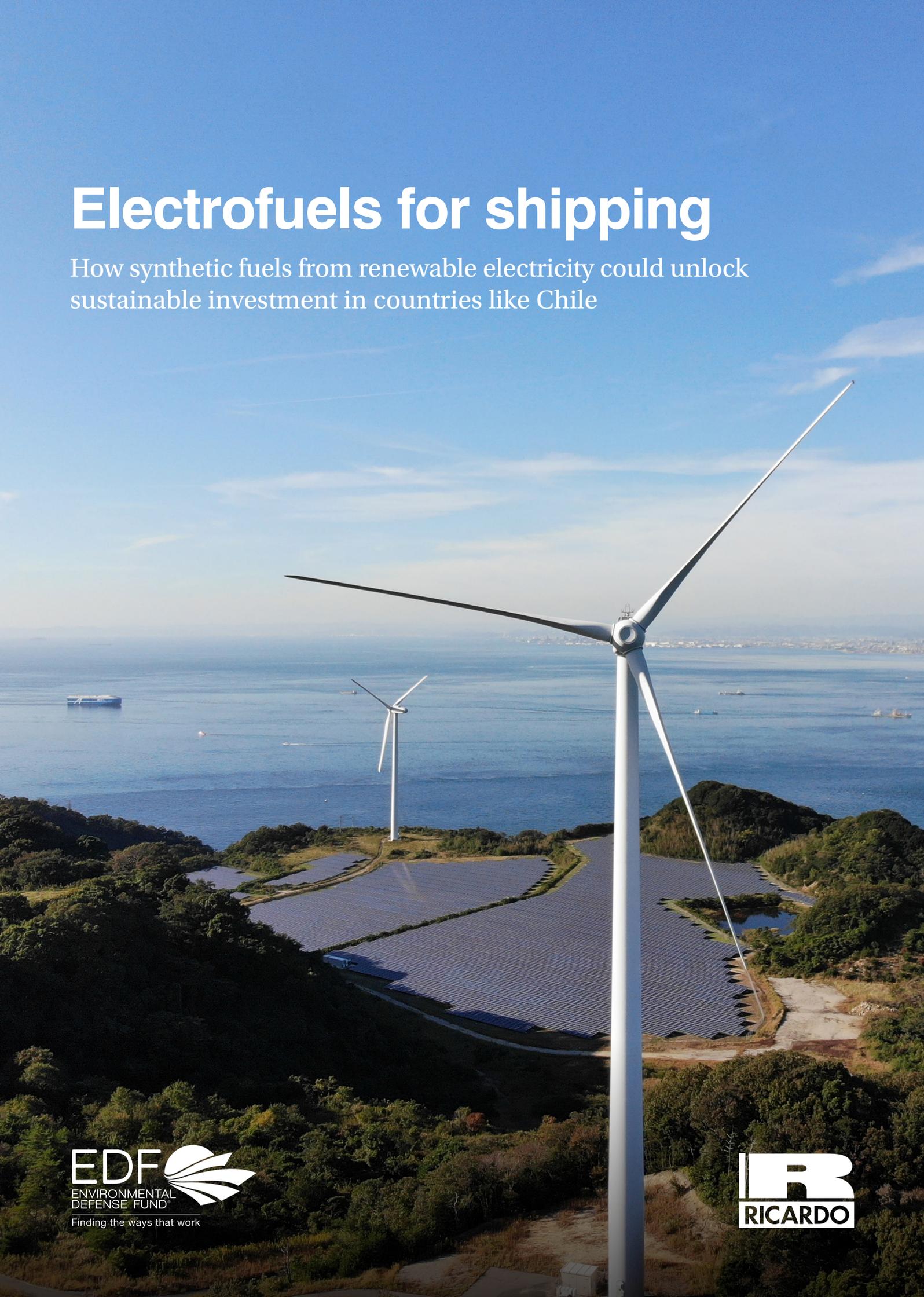


Electrofuels for shipping

How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile



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Executive summary

This report discusses how, in the future, electrofuels could play an important role in decarbonising the international shipping sector and the role that Chile might play in delivering that future.

Hydrogen can be made by separating water in electrolyzers powered by renewable electricity. It can then be further processed to produce green ammonia or methanol.

The purpose of this report is to illustrate in a practical way how countries which possess large untapped renewable resources could use the energy demand from ships to unlock investment in new clean energy infrastructure.

Chile is one such country and this report identifies the following key findings:

- There are at least three potential clean fuels derived from untapped renewable resources that can be used on ships adapted for their use: hydrogen, ammonia and methanol. Each has advantages and disadvantages. A key advantage of ammonia and methanol is that they can be used in existing ship engines with minimal adaptation.
- The production processes for these fuels use known, commercially available technologies that can be deployed at scale relatively quickly.
- Chile is reliant on shipping for both domestic transportation and international trade with 89% and 97% of imports and exports, respectively (in tonnage terms), passing through its ports.
- Chile has among the world's best potential for renewable energy generation with over 1,200 GW of solar potential alone.
- Total land area of about 1,600 km² would be required for solar photovoltaic plants to generate the electricity required to produce electrofuels to meet Chile's domestic and international shipping demand in one year (based on 2018 traffic).
- Chile's electricity market is experiencing a growth in investment in renewables – demand from shipping (270 to 290 GWh per day) could increase the pace and scale of investment.
- Excess electricity produced by variable renewables can be consumed by electrofuel plants when demand from other sectors is low (i.e. excess power that might otherwise be curtailed can be converted to storable fuel).
- Four electrofuels plants with dedicated renewable facilities located adjacent to the port of Mejillones could provide fuel to 730 mid-size vessels per year or about 10% of the fuel demand for ships visiting Chile's ports in 2018.
- Supplying clean electrofuels for all ships departing Chile's ports could unlock an estimated 65 to 90 billion U.S. Dollars' worth of investment in clean infrastructure.

Chile's distance from the largest global markets can be seen as something of a disadvantage, however thanks to its advantageous renewable resources, it is well positioned to play a leading role in the adoption of clean fuels for shipping into the future. The international shipping sector has agreed to introduce policies to deliver reductions in greenhouse gas emissions of at least 50% by mid-century (compared to the 2008 level). This will necessitate investment in new clean propulsion systems which will need to be supported financially to make them commercially competitive and Chile is well placed to be an early recipient of this investment.

The production of renewable electrofuels could attract investment to any country or region that has abundant excess potential capacity for generating renewable electricity.

1. Introduction

In May 2019, Environmental Defense Fund (EDF) published its report *Sailing on Solar – Could green ammonia decarbonise international shipping?* [1], which showed that green ammonia, made with renewable energy, is one credible carbon-free fuel option for the marine sector. The report included a case study showing how green ammonia could be produced in Morocco, using its vast potential for solar power. The report made five main points:

1. Carbon-free fuels will be needed in international shipping, which has set itself the goal of at least halving greenhouse gas emissions by mid-century.
2. Ships and ports could provide a strong investment case for fuels derived from renewable electricity in a wide range of countries with abundant untapped renewable resources.
3. One option, green ammonia, can be manufactured and used in a way that does not emit greenhouse gases using existing and familiar technologies (i.e. internal combustion engines);
4. There are established international safety protocols for storing and transporting ammonia though more work is needed to establish safety protocols for use on board vessels. Urea, a compound closely related to ammonia, is used for scrubbing of NO_x emissions and so is already being handled on vessels fitted with scrubbers.
5. Costs of carbon-free fuels are currently high and policy support will be needed in order to bring these fuels to market.

Although the *Sailing on Solar* report focused on green ammonia, there are multiple renewably-produced “electrofuels” – a group of synthetic fuels derived from hydrogen – that could be used on ships. The production of renewable electrofuels could attract investment to any country or region that has abundant excess potential capacity for generating renewable electricity.

In this report we take a more detailed look at the potential benefits if Chile used its vast renewable potential to produce zero-carbon electrofuels for the shipping sector, including hydrogen, ammonia and methanol.

2. Electrofuels could be used to decarbonise shipping

The shipping sector – with the International Marine Organization as an international rule-making body – is uniquely placed to implement incentives to encourage adoption and drive down production costs.

2.1 Introducing three candidate electrofuels

Many candidate fuels have been proposed as alternatives to the carbon-intensive fossil fuels that have dominated the shipping sector in recent decades. The advantages and disadvantages of some of these were discussed in *Sailing on Solar*. Electrofuels made with surplus or untapped renewable energy have emerged as leading candidates [2] [3]. It has become convention to use “green” as a prefix for these fuels (e.g. “green hydrogen”) to indicate that they are produced using renewable energy rather than derived from fossil fuels.

A key barrier to widespread adoption of electrofuels is that they are currently more costly per unit of energy than fossil fuels. However, the shipping sector – with the International Marine Organization as an international rule-making body – is uniquely placed to implement incentives to encourage adoption and drive down production costs with relatively low risks of disadvantaging segments of the market.

Electrofuels can be grouped into two subcategories: carbon-based and non-carbon. A wide range of carbon-based electrofuels can be produced by combining hydrogen with carbon dioxide or carbon monoxide in various chemical processes. Rather than considering all of these carbon-based variants individually, this report selects one fuel – methanol – and uses this as a representative example.

The non-carbon electrofuels are hydrogen and ammonia, which do not contain carbon and therefore do not emit carbon dioxide when combusted.

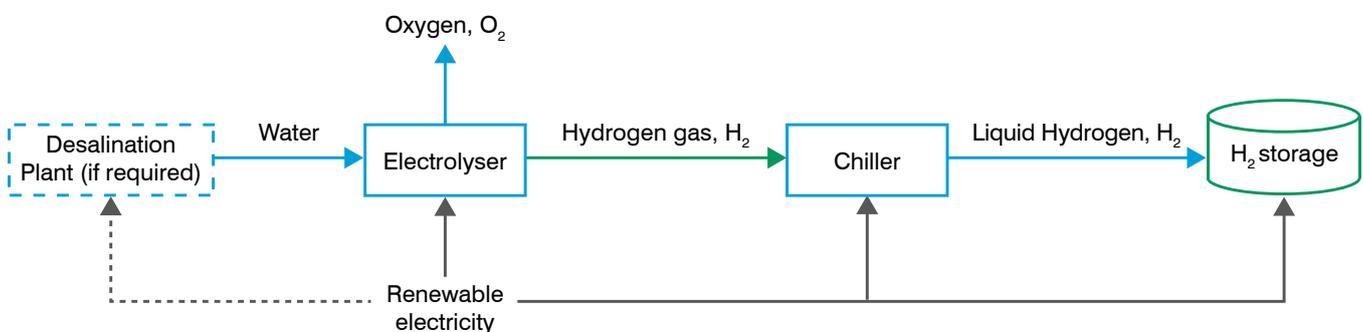
The next few sections of this report compare and contrast hydrogen, ammonia and methanol – all produced from renewable electricity¹ – as candidate fuels for the shipping sector. In section 2.2 each fuel is introduced briefly and all three are compared and contrasted in section 2.3.

2.2 How the electrofuels are produced

2.2.1 Green hydrogen

Hydrogen is a precursor to all electrofuels and can be used as a fuel in its own right. The production process for green hydrogen as a fuel is shown in Figure 1.

FIGURE 1:
Production process for green hydrogen



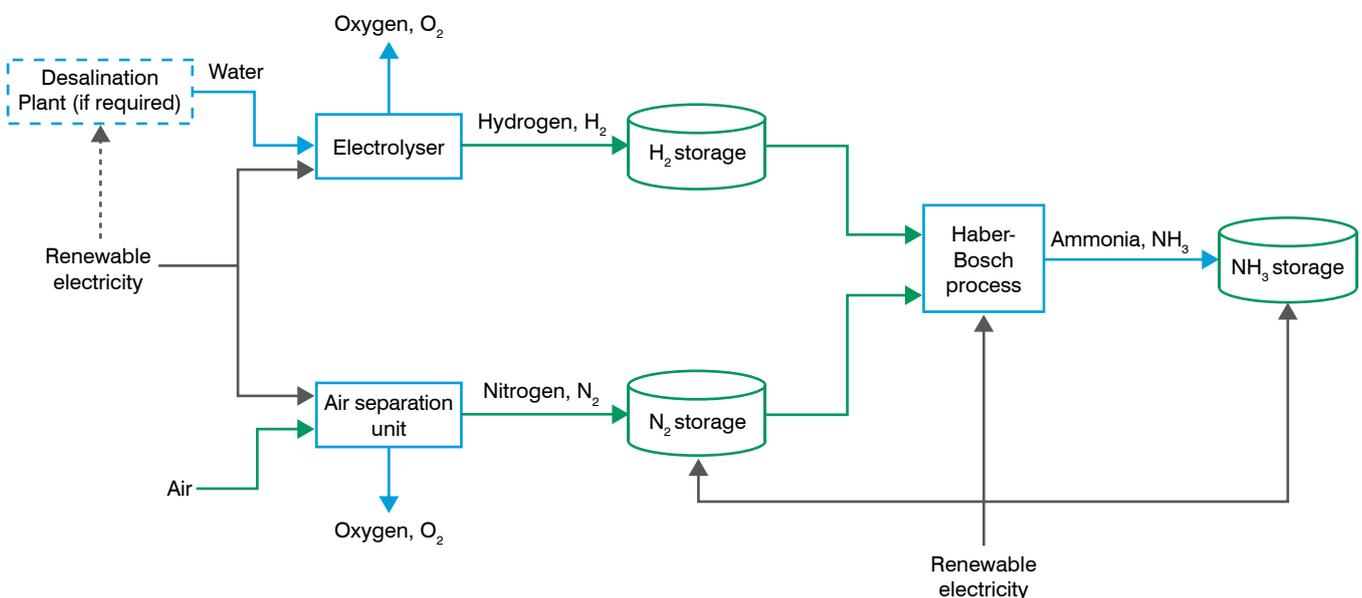
¹ Provided that there are no indirect effects; i.e. that renewable electricity is not diverted from other uses where electricity from fossil fuels is required to make up the shortfall.

This process uses commercially mature technologies that have been proven at scale. However, as described in section 2.3, hydrogen has some disadvantages because it is highly flammable and requires a larger storage volume than the other electrofuels. To store hydrogen in large volumes to make it useful as a fuel for the marine sector, it needs to be converted to a liquid, which requires cryogenic cooling to minus 253 °C. The process of converting hydrogen to a liquid for storage also consumes energy, which reduces the overall efficiency of the process [4].

2.2.2 Green ammonia

The production process for green ammonia is shown in Figure 2.

FIGURE 2:
Production process for green ammonia



Again, the process combines commercially mature technologies and is well understood. There is also some potential to optimise the Haber-Bosch production process to suit the intermittency of renewable electricity sources, such as solar and wind, in combination with fluctuations in demand from other consumers during the day and throughout the year [1].

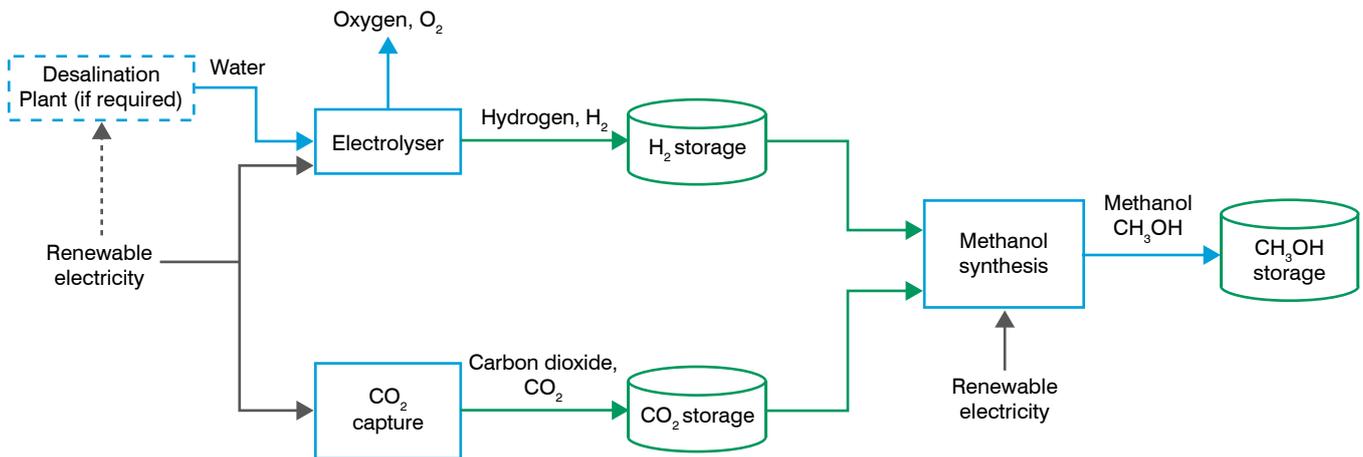
The main challenge for ammonia is that it is toxic to humans and aquatic life. Since ammonia is currently shipped around the world in significant quantities, there are established risk mitigation measures available, but these would need to be formalised into industry regulations and more research undertaken into protocols for use as a fuel before ammonia could be widely adopted.

Combustion of ammonia also produces nitrous oxide (N₂O), which is a greenhouse gas and depletes the ozone. However, N₂O emissions are not expected to be higher than those currently generated by combustion of conventional marine fuels [1].

2.2.3 Methanol

Methanol (or methyl alcohol) is produced by combining hydrogen and carbon dioxide, as shown in Figure 3.

FIGURE 3:
Production process for green methanol



There are a number of options for methanol synthesis with differing levels of commercial maturity and electricity consumption requirements [5]. The drawbacks of methanol (and all carbon-based electrofuels) stem from the presence of carbon in its composition. Since it unavoidably produces carbon dioxide when used, the lifecycle carbon emissions depend on the source of the carbon dioxide used in its production. If the carbon dioxide is removed from the exhaust gases of another process, such as a fossil fuel power plant or a manufacturing plant, then the carbon dioxide is effectively recycled (with some additional energy costs) before being emitted into the atmosphere. From a climate perspective, displacing fossil fuel use would be the best approach. However, if energy is going to be used to capture carbon dioxide from an exhaust stream, then it would be preferable to store it away permanently (in underground salt caverns, for example) so that the emissions to atmosphere are avoided.

Reliance on capturing carbon dioxide from an external process introduces other drawbacks. For example, methanol plants would need to be in the proximity of significant sources of carbon dioxide, limiting locational flexibility.

Other sources of carbon dioxide are also available, such as steam released from underground reservoirs in geothermal power plants, which has been demonstrated in Iceland [6]. However, this also introduces locational constraints.

To produce methanol with net zero carbon emissions over the lifecycle, carbon dioxide must be removed directly from the air or seawater [7] (assuming the energy used does not have associated greenhouse gas emissions).

2.3 Comparing the three electrofuels

The characteristics of the three electrofuels described in the previous paragraphs – hydrogen, ammonia and methanol – are compared in Table 1.

TABLE 1:

Comparison of the characteristics of hydrogen, ammonia and methanol as electrofuels for shipping

	Hydrogen	Ammonia	Methanol
Temperature for liquid storage	- 253 °C	- 34 °C ²	Ambient
Compatibility with existing bunkering infrastructure	Low (requires refrigerated tanks)	Low (requires refrigerated tanks)	High
Storage volume compared to marine gas oil for a fixed energy content	x7.6	x4.1	x2.3
Electricity required to produce enough fuel for one day's sailing of a Panamax container vessel ³	1.2 GWh	1.4 GWh	1.6 GWh (biogas source) 1.7 GWh (flue gas source)
			1.8 GWh (seawater source) 2.0 GWh (air source)
Requires co-firing with another fuel in compression ignition engines	Yes – carbon-based fuel	Yes – carbon-based fuel	Yes – carbon-based fuel
Requires co-firing with another fuel in spark ignition engines	No	Yes – hydrogen or carbon-based fuel ⁴	No
Toxic to humans	No	Yes but there are well-understood mitigation measures	Yes but there are well-understood mitigation measures
Toxic to aquatic life	No	Yes	No
Flammability	Very high	Low	High

■ Best performing
 ■ Acceptable
 ■ Problematic

See Appendix A for calculations and sources.

² Or pressurised to 10 bar for smaller applications.

³ The vessel fuel consumption has been calculated based on average fleet consumption data quoted in Table 4 of the Third IMO Greenhouse Gas Study [38], without any adjustments for improvements in energy efficiency since then or in the future. It is assumed that the engine output and thermal efficiency would be the same as for traditional liquid fossil fuels with the necessary development of engine technology to be optimised for use with these fuels.

⁴ A small amount of hydrogen can be separated from the ammonia fuel supply onboard and mixed with the ammonia.

In compression ignition engines, all three fuels need to be mixed with a small amount of carbonaceous fuel to maintain stable combustion, which results in a small amount of additional carbon dioxide emissions. For methanol, the resulting carbon dioxide emissions are about 18% lower than for diesel [12]. The values for hydrogen and ammonia, however, would be more than 90% lower than diesel. These are the emissions from an engine at the point of use, but this report stresses that greenhouse gas emissions should be quantified and compared on a lifecycle basis

Both methanol and hydrogen can be burned alone in spark ignition engines with some further development required for marine engines [13] [14], while ammonia needs a support fuel [1]. It is possible to mix ammonia with hydrogen in a spark ignition engine, resulting in zero carbon dioxide emissions. In this case, the hydrogen can be separated from the ammonia fuel supply using a cracker onboard, so it is not necessary to have a separate hydrogen storage tank. It should be noted however, that the use of ammonia results in the formation of nitrogen oxides, which would need to be managed by selective catalytic converters (with ammonia slip catalyst).

All three of these fuels can also be used to power suitable fuel cell propulsion systems without the need to mix with a fossil fuel. However suitable fuel cell technology is still being developed for large marine applications, so this report focuses on conventional combustion engines.

Hydrogen requires about 1.9 times more onboard storage space than ammonia and 3.3 times more than methanol (see Table 1). Fuel storage volume is a key consideration for vessels because it reduces the amount of space available for cargo or passengers. Therefore, the shipping sector will need to determine the best bunkering strategy for each electrofuel (onboard storage volume and frequency of bunkering stops) to suit each application.

The main advantages of methanol are that it is a liquid at ambient conditions and it is compatible with existing bunkering infrastructure. Methanol has not been included in the Chile case study because carbon-neutral production and use (on a life-cycle basis) requires direct air capture technology, which is not currently available at the necessary scale.

The remainder of this report concentrates on green hydrogen and green ammonia (both produced entirely from renewable energy⁵) as representative candidates to decarbonise international shipping. The following sections present a case study for Chile to illustrate in a practical way how countries with large untapped renewable resources could use the energy demand from ships to unlock investment in new clean energy infrastructure.



⁵ Provided that there are no indirect effects; i.e. that renewable electricity is not diverted from other uses where electricity from fossil fuels is required to make up the shortfall.

3. Chile has a vibrant commercial shipping sector

Chile has more than 50 ports and harbours, distributed across 6,435 km of coastline. The top ten ports in terms of commercial throughput are located in the northern half of the country and represent two thirds of the national total [15]. These ports, listed in Table 2 and shown in the adjacent map, would be prioritised to investigate potential locations for electrofuels production and bunkering.



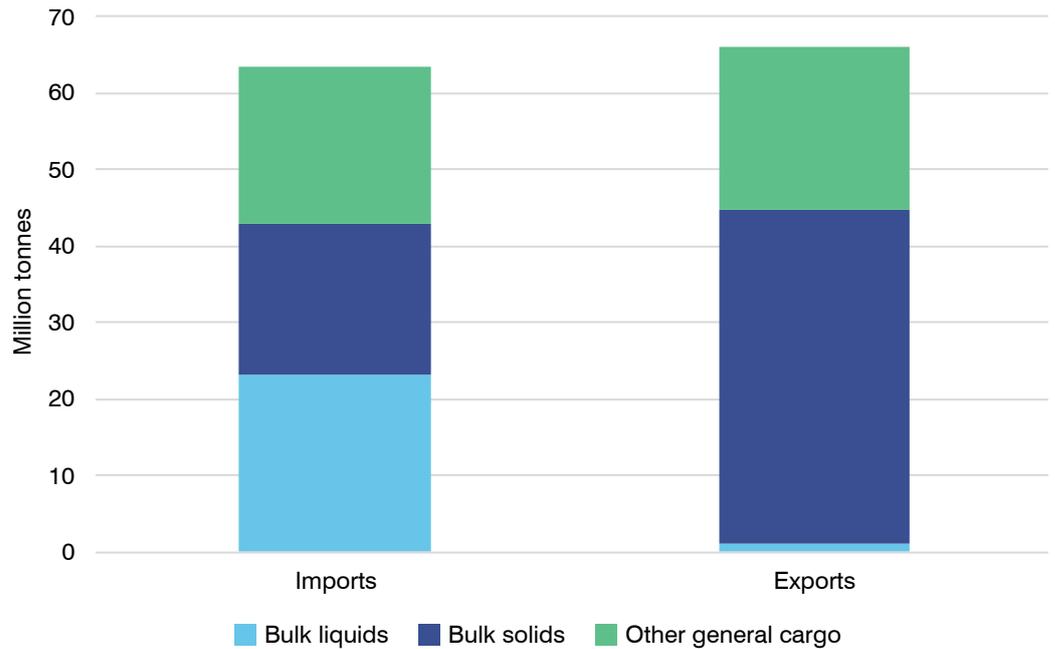
TABLE 2:
Chile’s top 10 ports in terms of throughput in 2018

Name	Throughput in 2018 (million tonnes)	Primary cargo type	Landfalls in 2018
1. San Antonio	17.2	Containers	1,317
2. San Vicente	15.8	Bulk liquids	642
3. Quintero	11.9	Bulk liquids	641
4. Mejillones	11.6	Bulk liquids	906
5. Coronel	9.7	Bulk solids	335
6. Huasco / Guacolda	9.2	Bulk solids	100
7. Valparaíso	8.1	Containers	834
8. Caldera / Calderilla	7.5	Bulk solids	174
9. Caleta Patillos	6.3	Bulk solids	138
10. Puerto Ventanas	6.1	Bulk solids	184

Source: [15, 34]

Ports are the main transport channel for Chile's international trade, with 89% and 97% of imports and exports (in tonnage terms) respectively [15]. Trade flows to the Americas and Asia represented 82% of Chile's total imports and exports in 2018. The composition of imports and exports via Chilean ports in 2018 is shown in Figure 4.

FIGURE 4:
Composition of imports and exports through Chilean ports by cargo type in 2018



Ports are the main transport channel for Chile's international trade, with 89% and 97% of imports and exports (in tonnage terms) respectively.

Source: [15]

Bulk liquids represented the largest share of imports (41%), comprising mainly of fossil fuels, followed by bulk solids (34%), which is primarily coal and general cargo (25%), dominated by vehicles and manufactured goods. It is anticipated, however, that Chile's reliance on imported fossil fuels (particularly coal) will reduce significantly in the coming years as it pursues its decarbonisation targets (see section 5).

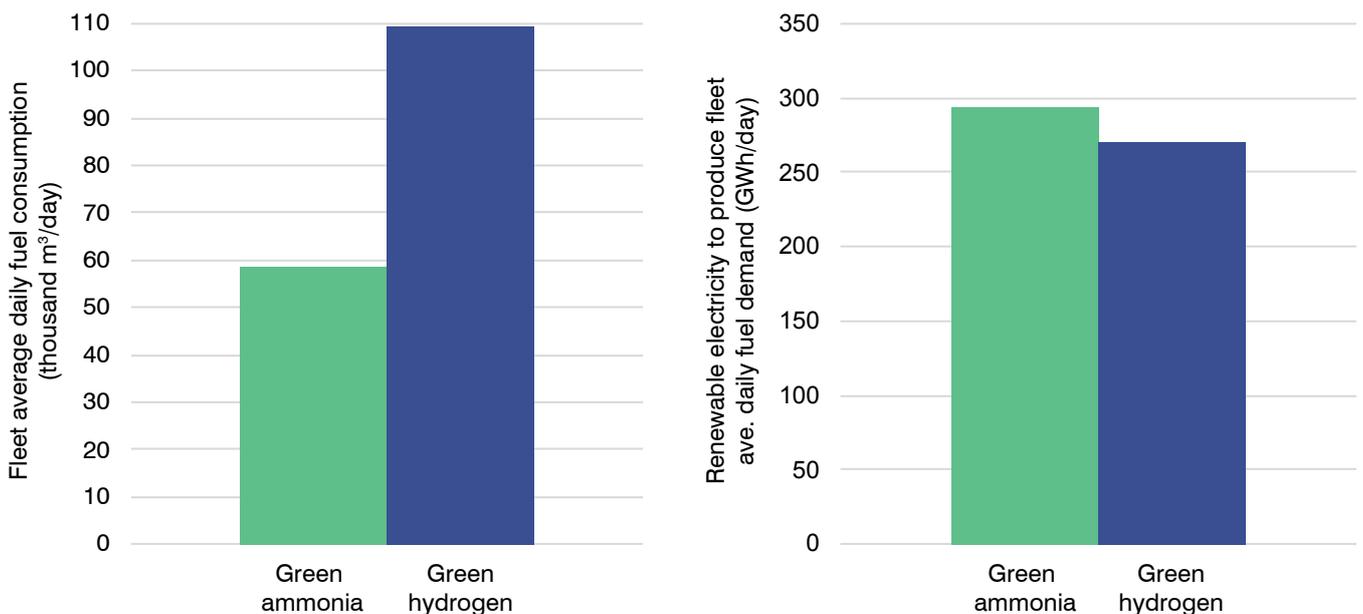
The largest share of exports via ports in 2018 was bulk solids at 66% of the total. These are primarily natural resources, dominated by copper and related products. General cargo (mainly wood products) represented 32% and bulk liquids only 2% of exports.

4. The hypothetical demand for electrofuels in Chile

This section investigates the potential demand for electrofuels for merchant vessels calling at Chile's ports, based on trade activity. Figure 5 shows what the fuel consumption would have been if the ships visiting Chile's ports in 2018 had refuelled in Chile with hydrogen or ammonia⁶.

FIGURE 5:

Hypothetical fuel consumption for merchant fleet visiting Chile's ports in 2018 and corresponding renewable energy consumption to produce these volumes of green ammonia or green hydrogen



The consumption is shown on a volumetric basis (cubic metres) because space is more relevant than mass for commercial shippers. For reference, the equivalent hypothetical consumption of marine gas oil would be about 15 thousand m³/day, underlining the storage data that was presented in Table 1. About 290 GWh per day of renewable electricity would be required to produce this volume of green ammonia and 270 GWh per day for green hydrogen.

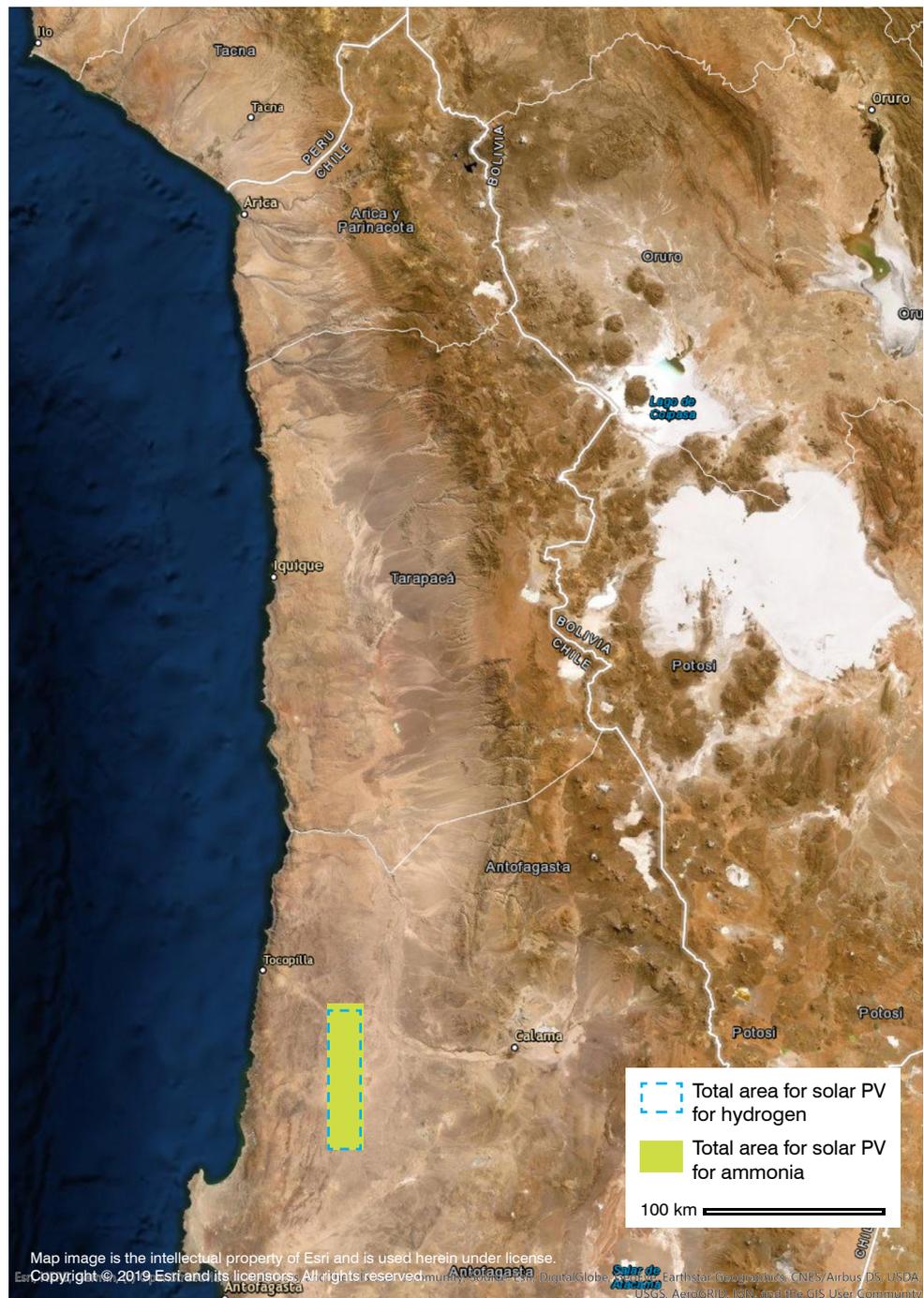
⁶ The analysis was based on the national ports' total throughput in 2018 based on representative vessel size distributions and average fuel consumptions taken from Third IMO Greenhouse Gas Study [38]. The analysis assumes that each ship takes onboard fuel for 33 days' sailing, reflecting the mix of short and long-range vessels in the fleet.

The map in Figure 6 shows the size of a hypothetical solar PV plant required to generate these amounts of electricity for the Chilean fleet. The dimensions would be 19 km x 78 km for green hydrogen and 20 km x 81 km for green ammonia.

The current status and future plans for Chile's electricity sector are presented in the next section.

FIGURE 6:
Map showing the size of a hypothetical solar PV plant required to supply the electricity required to produce green ammonia and green hydrogen for Chile's fleet

Total land area of about 1,600 km² would be required for solar photovoltaic plants to generate the electricity required to produce electrofuels to meet Chile's shipping demand in one year.



Indicative targets have been set for renewable generation in Chile, namely 60% of electricity generated by 2035, and 70% by 2050.

5. Chile's ambitious plans for renewable electricity

Chile's electricity sector has experienced significant change over the last decade, mainly driven by the country's increasing demand for electricity and a rapid build-out of new renewable plants. The Chilean government has sought to capitalise on its vast renewable potential to increase energy security, reduce reliance on imported fossil fuels and hopes to reduce end-user prices as a result on the back of capital cost reductions in wind and solar technologies.

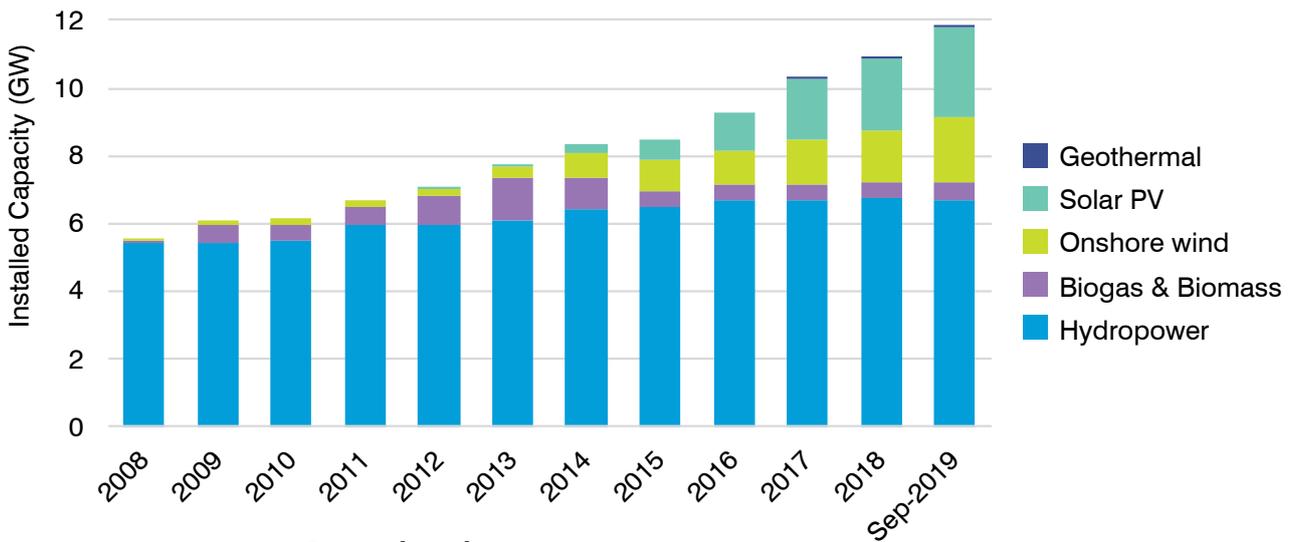
The electricity demand in Chile has more than tripled over the last twenty years and the Ministry of Energy expects this trend to continue. According to its Long-Term Energy Plan 2019 [16], electricity generation is expected to increase between two and four times by 2050, to reach consumption in the range of 135,000 to 215,000 GWh per year. Over 85% of this is expected to come from renewables. These figures do not include the electricity required for shipping electrofuels which, from the data in Figure 5, would represent a further significant increase depending on adoption rates.

The government has also set ambitious targets to reduce greenhouse gas emissions from the electricity sector, which requires a larger contribution from renewable sources. One of these targets is to reduce the greenhouse gas intensity of Chile's economy by 30% from the 2007 level by 2030 [17]. Investment in renewable energy generation is crucial in reaching this target. In fact, the previous government has set indicative targets for renewable generation in Chile, namely 60% of electricity generated by 2035, and 70% by 2050 [18]. Furthermore, the current government is developing a climate change law and has obtained a voluntary commitment from generation companies to phase out coal-fired power plants [19].

The commitment to increase renewable electricity generation has been welcomed by renewable developers and has been further encouraged by additional regulatory measures, such as technology-neutral public tenders for electricity supply to regulated clients. This has resulted in a high share of renewables among winning bids for generation in recent years [20].

Between January 2008 and September 2019, renewable energy capacity in Chile has more than doubled from 5.5 GW to 11.8 GW [21] [22]. This represents about half of the total installed capacity of 24.6 GW (including fossil fuel plants) in September 2019. Figure 7 shows how this trend has progressed over time and how the energy mix has diversified as solar, wind, hydro and geothermal plants have been added to the system.

FIGURE 7:
Installed renewable capacity in Chile between 2008 and 2019



Sources: [21, 23]

While the contribution of renewables in the energy mix is rapidly growing, there is significant scope for further expansion. It is estimated that the exploitable potential for onshore wind and solar energy in Chile is 36 GW and 1,261 GW respectively.

Between 2015 and 2019, the installed capacities of wind and solar energy increased by 112% and 358% respectively, aided by a significant drop in their capital costs. In terms of production values, the electricity produced by solar and wind sources (in MWh terms) was 10.9% of the total in 2018, up from 1.1% in 2010 [24].

While the contribution of renewables in the energy mix is rapidly growing, there is significant scope for further expansion. It is estimated that the exploitable potential for onshore wind and solar energy in Chile is 36 GW and 1,261 GW respectively [39]. Therefore, the current installed capacity of 1.9 GW wind and 2.6 GW solar represent 5.1% and 0.2% of the total for these resources respectively. Notably for electrofuel plants, which will typically be located near the shore, Chile has not yet begun to take advantage of its offshore wind potential. However, the seabed tends to have a steep slope from the Chilean shoreline, which poses a challenge for installation of conventional offshore turbines. Floating turbines hold promise for the future, but currently the focus is on developing onshore wind farms, which are cheaper.

Hydropower has traditionally played a significant role in Chile's electricity sector and still makes up more than half (6.7 GW) of the installed capacity of renewables, as Figure 7 shows. However, the electricity produced by hydro plants can vary significantly from year to year depending on whether there was high or low rainfall.

It is estimated that the potential for geothermal energy is at least 3 GW [25] and around 240 GW for wave and tidal power [26]. There is opportunity to build more geothermal plants in Chile, but the resources are located inland and would need to be fed to electrofuel plants by transmission lines. Wave and tidal technologies also hold much promise considering Chile's long coastline [27], but they are still at a relatively early stage of development with a limited number of utility-scale plants in operation around the world.

A higher penetration of variable renewables in the energy mix will require more capacity which will need to be converted to a storable form of energy to fully decarbonise – shaving the peaks of over-supply and supplying power during the troughs. Electrofuels can help with this.

On the demand side of the equation, the hourly average demand in 2018 was about 8.7 GW [24] with a maximum peak of 10.6 GW [28]. Figure 7 shows that the installed capacity of renewables has exceeded this value since 2016. However, it should be borne in mind that the output from wind and solar plants fluctuates based on the wind speed and solar irradiation, so they are not able to meet the full demand all of the time. As described above, the output from hydro plants is also not guaranteed to be available at all times.

Until 2017, Chile had two main electricity systems that were operated independently: the Central Interconnected System (“SIC”) and the Grand North Interconnected System (“SING”), which together represented about 99% of the country’s installed capacity⁷ [29]. The Electricity Transmission Law 2017 created a new National Interconnected System by aggregating two main electric systems and establishing a single System Operator. It also introduced regulatory reforms with the aim of establishing correct incentives for the secure expansion of the system and accommodating future renewable generation at a competitive cost.

The interconnection of the two systems included more than 750 km of new transmission lines at a cost of about 1 billion U.S. Dollars [30]. The initial connection was made in 2017 and was completed in 2019. Despite this significant advancement, there are still challenges associated with transmitting electricity from the solar-rich north to the main load centres in the central region.

Since 2015, solar and wind plants have had to forcibly reduce their output (a process known in the industry as “curtailment”) when demand in the northern central region has been low and production has been high [31]. Official data on regional curtailment levels is not available, but analysis of regional wholesale electricity prices does provide some insight. Wholesale prices tend to drop to zero at times of curtailment, reflecting the excess supply. This happened repeatedly between September 2018 to August 2019 [32], indicating that curtailment is still being experienced in some regions.

Curtailment is a symptom of supply outstripping demand for electricity. Improvements in the electricity grid can help, but additional solutions will be required to allow Chile to achieve its ambitious renewable targets. A higher penetration of variable renewables in the energy mix will require more capacity which will need to be converted to a storable form of energy to fully decarbonise – shaving the peaks of over-supply and supplying power during the troughs. Electrofuels can help with this.

An example of how this might look in practice is given in the next section.



Sunrise over solar panels in Chile’s Atacama Desert.

⁷ The remaining 1% comprised of two smaller systems – Aysen and Magallanes – and several other smaller isolated systems (e.g. Easter Island).

6. A Chilean example of an electrofuel plant

Four plants each producing 700 tonnes of ammonia per day would be enough for two mid-size vessels (approx. 17,000 dwt) to refuel every day, serving 730 vessels per year.

Mejillones, a small town located in the region of Antofagasta in northern Chile, was identified as an ideal candidate to bring to life the possible scale of electrofuel plants in Chile to supply the marine sector. The town's commercial port is Chile's fourth-largest measured by volume (see section 3) and is surrounded by sparsely populated desert with some of the best solar resources in the world.

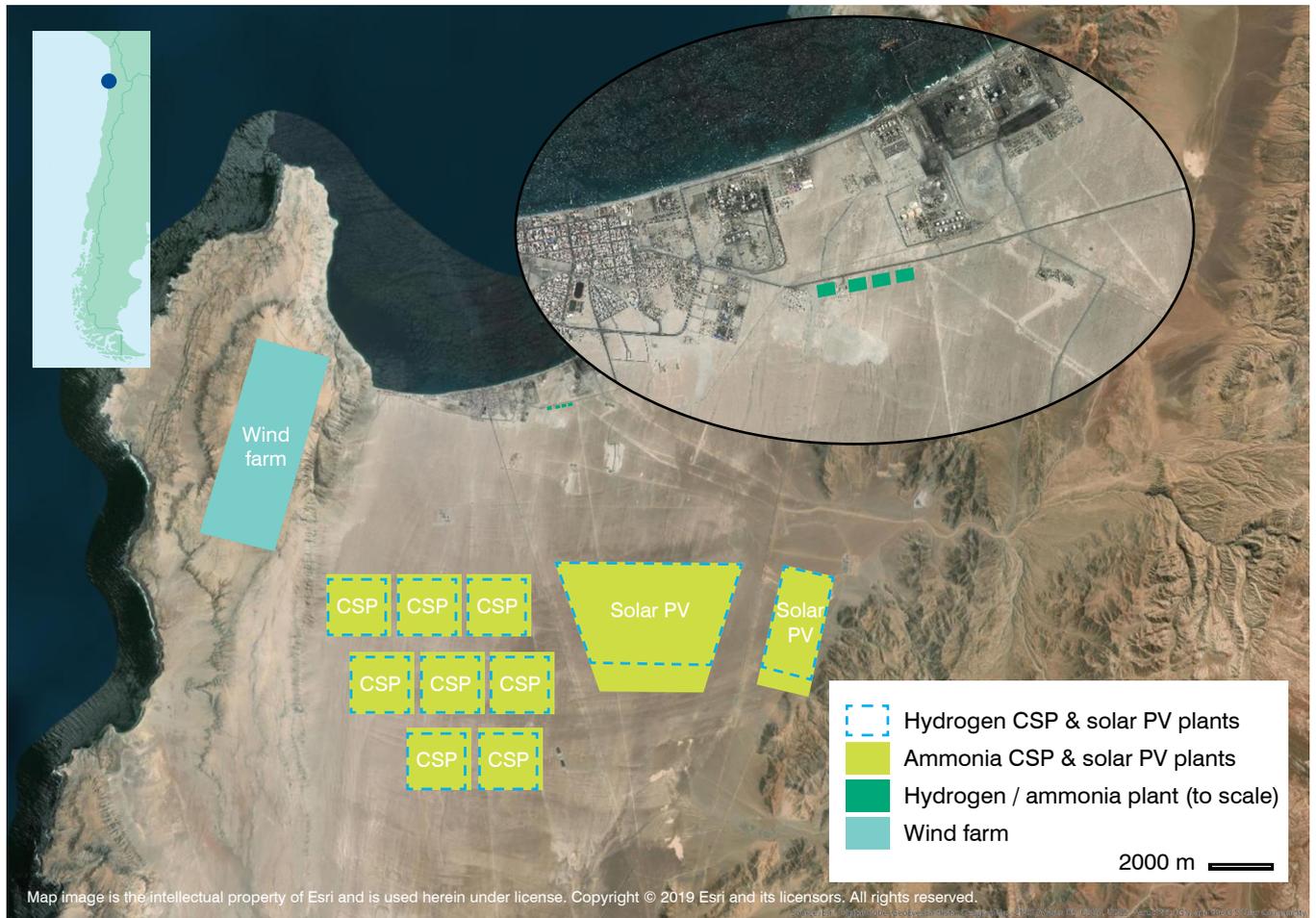
Most of the surrounding Atacama Desert's coastline experiences morning fog from the Pacific Ocean, which reduces the effectiveness of solar plants and can cause corrosion. However, the plain to the south of Mejillones ("Pampa de Mejillones") is protected from this fog by the Cerro el Morro and Morro Moreno mountains to the east [33], and provides a convenient location near the port for solar farms.

In 2018, between two and three ships docked in the port every day on average, carrying an average cargo of 16,700 tonnes [34]. Ships of this size would consume about 42 tonnes of ammonia per day on average or about 6 tonnes of hydrogen.

Assuming that green ammonia was produced and bunkered at the port, four plants each producing 700 tonnes of ammonia per day would be enough for two mid-size vessels (approx. 17,000 dwt) to refuel every day⁸, serving 730 vessels per year. Each plant would consume 306 MW of renewable electricity.

⁸ Assuming each vessel takes on fuel for 33 days' sailing.

FIGURE 8:
Scale of renewable plants required for four electrofuel plants at Mejillones



The arrangement in Figure 8 assumes that one solar photovoltaic (PV) plant of 306 MW would serve each ammonia plant to provide electricity during daylight hours, supported by two concentrating solar power (CSP) plants of 150 MW capacity each. The CSP plants would be equipped with molten salt storage facilities to store energy to allow for operation through the night. The first of these types of CSP plants are currently being constructed in Chile [35] and others are planned [36]. The storage facility will allow the CSP plants to generate electricity to make up the shortfall at times when the PV plants are operating at less than 100% and through the night.

These solar plants would provide about 80% of the renewable energy requirements to allow the ammonia plant to operate at full capacity. The remaining 20% could be provided by the nearby wind farm or excess renewable electricity from the grid.

Similarly, to provide green hydrogen for the 730 vessels of the same size per year, four 100 tonne-per-day production plants would be required. The same arrangement of PV and CSP plants would be used, but they would be slightly smaller at 257 MW and 2 x 126 MW respectively. Again, the remaining 20% could be supplied by the wind farm or imported from the grid.

The scale of these plants is in keeping with other renewable projects that are being developed in other parts of Chile and could be replicated at other ports to suit the renewable resources at those locations.

7. Potential level of investment

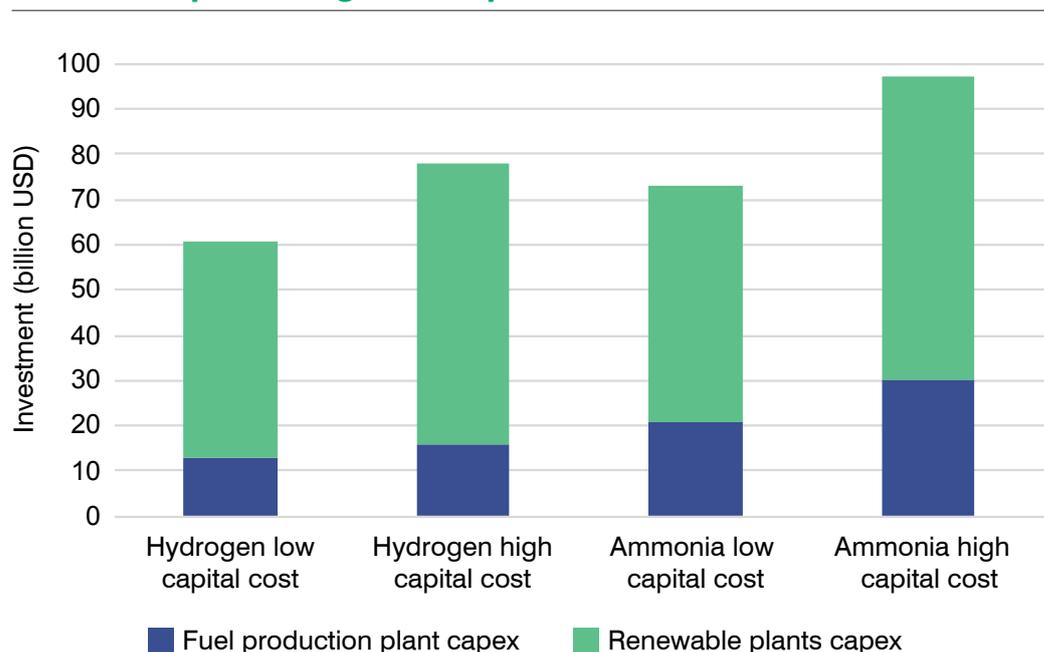
When the global shipping sector makes a decisive shift towards decarbonisation and introduces policies to support investment in electrofuels, then the additional demand could unlock investment in renewable plants in countries like Chile that are active in marine trade and have access to renewable resources.

Figure 9 shows the potential level of investment that would be required to produce enough hydrogen and ammonia to fuel all of the vessels that visited Chile's ports in 2018. The underlying calculations are provided in Appendix B.

If the shipping sector made a decisive shift towards decarbonisation through the adoption of hydrogen and ammonia as fuels, then the additional demand for electricity could unlock investment in renewable plants in countries like Chile that are active in marine trade and have access to renewable resources.

FIGURE 9:

Estimated level of investment for hydrogen and ammonia to fuel the ships visiting Chile's ports in 2018



The investment requirements for ammonia are expected to be about 20 to 25% higher than for hydrogen. In the case of hydrogen, the total level of investment would be in the region of 60 to 80 billion U.S. Dollars. About 20% of this investment cost would be for the fuel production plant and the remainder would be for the renewable plants to provide electricity. For ammonia the level of investment would be between 70 and 95 billion U.S. Dollars. Of the total cost, 30% would be for the ammonia production plants and 70% for the renewable electricity plants. The assumed mix of renewable sources is given in Appendix B.

8. Conclusion

Shipping is ideally placed to facilitate widespread adoption of electrofuels thanks to the International Marine Organization's recently agreed greenhouse gas targets and the need to develop zero-carbon propulsion technologies to achieve them. With its ability to make internationally-binding rules, the shipping sector can implement incentives to encourage adoption globally and drive down production costs with relatively low risks of disadvantaging segments of the market. Chile has great potential to attract investment under such a policy.

With its vast renewable resources and significant commercial maritime activity, Chile is ideally placed to become a hub for the supply of zero-carbon electrofuels for the marine sector. Traditionally Chile's location away from the main trade routes has placed it at a disadvantage, but it has an opportunity to use its advantageous renewable energy endowments to play a leading role in the adoption of clean fuels for shipping into the future.

Chile has increased the share of renewable sources in the electricity sector significantly over the last few years and has plans to continue increasing the contribution from renewables to at least 70% by 2050 [37] compared with 11% in 2018.

Chile has huge potential to decarbonise not only the shipping sector but its whole economy and implementation of zero-carbon marine fuels can be a driving force. This would also increase the country's energy security and minimise its reliance on fossil fuel imports.

With this approach, the International Maritime Organization's decarbonisation goals for the marine sector could have knock-on benefits in countries like Chile with significant renewable potential by catalysing development of sustainable infrastructure. The production of zero-carbon electrofuels could thereby attract inward investment, create jobs and improve trade balances through reduced reliance on imported fuels.

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Appendix A: Calculations and sources for Table 1

Calculation of electricity required to produce electrofuels in Table 1

	Heavy fuel oil (HFO)	Hydrogen	Ammonia	Methanol
Lower heating value (LHV), MJ/kg	41.8	120	18.8	19.9
Electricity consumption per tonne of fuel, GWh/t	-	0.062	0.011	Biogas source: 0.013 Flue gas source: 0.014 Seawater source: 0.015 Air source: 0.016
Daily fuel consumption of Panamax container vessel, tonnes/day	58.7 ¹	20 ²	131 ²	123 ²
Electricity required to produce daily fuel consumption, GWh/day	-	1.2	1.4	Biogas source: 1.6 Flue gas source: 1.7 Seawater source: 1.8 Air source: 2.0

Notes:

1. From average fleet consumption data quoted in Table 4 of the *Third IMO Greenhouse Gas Study* [38].
2. Calculated based on ratios of LHV without any adjustments for improvements in energy efficiency since then or in the future. It is assumed that the engine output and thermal efficiency would be the same as for traditional liquid fossil fuels with the necessary development of engine technology to be optimised for use with these fuels.
3. Electricity consumption for methanol is taken from Hänggi et. al, 2019 [7].

Sources for data presented in Table 1

	Source
Temperature for liquid storage	[1]
Compatibility with existing bunkering infrastructure	[8]
Storage volume compared to marine gas oil for a fixed energy content	[1]
Electricity required to produce enough fuel for one day's sailing of a Panamax container vessel	See calculation in table above
Requires co-firing with another fuel in compression ignition engines	[1, 9, 10]
Requires co-firing with another fuel in spark ignition engines	[1, 11, 9]
Toxic to humans	[1]
Toxic to aquatic life	[1]
Flammability	[1]

Appendix B: Assumptions and calculations for investment

Consumption inputs

Description	Units	Value	Source/Notes
Year		2018	
Container volume	mill. tonnes	42.25	[15]
Bulk solids volume	mill. tonnes	71.09	[15]
Bulk liquids volume	mill. tonnes	29.08	[15]
Fuel storage capacity	days	33	
Ammonia fuel consumption - container vessels	tpd	57.3	Notes 1, 2
Hydrogen fuel consumption - container vessels	tpd	9.0	Notes 1, 2
Ammonia fuel consumption - bulk solids carriers	tpd	25	Notes 1, 2
Hydrogen fuel consumption - bulk solids carriers	tpd	4	Notes 1, 2
Ammonia fuel consumption - bulk liquids carriers	tpd	13	Notes 1, 2
Hydrogen fuel consumption - bulk liquids carriers	tpd	2	Notes 1, 2
Electricity consumption - ammonia production	MWh/t	10.5	
Electricity consumption - hydrogen production	MWh/t	61.7	

Consumption outputs

		Ammonia	Hydrogen
Total ave. production - container vessels	tpd	10,542	1,652
Total ave. production - bulk solids carriers	tpd	8,255	1,293
Total ave. production - bulk liquids carriers	tpd	9,128	1,430
Total	tpd	27,925	4,375
Elec. consumption - container vessels	GWh/day	111	102
Elec. consumption - bulk solids carriers	GWh/day	87	80
Elec. consumption - bulk liquids carriers	GWh/day	96	88
Total	GWh/day	293	270

Renewable and financial assumptions

		Low	High
Ammonia plant capex	2020 USD/t	0.75	1.08
Hydrogen plant capex	2020 USD/t	446	362

	Capacity factor ³	Installed capacity for ammonia (assumed)	Energy production for ammonia (assumed)	Installed capacity for hydrogen (assumed)	Energy production for hydrogen (assumed)	Assumed investment cost (Low capex)	Assumed investment cost (High capex)
		GW	GWh	GW	GWh	2020\$/MW	2020\$/MW
Solar PV	0.30	12	88.0	11	81.0	0.59	0.70
Solar CSP	0.51	7	88.0	7	81.0	3.79	5.14
Wind onshore	0.34	13	102.6	12	94.5	1.04	1.24
Wind offshore	0.43	1	14.7	1	13.5	3.17	4.30
Total		33	293	31	270		

Financial outputs

		Hydrogen low capital cost	Hydrogen high capital cost	Ammonia low capital cost	Ammonia high capital cost
Fuel production plant capex	2020\$b	13	16	21	30
Renewable plants capex	2020\$b	48	62	52	67
Total		61	78	73	97

Notes:

1. Weighted based on dwt for size distributions given in IMO 2014 "Third GHG Study"
2. Fuel consumption calculated as a ratio of calorific values against HFO reference, assuming same combustion efficiency as HFO.
3. Capacity factors taken from [39] Santana 2014, except for offshore wind, which is the world average for 2018 from [22] IRENA 2019.



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