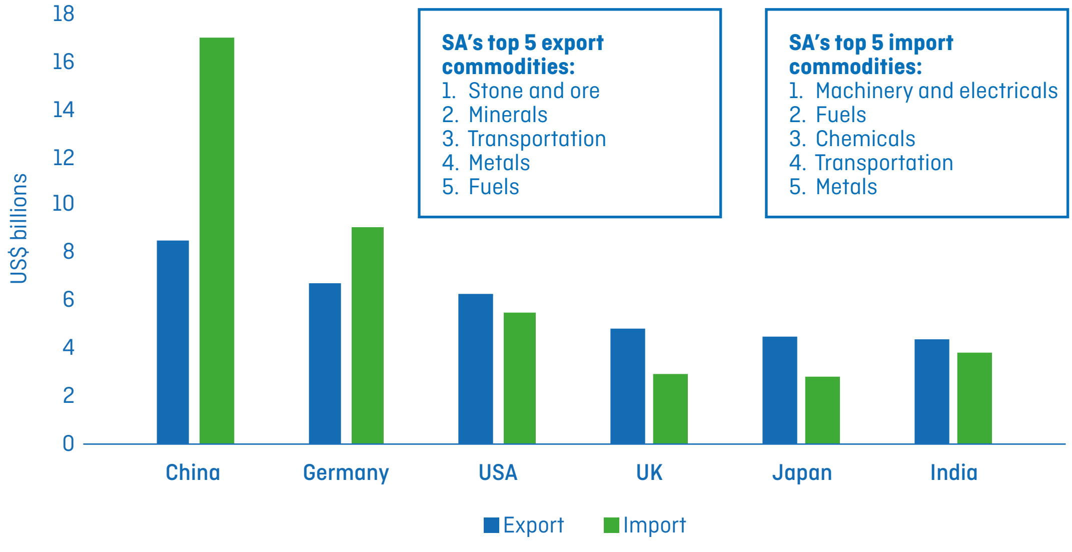
Section 4

South Africa's economic development and geography make it a major trading centre on the African continent

South Africa is located at the southern tip of the African continent with coastline stretching more than 2,800 km on both the South Atlantic Ocean on the west and the Indian Ocean on the east. It is situated on one of the busiest international sea routes as a passing point between Asia and South America and Europe; boasting strong trade links with China, Germany, United States, United Kingdom and India.

South Africa is the second largest economy in Africa and the 34th largest economy in the world [15]. It is rich in natural resources, precious stones, metals, and minerals; with mining, manufacturing, textiles and chemicals as major industries. South Africa is a major exporter of precious stones and metals, ores and motor vehicles [12].

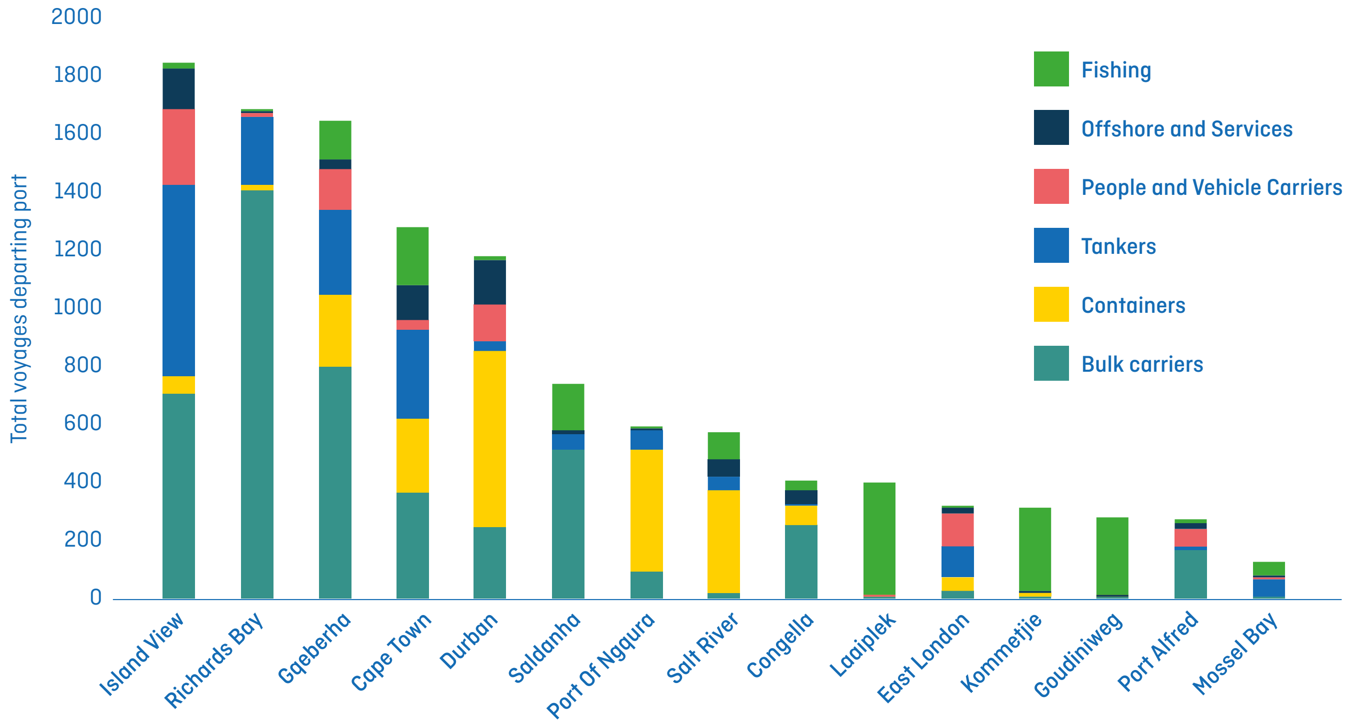
Exhibit 4: South Africa's largest trading partners by export and import.



South Africa's position as a major trade hub is illustrated by the range of vessel types visiting its ports. The majority of vessel traffic at South African ports is from bulk carriers, and this vessel category also makes up about 30% of total fuel energy usage. More broadly international and domestic cargo vessels account for about 91% of vessel energy demand[1] in South African ports, with the remainder from people and vehicle carriers, offshore and services and fishing vessels [16, 17]. Commercial cargo vessels, such as bulk carriers tankers and containers, arriving at South African ports are mainly international vessels.

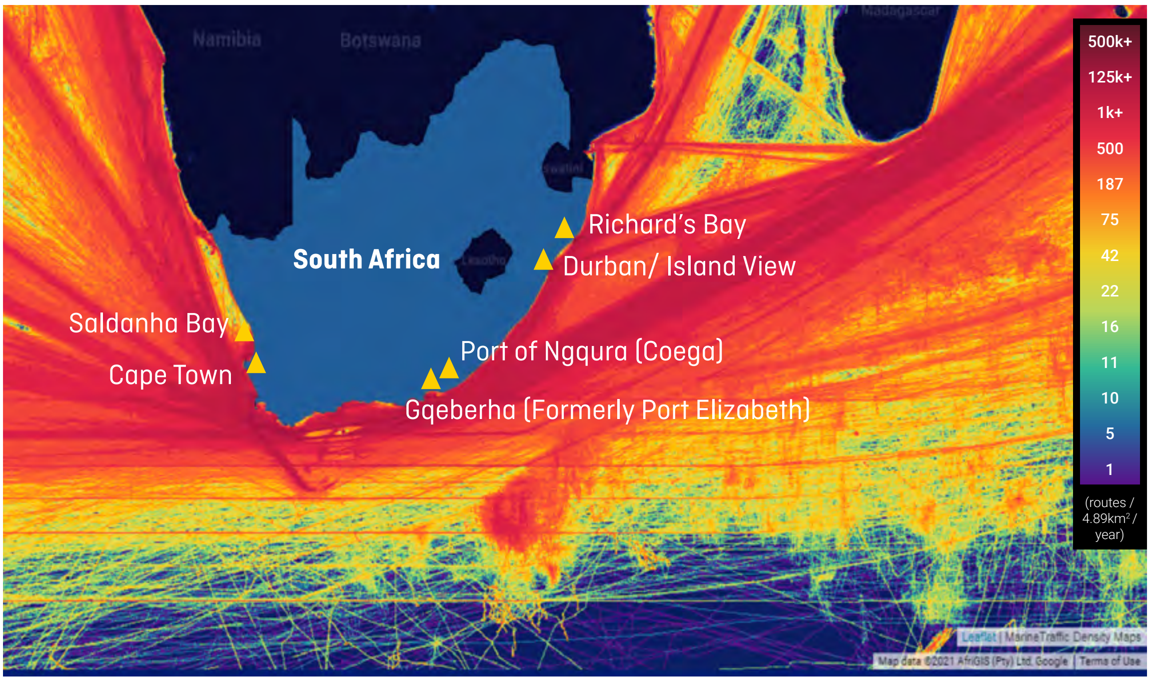
1 Throughout this report, vessel energy demand is the calculated energy demand of departing journeys from South African ports based on data from 2018 [17, 16]

Exhibit 5: Vessel traffic at the 15 busiest ports in South Africa (vessel departures in 2018).



South Africa has a relatively small number of major ports receiving large commercial vessels. The largest ports are Richards Bay and Durban on the east coast. Durban is the closest port to Johannesburg, South Africa's commercial and economic centre, as well as the executive capital, Pretoria. Richards Bay is South Africa's main coal export hub. On the west coast lies Saldanha which primarily exports iron ore, and Cape Town, an urban centre. On South Africa's south-eastern coast, in the Eastern Cape, are Gqeberha (formerly Port Elizabeth) and the Port of Ngqura (Coega).

Exhibit 6: Map of South Africa illustrating vessel traffic and South Africa's busiest sea ports. Vessel traffic data from Marine Traffic.com used with permission.



Source: Marinetraffic.com

Section 5

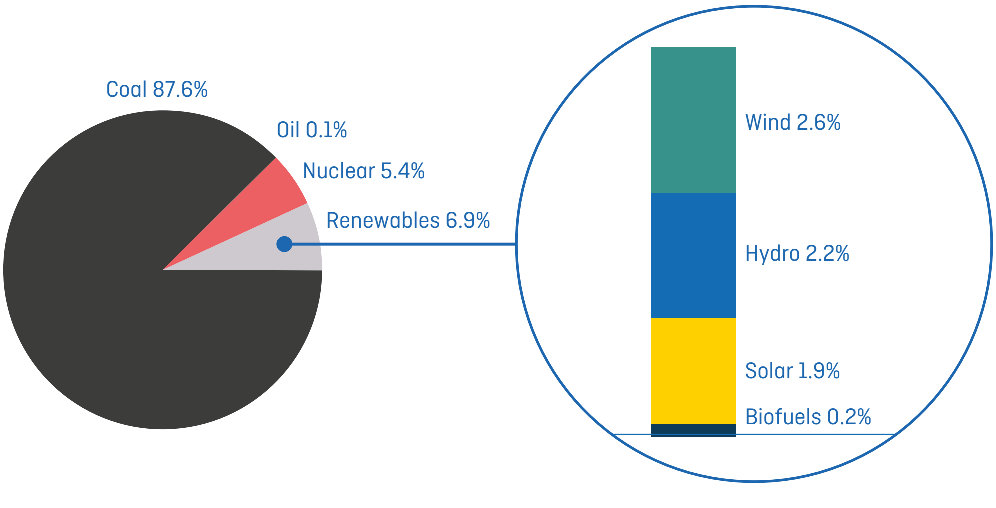
South Africa currently relies heavily on fossil fuels for electricity generation but has ambitions to reduce carbon emissions

The generation and transmission of electricity in South Africa is the responsibility of Eskom, the state-owned utility. In addition, there is a growing number of renewable energy independent power producers (REIPPs), which primarily sell electricity directly to Eskom.

In 2018, around 90% of all households in South Africa had access to electricity [15]. The government's aim expressed in the Integrated National Electrification Programme (INEP) is for all households to have access to electricity by 2025 [18]. Remote communities far from the electricity grid will have mini-grids and standalone systems which already serve about 12% of the population [19].

Coal has historically played a significant part in the South African energy mix, making up 88% of electrical generation [20]. However, this is set to reduce in the future; the government's Integrated Resource Plan (IRP) for the electricity sector predicts that coal will make up 55% of the electricity production share in 2030 and 39% in 2050 [18]. This highlights the significant role coal will continue to play in the South African energy mix in the coming years.

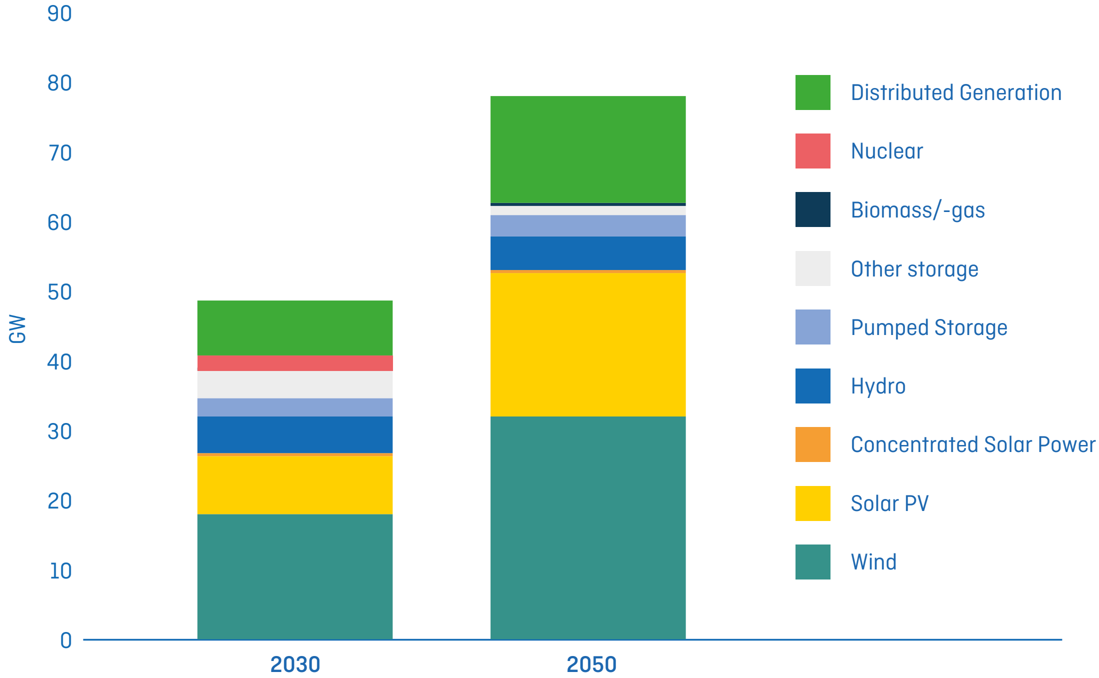
Exhibit 7: Total electricity generation by source in South Africa in 2019 [20].



Although South Africa is the 14th largest producer of greenhouse gases in the world, the South African Low Emission Development Strategy states an ambition to achieve net zero carbon emissions by 2050 [21]. In the interim, it aims to limit greenhouse gas emissions to 510 MtCO_2e in 2025 and 398 to 440 MtCO_2e by 2030. This amounts to a reduction of 42% below business as usual emissions by 2025 [22].

The South African government has a vision of a just and equitable transition to a greener economy, where renewables will play a significant role [23]. In line with this ambition, the IRP projects an increasing role for wind and solar generation, as shown in Exhibit 8 [18].

Exhibit 8: Projections of low carbon energy sources from the South African Government's Integrated Resource Plan.



Projections based on Integrated Resource Plan (2019)

There is provision within the legislative context for development of renewable plants that are dedicated to a single consumer. However, connecting these plants to the grid may add complexity because such schemes are not routinely dealt with by the National Energy Regulator of South Africa (Nersa). There is an opportunity for capacity building and efficiency improvements within Nersa that could improve this process in the future.

Currently, renewable projects larger than 100 MW capacity must be developed within the quotas laid out in the IRP [24]. Moreover, the IRP does not envisage projects for large-scale green hydrogen production. These barriers would need to be mitigated to avoid unnecessary limitations and regulatory hurdles for the development of renewables for zero carbon shipping applications. It is anticipated that the upcoming Hydrogen Society Roadmap, spearheaded by the Department of Science and Innovation, will address these barriers.

Regarding the transport sector (responsible for 11% of greenhouse gas emissions), South Africa's Green Transport Strategy aims to minimise the adverse effects of transport activities on the environment and promote the low carbon transition of the sector, to assist with the aligning and developing of policies which promote energy efficiency and emission control measures in all transport modes [25]. Adoption of zero carbon shipping technologies clearly supports these aims.

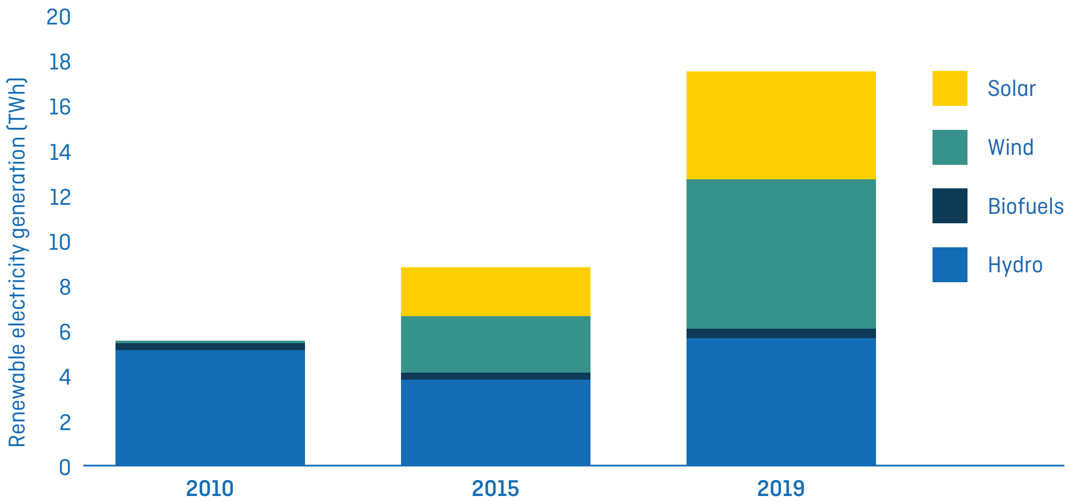
Section 6

South Africa has abundant renewable potential to supply its future demand and more

Historically, renewable electricity generation has not made up a significant proportion of the energy mix, providing about 7% of electricity in 2019 [20]. Yet, there is abundant potential to significantly increase the number of renewable plants, particularly wind and solar.

Despite having a successful procurement programme for renewable electricity from 2011, project implementation in recent years was delayed by political factors which has dented private sector confidence. However, the sector is starting to experience renewed growth following changes in government. This is evident in the increase in contribution from wind and solar plants since 2010 as shown in Exhibit 9.

Exhibit 9: South Africa's historical renewable and low carbon generation [20].



Some of the resistance to renewables has been from trade unions and other stakeholders in the coal sector, including Eskom. This is due to the perceived risks that renewables could pose to the local coal sector, which plays an important role in the economy. The government is working on plans for a just and equitable transition for people that are currently dependant on the coal sector for income as the country embraces increased contributions from renewable sources to the grid. The IRP estimates that renewables will make up about a third of South Africa's electricity production share by 2030 and about 40% by 2050 [18].

The renewable electricity plants for zero-carbon shipping would need to be built in addition to those planned in the IRP to avoid undermining the decarbonisation of the electricity system. These plants would be primarily used to support zero-carbon propulsion, which is a completely new source of demand, rather than displacing existing power plants from the grid. Therefore, they should not be perceived as a direct threat to the coal sector and should be able to garner unanimous public support. This means that the shipping sector could enable South Africa to capitalise on its abundant potential and drive investment in renewables without being held back by concerns about the impact on the coal sector.

Despite the relatively low roll-out of wind and solar plants to date, South Africa has abundant potential for these resources. One paper by International Renewable Energy Agency and Sweden's Royal Institute of Technology [26] estimated a theoretical potential of about 48,000 TWh per year from solar and onshore wind resources alone. This number will decrease when economic, environmental and practical considerations (for example proximity to the electricity grid, land use change and land ownership) are taken into account, but the potential renewable energy resource in South Africa is still very large. The following paragraphs identify the renewable potential that could be reasonably accessed by 2030 based on current technologies and land-use limitations.

Onshore and offshore wind

Onshore wind resources in South Africa are particularly promising. Between 50% and 70% of the land in South Africa (excluding protected and sensitive areas) would be suitable for wind farms based on current turbine technology [27]. This represents thousands of terawatt-hours of electricity potential per year. Further detailed studies are required to identify the feasible onshore wind potential, taking into account proximity to the existing grid and project finance considerations. In the absence of such studies, a study by Fluri [28] calculated the land area within 20 km of high voltage transmission lines that have good potential for renewable plants. The areas in the Northern Cape and Eastern Cape provinces have typical wind capacity factors[2] of about 30%, which is suitable for wind turbines. A high level assessment of these areas indicates that about 250 TWh per year[3] of wind potential would be available in the Northern Cape and Eastern Cape alone. A more detailed analysis would be required to review the additional feasible potential in the other 7 provinces.

In addition, South Africa has a large amount of offshore wind potential hugging the coast, with the potential for 190 TWh/year of fixed and 3,360 TWh/year of floating offshore wind capacity[4] [29]. Floating offshore wind is expected become commercially viable by 2030, so could be an extremely valuable resource to supply South Africa's ports with renewable energy.

Solar

South Africa also has excellent solar potential. The study by Fluri [28] focussed on concentrating solar power (CSP) plants located within 20 km of power lines, estimating potential of about 1,860 TWh per year with most of the potential in the Northern Cape. If this was solar photovoltaic (PV) rather than CSP, then the potential would be about 1,100 TWh/y[5].

2 For renewable plants, capacity factor is defined as the amount of electricity produced in a year divided by the amount of electricity the plant would have produced if it had operated at its peak capacity for the whole year. The capacity factors used in this study are typical for South Africa and relatively high compared to international averages.
3 Based on an area of about 25,500 km^2, installed capacity of 96 GW and nominal capacity factor of 30%.
4 Based on installed capacities of 49 GW fixed and 852 GW floating at nominal capacity factor of 45%.
5 Based on capacity factors of 38.8% for CSP [28] and 23% for solar PV.

Total potential

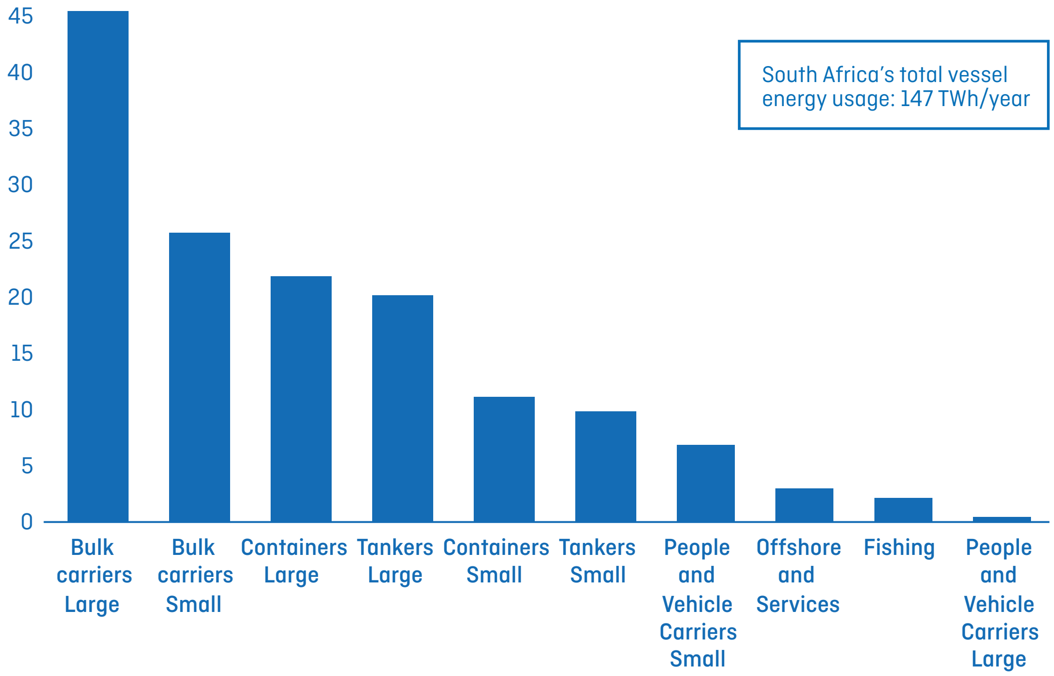
The combination of the estimates for wind and solar technologies, together with an estimate of 21 TWh for hydro potential [30] gives a total potential supply from renewables of between 1,570 and 5,690 TWh. This is an indicative range based on various sources and does not represent an upper limit. Further studies are required to gain a more detailed understanding of the renewable potential that could be feasibly developed and the value is likely to increase as technologies improve over time. Nevertheless, as the next section describes, it does demonstrate that the potential comfortably exceeds the forecast demand for renewable electricity from the grid plus the renewable electricity required to decarbonise the vessels visiting South Africa's ports.

It is vital that renewable generation infrastructure is established responsibly, with the environmental and social impacts being taken into consideration. This includes considering direct and indirect land use change – especially where renewable generation infrastructure is established on land that would otherwise be used for food-producing agriculture. Where agriculture is displaced by renewable electricity generation infrastructure, this activity may be forced to move to other locations leading to destruction of habitats or other environmental and ecological impacts.

Section 7

South Africa's abundant renewable energy potential puts it in a strong position to produce zero carbon fuels

Exhibit 10: Energy usage by vessel category in 2018, based on energy required at departure.



The energy requirement for South Africa's shipping sector is dominated by large commercial vessels, mainly bulk carriers carrying products such as iron ore and coal. In total, the fuel energy demand from all domestic and international commercial vessels providing Automatic Identification System (AIS) data departing South African ports was approximately 145 TWh/year in 2018 [16, 17][6]. 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 [16], giving a total energy demand of approximately 147 TWh/year [17].

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 full adoption of zero carbon vessel technologies by 2030, South Africa would require approximately 275 TWh/year of renewable electricity to satisfy demand.

6 Calculated energy demand of departing journeys from South African ports based on Automatic Identification System (AIS) data from 2018 [17, 16]

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 decarbonisation targets [31]. While this number is not meant to reflect targets for each individual country, it is used here as a reasonable scale of take up of zero carbon fuels to produce example results. Assuming a 5% uptake of zero carbon fuels by vessels visiting South Africa's ports and that all of these vessels refuelled during their visits, about 13.7 TWh/year of renewable generation would be required (see Appendix D).

In monetary terms, there is a possibility to attract investment of between 122 and 175 billion Rand to build the infrastructure required by 2030 to provide renewable electricity and zero carbon fuels to decarbonise 5% of the vessels visiting South Africa's ports. Of this between 79 and 118 billion Rand 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.

It is important that renewable electricity should be used to decarbonise South Africa's national electricity grid, as well as to provide fuels for shipping. The 2019 IRP predicts the national electricity demand to be between 280 and 320 TWh/year by 2030 [18]. As detailed in the previous section, South Africa holds the potential to generate at least 1,570 to 5,670 TWh/y in renewable electricity from solar, onshore wind and offshore wind. This illustrates that, on a national scale, there is abundant renewable generation potential available in South Africa to decarbonise the electricity grid as well as cater for adoption of zero carbon vessel propulsion technologies.

Required renewable electricity generation to support 5% adoption of zero carbon vessel technologies in 2030:
~13.7 TWh/year

The investment potential for infrastructure to support 5% adoption of zero carbon vessel technologies by 2030:
122 – 175 billion Rand

South Africa's national electricity demand to in 2030 is forecast to be:
280 to 320 TWh/year

South Africa's approximate feasible renewable potential:
1,570 – 5,690 TWh/year

Section 8

Adoption of zero carbon shipping fuels can bring benefits far beyond the shipping sector

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

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

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

The production of alternative fuels would be accompanied by the creation of a wide range of jobs within the supply chains of zero carbon fuels. As jobs in fossil fuel extraction, transport and electricity generation decrease, the creation of jobs within sustainable supply chains could play a pivotal role in supporting a just transition. This includes a range of job roles, skill levels and education requirements, and includes roles in renewable generation, fuel generation, storage and handling, research and manufacturing of related technology solutions such as fuel cells. Current policies in South Africa ensure the involvement of local small to medium enterprises in projects, ensuring that benefits reach local residents.

The International Energy Agency [32] advises that governments should engage with all stakeholders to gain an understanding of how the jobs created in the clean energy sector relate to the jobs that are lost in fossil fuel sectors as the energy transition progresses. This is because the jobs created may not offer direct replacements for those lost by the fossil fuel sector, requiring a strategic approach to managing the transfer of skills as well as re-training those whose skills are no longer relevant. There is also a need to manage the risks of jobs being created in different locations to where fossil fuel jobs are lost. In investigating these needs, the South African government could consider how demand for minerals such as platinum group metals is expected to increase along with demand for low carbon technologies like electrolysers and fuel cells. This could provide alternative job opportunities for those who have experience in coal mining, for example.

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 Japan, Germany and the Netherlands [4]. If South Africa adopts zero carbon fuels early it could establish itself as a world leader in production and could feed into these markets benefitting from its location on major shipping routes.

Production of green hydrogen and ammonia would also position South Africa 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, South Africa will be at an advantage being able to offer these options to vessels.

Similarly, the production of green steel, by means of green hydrogen, is a commodity that could feed directly into these growing green commodity markets. South Africa could also leverage further opportunities in related zero carbon fuel technologies. For example, South Africa has a strong record of accomplishment in fuel cell research, and the establishment of zero carbon fuels could further develop this skill set as well as develop new employment in a new sector.

Cleaning up port operations

Increased availability of renewable electricity will also allow ports to decarbonise their own operations as well as improve air quality. In addition to decarbonising the ports' vessels, they could electrify or provide zero-carbon fuels for trucks, forklifts, cranes and other land-based vehicles. The Ports of Los Angeles, Antwerp and others have led the way in this area, also showing that renewable electricity can be used to provide shore power to provide vessels' onboard power needs while they are docked, avoiding the need to run auxiliary engines. These relatively simple measures would reduce the carbon footprint, noxious gases and particulates around the port, to the benefit of the surrounding community and environment.

A catalyst for decarbonisation of the South African economy

Investment in renewable electricity, zero carbon fuels and sustainable infrastructure, can support the decarbonisation of the South African economy far beyond shipping. Establishing renewable generation at scale within South Africa will support wider decarbonisation of the energy sector, through establishing strong supply chains, developing skills and experience with these technologies, and benefitting from economies of scale.

In addition, the availability of zero carbon fuels can be used to decarbonise other sectors, such as heavy transport, mining, agriculture, manufacturing and industry. This has significant potential in South Africa, with projects already investigating decarbonising heavy mining trucks and land freight.

Attracting foreign investment

The development of investible projects in renewable generation, zero carbon shipping fuels and associated co-benefits for industry would mean that the transition can be financed through international climate funding alongside partnerships with the domestic and international private sector.

After initial transition to zero carbon fuels the cost of production in South Africa would reduce as methods and technology the commodity could become an even more competitive.

Conclusions

With its excellent renewable potential, South Africa could capitalise on the impetus to decarbonise international shipping to create a new export market for zero carbon fuels and develop 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, South Africa could attract foreign investment through international funding, which would present opportunities for local enterprises to grow and develop skills and expertise. The opportunity to attract this investment is significant, estimated to be between 122 and 175 billion Rand by 2030. This expansion could be sustained by demand from international shipping companies as adoption of zero carbon fuels increases over the coming years if the South African government puts the right policies in place and supports ambitious global policy at the International Maritime Organization.

The development of the zero carbon fuel sector would create a wide range of jobs across the whole range of skill and education levels, supporting a just and equitable transition towards a low carbon economy.

The production of zero carbon fuels requires significant amounts of renewable electricity, which would be over and above the requirements of the grid. This demand, especially for wind and solar power, will drive the development of supply chains and allow South Africa to capitalise on its excellent renewable potential.

Even as South Africa has great prospects to benefit in this way, there are similar opportunities for other developing nations in Africa 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 decarbonised shipping.

Potential for synergies and cooperation with surrounding countries

The benefits described in this report are not limited to South Africa, and a wider, regional adoption of zero carbon fuels would support trade routes and regional co-benefits. The map below provides some further examples of ports that have potential to benefit from decarbonisation of shipping activity. There are many more ports in the region that could benefit in similar ways.

Port of Mombasa, Kenya
The Port of Mombasa is Kenya's busiest and largest seaport, serving the hinterland by exporting important agricultural products and supporting the foundation of the Kenyan economy.

Porto Alexandre in Tômbua, Angola
Porto Alexandre is located in Angola is a natural bay that is home to a thriving fishing industry. The town is surrounded by desert with excellent solar and wind potential and it is conveniently located on a busy shipping route. Providing zero carbon refuelling facilities to passing vessels could be a major new source of income for the local community.

Maputo Port, Mozambique
There are two main components to the port, the Maputo Cargo Terminals, which include the citrus, sugar, container, iron and scrap terminals and, 6 km further upriver, the Matola Bulk Terminals with four deep-water berths for handling bulk minerals, Petroleum, aluminium and grain.

Port of Lüderitz, Namibia
The Port of Lüderitz serves the mines in the southern regions of Namibia and north-western South Africa with imports and exports of mining commodities. It is also an important base for the local fishing industry.

Port case study

Saldanha Bay, Western Cape: an opportunity to establish a low carbon economy in South Africa

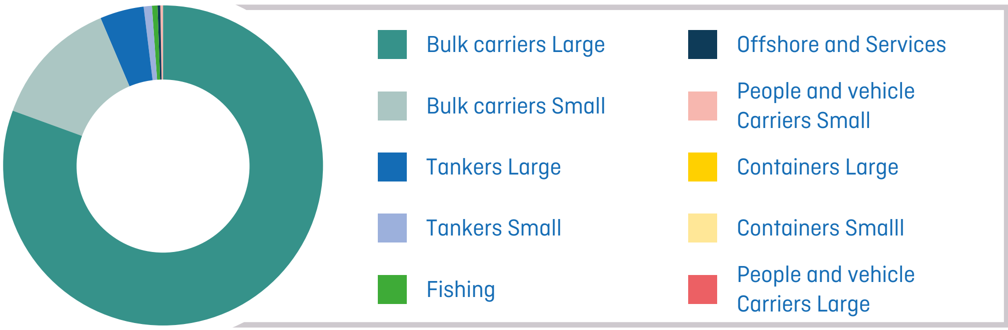
Saldanha Bay is one of the largest ore exporting ports in Africa and has established shipping routes to Asian, South American and European Markets. There is an opportunity to establish zero and low carbon industries exporting fuels and goods to the global market.

Saldanha Bay is located in the Western Cape province, approximately 150 km North of Cape Town. It is a natural sheltered harbour which has led to its development as a port for the export of iron ore from Sishen in the Northern Cape, which is transported to the port by rail. Saldanha Bay is one of the largest ore exporting ports in Africa, and is located in a Special Economic Zone (SEZ), with the aim of attracting foreign direct investment and encouraging the export of value-added goods and services. Recently Transnet, the state-owned company responsible for ports, has commissioned a crude oil terminal adjacent to Strategic Fuel Fund premises [31]. Saldanha Bay has robust value chains; port infrastructure requirements as well as vessel repair and maintenance.

This is the closest of the port case studies to South Africa's large solar PV potential, and there is significant fixed offshore wind potential to the north of Saldanha as well as floating wind potential over a wider area surrounding the coast.

Annual energy usage of vessels visiting Saldanha Bay is 16 TWh per year; 77% of which is made up of bulk carriers (see Exhibit 11). The adoption of green ammonia in particular would be appropriate for these vessels due to its relatively high energy density compared with hydrogen.

Exhibit 11 - Fuel energy requirement of vessels departing Saldanha Bay by vessel category (vessel category definitions can be found in Appendix C)



Saldanha Bay presents a great opportunity to create a zero carbon fuels hub

Saldanha Bay presents an opportunity to create a hub not only for bunkering zero carbon vessels but also for exporting zero carbon fuels as a commodity. There are also opportunities for synergies with local industry, leading to economic growth and the creation of jobs requiring a wide range of qualifications and skills. For example, a recently mothballed steel mill near the port has the potential to be converted to produce "green steel" with very low emissions. The bulkers carrying iron ore shuttle between the port and one or two destination ports provide opportunities for dedicated zero carbon shipping routes with refuelling infrastructure at both ends.

Port case study

Port of Ngqura, Eastern Cape: zero carbon fuels offering a competitive advantage on a low carbon global market

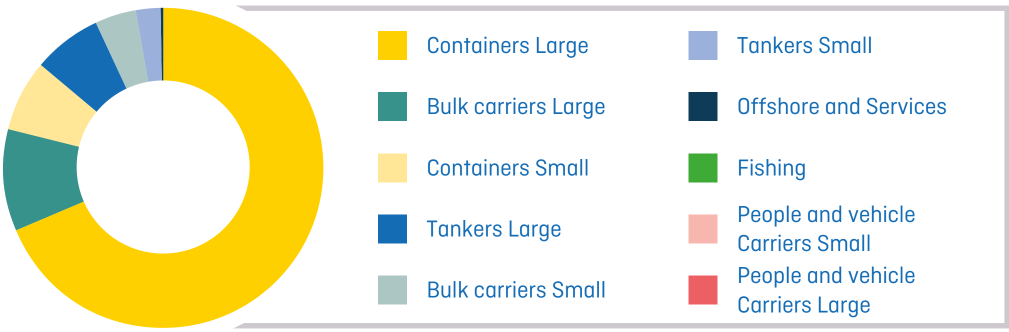
The Port of Ngqura is a SEZ and IDZ located in the Eastern Cape province. Container vessels make up the majority of vessels traffic making voyages across the globe. There is an increasing global demand for low carbon products, and providing the vessels visiting the Port of Ngqura with the option of zero carbon shipping fuels will be a competitive advantage.

The Port of Ngqura in the Coega SEZ is located in the Eastern Cape province about halfway between Cape Town and Durban. The port is in a natural harbour providing relatively shallow water around the port which has good fixed offshore wind potential as well as further potential for floating offshore wind to be developed when the technology is available. The potential of offshore wind provides Coega an opportunity to produce a supply of zero carbon fuels for the maritime industry as well as other industries. Having a large offshore wind potential close to the port means that this is an attractive option to provide energy for fuel production facilities, which is less likely to cause environmental, social and land use issues onshore.

Container ships account for almost 75% of vessel with bulk carriers and tankers comprising most of the balance. Container ships may have a particular drive towards decarbonised fuels as the market for the products and materials they transport is likely to see an increasing demand for zero carbon options. This may mean that container ports such as the Port of Ngqura will benefit from providing these options to vessels.

The energy demand of ships departing the Port of Ngqura is approximately 10 TWh/year. The vessels visiting this port are well suited to adopting green hydrogen and ammonia.

Exhibit 12: Fuel energy requirement of vessels departing the Port of Ngqura by vessel category (Vessel category definitions can be found in Appendix C)



The port is within an Industrial Development Zone (IDZ), which aims to provide industrial infrastructure linked to international sea or airport links for fixed direct investment into value-added and export-orientated manufacturing industries. Being part of an IDZ means that Coega has tax exemptions under special circumstances for supplies procured in South Africa, and duty suspensions on imports of certain production-related supplies, including assets used in export-focused production.

The Port of Ngqura could become a leader in low carbon goods

Container ships may have a particular drive towards decarbonised fuels as the market for the products and materials they transport is likely to see an increasing demand for zero carbon options. This means that container and bulk ports such as the Port of Ngqura may benefit from providing these options to vessels, establishing itself as a hydrogen and zero carbon fuelling hub. The port could also provide renewable electricity and fuels for wider industry around the port, supporting the production of lower carbon goods for use by South Africa or for export to the global market, actively supporting the aims of the IDZ.

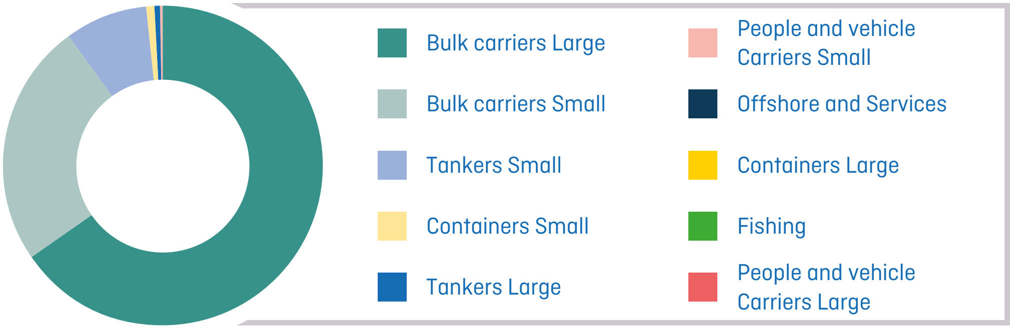
Port case study

Richards Bay, Kwazulu-Natal: an opportunity for a just and equitable transition to a low carbon alternative to fossil economies

Richards Bay is South Africa's main coal export hub. The port is presented with an opportunity to transition producing and exporting zero carbon fuels, enabling future growth for the port and surrounding industries.

Richards Bay is located 180 km north of Durban in Kwazulu-Natal province. Bulk carriers are the dominant vessel category however, various other vessel types feature too. Richards Bay has strong existing infrastructure for the bunkering of large vessels and transport of fuels to the port. The energy requirement of vessels departing Richards Bay is by far the highest of all case study ports, at 27 TWh per year: 71% of this is from bulk carriers [16].

Exhibit 13: Fuel energy requirement of vessels departing Richards Bay by vessel category (Vessel category definitions can be found in Appendix C)



Richards Bay would be suited to the establishment of green ammonia to supply its high demand from bulk carriers. It could be assumed that demand for small vessels servicing largo cargo carriers could benefit from adopting onboard batteries that are recharged on shore.

Richards Bay is suited to the development of fixed offshore wind as well as significant potential for floating offshore wind in the future. There is resonable solar potential surrounding Richards Bay however there is limited land avliability in the area. Onshore wind is a potential solution as there is good potential in proximity to the port, and wind infrastructure can be co-located with agricultural land with minimal impact, enabling a supply of renewable energy and provding an opportunity for the local agricultural industry. Residues from agriculture and industry such as sugar, paper and pulp could be a source of electricity from biomass, although this would be at relatively small scale. A mix of generation would create reliable power from intermittent generators.

Richards Bay can demonstrate a transition to a sustainable economy

As a key part of the coal supply chain, there is an opportunity for the port of Richards Bay to set an example of a just and equitable transition away from reliance on fossil fuels towards sustainable products. Bunkering of zero carbon fuels and export of green hydrogen could provide sustainable alternatives to the heavy reliance on coalhandling [32]. Zero carbon fuels could facilitate a just and equitable transition of livelihoods to new and more diverse markets.

References

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

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

[3] T. Creamer, "Cabinet expected to approve Hydrogen Society Roadmap by early 2022 at latest," Engineering News, 14 April 2021. [Online]. Available: https://www.engineeringnews.co.za/article/cabinet-expected-to-approve-hydrogen-society-roadmap-by-early-2022-at-latest-2021-04-14/rep_id:4136 [Accessed 16 April 2021].

[4] 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.

[5] Department of Economic Development and Tourisim, "Boegoebaai Port," Northen Cape , pp. 22-24, April 2020.

[6] Business Tech, "Government and businesses to look at massive 'Hydrogen Valley' project in South Africa," Business Tech, 2 April 2021. [Online]. Available: https://businesstech.co.za/news/energy/479901/government-and-businesses-to-look-at-massive-hydrogen-valley-project-in-south-africa/. [Accessed 16 April 2021].

[7] ABS, "Ammonia as Marine Fuel," American Bureau of Shipping, Spring, Texas, 2020.

[8] Korean Register, "Forecasting the Alternative Marine Fuel - Ammonia," Korean Register, Busan, 2020.

[9] DNV, "Ammonia as a Marine Fuel: Safety Handbook," DNV, Bærum, 2021.

[10] 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].

[11] Sasol, "Products," 2021. [Online]. Available: https://products.sasol.com/pic/products/home/index.html [Accessed 14 April 2021].

[12] World Bank, "South Africa Trade Statistics," World Bank, 2018.

[13] B. Rogers and A. Trevisan, "Fuel Focus - Ammonia," in Ship.Energy Summit 2021, Online, 2021.

[14] 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.

[15] World Bank, "South Africa Overview," 2021.

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

[17] J. Faber, S. Hanayama, S. Zhang, P. Pereda, B. Comer, E. Hauerhof, W. Schim van der Loeff and E. Al, "Fourth IMO GHG Study 2020," International Maritime Organization, London, 2020.

[18] Department of Mineral Resources and Energy, "Integrated Resource Plan," Department of Mineral Resources and Energy, Pretoria, 2019.

[19] International Energy Agency, "South Africa Energy Outlook," 2019.

[20] IEA, "Data and statistics: Electricity in South Africa," International Energy Agency, 2021. [Online]. Available: https://www.iea.org/data-and-statistics/data-tables?country=SOUTHAFRIC&energy=Electricity&year=2019. [Accessed 19 May 2021].

[21] Government of South Africa, "South Africa's Low Emision Development Stratergy 2050," 2019.

[22] Carbon Brief, "The Carbon Brief Profile: South Africa," 2018.

[23] Department of Energy, "The State of Renewable Energy in South Africa," Department of Energy, Pretoria, 2017.

[24] The Presidency Republic of South Africa, "President announces major reform to enable investment in embedded generation and promote energy security", 2021 [Online]. Available: http://www.thepresidency.gov.za/press-statements/president-announces-major-reform-enable-investment-embedded-generation-and-promote-energy-security

[25] Republic of South Africa, "Green Transport Strategy for South Africa (2018-2050)," 2018.

[26] S. Hermann, A. Miketa and N. Fichaux, "Estimating the Renewable Energy Potential in Africa, IRENA-KTH working paper," International Renewable Energy Agency, Abu Dhabi, 2014.

[27] S. Bofinger, B. Zimmermann, A. Gerlach, T. Bischof-Niemz and C. Mushwana, "Wind and Solar PV Resource Aggregation Study for South Africa (Presentation)," CSIR, Pretoria, 2016.

[28] T. P. Fluri, "The potential of concentrating solar power in South Africa," Energy Policy, vol. 37, pp. 5075-5080, 2009.

[29] World Bank Group, "Offshore Wind technical Potential in South Africa," 2021.

[30] K. Kusakana and H. Vermaak, "Hydrokinetic power generation for rural electricity supply: Case of South Africa," Renewable Energy, vol. 55, pp. 467-473, 2013.

[31] P. Osterkamp, T. Smith and K. Søgaard, "Five percent zero emission fuels by 2030 needed for Paris-aligned shipping decarbonization," Global Maritime Forum, 9 March 2021. [Online]. Available: https://www.globalmaritimeforum.org/news/five-percent-zero-emission-fuels-by-2030-needed-for-paris-aligned-shipping-decarbonization.

[32] IEA, "Net Zero by 2050," International Energy Agency, Paris, 2021.

[33] L. Bankes-Hughes, "New Saldanha Crude Oil Terminal Comissioned," Bunkerspot, 29 April 2020. [Online]. Available: https://www.bunkerspot.com/africa/50404-africa-new-saldanha-crude-oil-terminal-commissioned.

[34] PWC, "What a Just Transition means for jobs in South Africa".

[35] S. Suárez de la Fuente, "Green ambition: solutions and investment for a decarbonised future," The Naval Architect, pp. 28-31, January 2020.

[36] IRENA, "Global Trends," IRENA, [Online]. Available: https://www.irena.org/Statistics/View-Data-by-Topic/Costs/Global-Trends. [Accessed 25 May 2021].

[37] IRENA, "Global Renewables Outlook 2020," IRENA, Abu Dhabi, 2020.

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

[39] 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.

[40] 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.

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

[42] D. Schlissel, "Boundary Dam 3 Coal Plant Achieves Goal of Capturing 4 Million Metric Tons of CO_2 But Reaches the Goal Two Years Late," Institute for Energy Economics and Financial Analysis, Lakewood, 2021.

[43] P. Balcombe, K. Anderson, J. Speirs, N. Brandon and A. Hawkes, "Methane and CO_2 emissions from the natural gas supply chain," Imperial College London, London, 2015.

[44] CCC, "Hydrogen in a low-carbon economy," Committee on Climate Change, London, 2018.

[45] D. Sadler and A. Et, "Leeds City Gate h21," Leeds City Gate, Leeds, 2016.

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

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

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

Sources: Ricardo analysis and discussions with University College London [16]

Appendix D: Electricity demand for zero carbon propulsion in 2030

Input assumptions - Demand

Description	Value	Units	Reference
Shipping demand growth 2018 - 2030	2%	p.a.	[17]
Energy efficiency improvement 2018 - 2030	1.2%	p.a.	[35]
Uptake of zero/low carbon fuels in 2030	1%	Low estimate	
Uptake of zero/low carbon fuels in 2030	5%	High estimate	[31]
ZAR/USD exchange rate	16.47		Exchangerates.org.uk average for 2020
Costs indexed to this year	2020		

Input assumptions - Renewables supply

Technology	Assumed contribution	Capacity factor	Installed cost (low case)	Installed cost (high case)
			USDm/MW in 2030	USDm/MW in 2030
Solar PV	23%	0.23	0.40	0.60
CSP	12%	0.39	1.89	2.84
Onshore wind	50%	0.30	0.93	1.40
Offshore wind	15%	0.45	1.53	2.30
References			[36] for 2018 costs, reduction to 2030 as per [37]	

Fuel/storage data from MCA

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

Calculated energy requirements

Vessel category	Preferred fuel/ storage from MCA	Powertrain tech	Fossil fuel energy demand 2018	Fossil fuel energy demand 2030	Zero/low carbon fuel energy demand 2030, 100% uptake	Zero/low carbon fuel energy demand 2030, 1% assumed uptake	Zero/low carbon fuel energy demand 2030, 5% assumed uptake	Renewable electricity requirement 2030, 100% assumed uptake	Renewable electricity requirement 2030, 1% assumed uptake	Renewable electricity requirement 2030, 5% assumed uptake
			GWh/y	GWh/y	GWh/y	GWh/y	GWh/y	GWh/y	GWh/y	GWh/y
Bulk carriers: Large	Green Ammonia	ICE - Compression	45,546	50,226	50,226	502	2,511	89,689	897	4,484
Bulk carriers: Small	Green Hydrogen	ICE - Compression	25,652	28,288	28,288	283	1,414	50,515	505	2,526
Tankers: Large	Green Ammonia	ICE - Compression	21,697	23,927	23,927	239	1,196	42,727	427	2,136
Tankers: Small	Green Ammonia	ICE - Compression	10,927	12,050	12,050	120	602	21,517	215	1,076
Containers: Large	Green Ammonia	ICE - Compression	19,832	21,870	21,870	219	1,093	39,054	391	1,953
Containers: Small	Battery	ICE - Compression	9,813	10,821	6,012	60	301	6,328	63	316
People & Veh. Carr: Large	Green Ammonia	ICE - Compression	411	453	453	5	23	809	8	40
People & Veh. Carr: Small	Green Hydrogen	ICE - Compression	6,644	7,327	7,327	73	366	13,084	131	654
Offshore and Services	Green Ammonia	ICE - Compression	2,726	3,007	3,007	30	150	5,369	54	268
Fishing	Green Ammonia	ICE - Compression	2,105	2,322	2,322	23	116	4,146	41	207
Small boats: Industrial	Battery	Electric motor	2,088	2,302	1,279	13	64	1,346	13	67
Small boats: Fishing / Small	Battery	Electric motor	91	100	56	1	3	58	1	3
Grand total			**147,532**	**162,692**	**156,815**	**1,568**	**7,841**	**274,642**	**2,746**	**13,732**
Total - Battery					**7,346**	**73**	**367**	**7,733**	**77**	**387**
Total - Green Ammonia					**113,854**	**1,139**	**5,693**	**203,310**	**2,033**	**10,166**
Total - Green Hydrogen					**35,615**	**356**	**1,781**	**63,599**	**636**	**3,180**

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	ZARm
Battery	387	8760	44	0.15	7	109
Green Ammonia	10,166	8000	1,271	1.58	2,008	33,067
Green Hydrogen	3,180	8000	397	1.61	640	10,540
Total	**13,732**		**1,712**		**2,654**	**43,716**

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

Fuel type	Annual electricity requirement	Installed capacity	Investment cost - Renewables plants	Investment cost - Renewables plants
	GWh/y	MW	USDm	ZARm
Solar PV	3,158	1,568	632	10,410
CSP	1,648	482	912	15,014
Onshore wind	6,866	2,613	2,430	40,018
Offshore wind	2,060	523	799	13,167
Total	**13,732**	**5,185**	**4,773**	**78,610**

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	ZARm
Battery	387	8760	44	0.28	12	204
Green Ammonia	10,166	8000	1,271	2.10	2,668	43,949
Green Hydrogen	3,180	8000	397	2.07	823	13,552
Total	**13,732**		**1,712**		**3,504**	**57,704**

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

Fuel type	Annual electricity requirement	Installed capacity	Investment cost - Renewables plants	Investment cost - Renewables plants
	GWh/y	MW	USDm	ZARm
Solar PV	3,158	1,568	948	15,615
CSP	1,648	482	1,367	22,521
Onshore wind	6,866	2,613	3,645	60,027
Offshore wind	2,060	523	1,199	19,751
Total	**13,732**	**5,185**	**7,159**	**117,915**

Summary of investment potential

	Low case	High case
	ZARm	ZARm
Fuel production & delivery	43,716	57,704
Renewable plants	78,610	117,915
Total	**122,326**	**175,619**

Appendix E: Lifecycle greenhouse gas emissions of blue fuels

As described in Section 1, blue hydrogen is a commonly accepted term for the production of hydrogen using the steam methane reforming (SMR) process where some of the carbon dioxide emissions are captured and prevented from going to atmosphere. Blue hydrogen and its derivative, blue ammonia, could play an important role in the decarbonisation of shipping. It has the advantage of being cheaper to produce than green hydrogen in most jurisdictions based on current costs of natural gas (for blue hydrogen) and renewables (for green hydrogen) [38].

The lifecycle greenhouse gas (GHG) emissions of blue hydrogen are an important consideration when assessing its potential as a low carbon shipping fuel. Current carbon capture technologies do not capture 100% of the carbon dioxide emitted from the SMR plant. In addition, there are GHG emissions to consider in the natural gas supply chain as well as the process where the captured carbon dioxide is transported and stored. EDF and UMAS [39] 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 [40] as 0.27 kg CO_2e/kWh[7].

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).

7 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 the IEAGHG [41] 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 [42]. 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[8] 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[9].

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. [43] 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 HHV[10] 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

8 Lower heating value of hydrogen = 33.3 kWh/kg
9 Lower heating value of diesel = 11.93 kWh/kg [40]
10 HHV means higher heating value

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 [41]). Assuming the median scope 3 emissions excluding natural gas liquefaction from [43] (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