The role of shore power in the future maritime fuel mix

CE Delft

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Content

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Jasper Faber

Preface

The Port of Rotterdam on behalf of WPCAP (World Ports Climate Action Program) has commissioned this study into the future of OPS in a decarbonising shipping sector.

On the basis of this study, WPCAP concludes that providing shore power to seagoing vessels is a mature technology that can substantially reduce local emissions in the port, such as NO_x, particulate matter and CO_2. Yet shore-side electricity for maritime shipping is not yet an accepted and widely supported practice worldwide. Ports, terminals and shipowners are often unwilling to invest in shore power infrastructure due to the high costs involved and the lack of a revenue model or uncertainties surrounding it. Looking globally at successful examples of shore power use by maritime shipping, almost all involve one or more of the public facilities listed below:

- a public form of (partial) financing of shore-based infrastructure;
- regulation for ports/terminals to make the provision of shore-side electricity mandatory;
- regulation for ocean-going vessels to make shore power mandatory.

To harness the huge potential of shore-side electricity and accelerate its uptake, there should be global regulation to regulate and finance shore-side electricity, both onshore and on vessels. But there is no international organisation with the mandate to do this. Therefore, (supra-)national and/or regional governments around the world should decide to start regulating and financing shore-side electricity. Prominent examples can already be found in China, Europe and the West Coast of North America.

A major reason why governments do not decide to regulate and finance shore power on a much larger scale is that there are doubts about whether shore power is a future-proof choice. These doubts are fuelled by the line of thought that climate policy will lead to emissions-free ships, with which shore-based power infrastructure will become less and less utilised and rapidly depreciate in value (stranded assets). This report analyses whether these doubts are justified, or whether, on the contrary, shore-side electricity fits perfectly into a future world where ships sail on renewable fuels.

World Ports Climate Action Program

Summary

Onshore power supply (OPS) to ships at berth is a well-established technology which helps reduce emissions in ports. It allows ships to shut down their engines and generators and use electricity generated onshore, which often results in significantly lower emissions of air pollutants. An increasing number of jurisdictions impose requirements on ports to supply onshore power and ships to use it. At the same time, maritime shipping is starting a transition from fossil fuels to renewable fuels with the aim of decarbonization.

Most requirements for the use of OPS at berth exempt ships with zero- or low emissions technologies. This means that when the number of ships using alternative fuels increases, demand for OPS may decrease. However, there could still be other reasons for ships using alternative fuels to link to OPS, e.g. when it provides a cheaper source of power.

This report analyses whether there is a risk that OPS becomes a stranded asset when the shipping sector undergoes a fuel transition towards decarbonization, thus releasing ships of the requirement to connect to OPS at berth.

The report finds that there are several reasons which make it unlikely that OPS becomes a stranded asset.

First, the variable costs of shore power are projected to be lower than electricity generated on board with a decarbonized fuel, at least in Europe and North America, even when the fuel is produced and bunkered in regions with very low renewable electricity prices.

Second, ships that sail on fully renewable fuels may still have air pollutant emissions, especially when the renewable fuels are used in internal combustion engine with a pilot fuel. Depending on the precise regulation, these ships may not be exempted from an obligation to use OPS.

Third, in all scenarios of decarbonization of shipping, a significant share of maritime fuels will still be fossil by 2040. Depending on the projection, the share ranges from 20 to 70%, with lower percentages associated with scenarios that model full decarbonization by 2050 and higher percentages with scenarios that model decarbonization at a later date. Ships sailing on fossil fuels are likely to still be legally required to connect to shore power at berth.

1 Introduction

1.1 Onshore power supply and decarbonization of shipping

Onshore power supply (OPS) to ships at berth is a well-established technology for certain ship types which helps reduce emissions in ports. It allows ships to shut down their engines and generators and use electricity generated onshore, which have significantly lower air pollutant emissions and, depending on the grid GHG emission factor, often also lower emissions of greenhouse gases.

An increasing number of jurisdictions is proposing to introduce or introducing requirements for ports to supply and for ships to use onshore power (see Section 1.3). At the same time, maritime shipping is starting a transition from fossil fuels to renewable fuels.

Many renewable fuels generate lower emissions when used in internal combustion engines and almost no emissions when used in fuel cells. E-fuels such as hydrogen and ammonia, as well as biomethanol and biomethane, are all considered to be potential alternative fuels with lower GHG-intensity. All these fuels have much lower emissions of sulphur oxides and particulate matter when used in internal combustion engines. When used in fuel cells, they would also not cause emissions of oxides of nitrogen.

Most requirements for the use of OPS at berth exempt ships with zero- or low emissions technologies. This means that when the number of ships using alternative fuels increases, demand for OPS may decrease. However, there could still be other reasons for ships to link to OPS, e.g. when it provides a cheaper source of power.

1.2 Aim of the study

Against this background, this report analyses the role of OPS in the future maritime fuel and power mix. Specifically, the report analyses:
- how variable costs of zero-GHG electricity delivered via OPS compare with variable costs of zero-GHG self-generated electricity, and how this comparison will evolve over time;
- under which circumstances there is a positive business case for OPS and which design options can improve the business case; and
- how other benefits of OPS will evolve during a maritime fuel transition.

Together, these analyses provide an answer to the question whether there is a risk that OPS becomes a stranded asset when the shipping sector undergoes a fuel transition towards decarbonization.

1.3 Regulation of OPS and fuel transition

The use of OPS is currently to a large extent driven by regulation. Different jurisdictions have implemented or proposed regulations on the supply of OPS by ports and terminals (Section 1.3.1) and on the use of OPS by ships at berth (Section 1.3.2). In addition, regulation addressing the use of fossil fuels by ships is also being proposed (Section 1.3.3). all these factors affect the demand for OPS.

1.3.1 OPS supply regulation

An increasing number of jurisdictions require ports or terminals to supply onshore power to ships.

The European Alternative Fuels Infrastructure Directive (2014/94/EU) requires Member States to assess the need for onshore-power supply for seagoing ships (the Directive refers to shore-side electricity supply). It also states that OPS shall be installed in ports by 31 December 2025, unless there is no demand and the costs are disproportionate to the benefits, including environmental benefits.

The European Commission has proposed to replace the Alternative Fuels Infrastructure Directive with the Alternative Fuels Infrastructure *Regulation* as part of the Fit for 55 package. The proposed Regulation (EC, 2021b) requires Member States to ensure that OPS is available for seagoing container and passenger ships in maritime ports from 1 January 2030 onwards. Specifically, ports have to have sufficient OPS supply to meet 90% of the demand of ocean going containerships and passenger ships of 5,000 GT and above, unless the number of these ships visiting the port is small.[1]

China's Law on the Prevention and Control of Atmospheric Pollution, adopted in 2016, required all newly build terminals to be equipped with shore power and existing terminals to progressively implement shore power (Yin et al., 2020). China's Ministry of Transport adopted a subsidy scheme which ran from 2016 to 2018 with the aim to ensure that 50% of all terminals would be equipped with shore power by 2020.

Californian ports and terminals with twenty or more visits from container, reefer, cruise, ro-ro, and/or tanker vessels (combined) in a calendar year are required to offer all regulated vessel a so called CARB Approved Emissions Control Strategy (CAECS), which can either be an OPS installation or an alternative with equivalently low emissions (CARB, 2020a).

Canada has subsidized OPS installations without a legal requirement for ports to install them (Qi et al., 2020).

1.3.2 OPS Demand Regulation

California, introduced the Ocean-Going Vessels At Berth Regulation in 2007 which required certain ships to use shore power on Californian ports (CARB, 2020b). The regulation has been revised several times. Currently, the Regulation requires all container, refrigerated cargo, cruise, ro-ro, and tanker vessels visiting Californian terminals to connect to OPS or take an equivalent emission reduction measure.

China's Ministry of Transport adopted Port and Ship Power Management Measures in 2019 which requires all ships that have an OPS connection to use OPS in Chinese ports when it is available and when their time in port is longer than a certain minimum (Yin et al., 2020).

The European Commission has proposed to that containerships and passenger ships would be required to use onshore power from 1 January 2030 (EC, 2021c). Exceptions apply for ships that stay at berth for less than two hours, as well as for ships that use zero-emission technologies, notably fuel cells, batteries and on-board generated wind and solar power. In addition, a temporary exemption until 2035 can be given when there is an insufficient

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[1] The threshold depends on the ship type: 50 container ships, 40 ro-ro passenger ships and high-speed passenger craft and 25 other passenger ships.

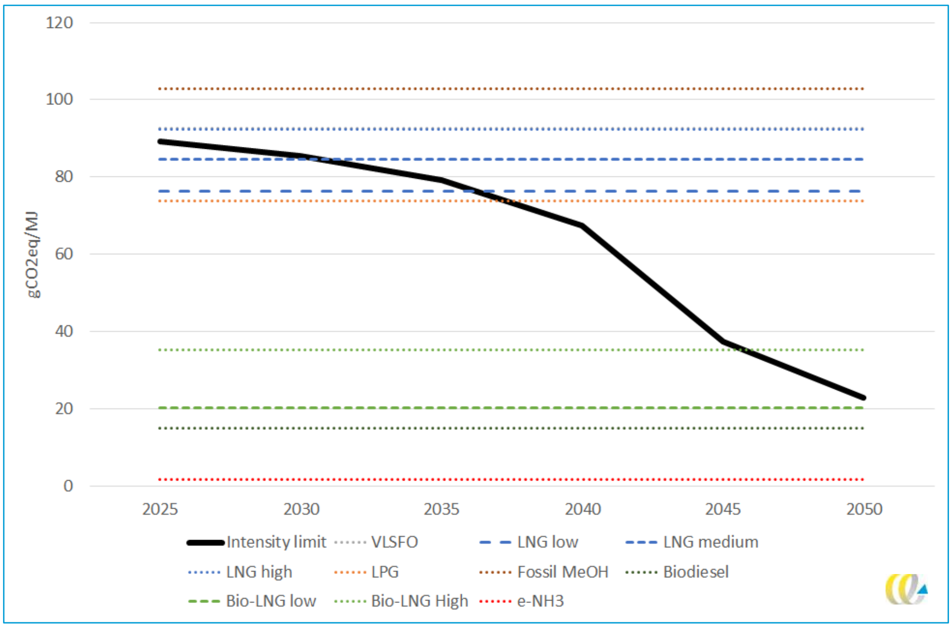
number of OPS connections available or when the on-board installation is not compatible with the shore-side installation.

1.3.3 Fuel transition regulation

The IMO has adopted its Initial Strategy to Reduce GHG Emissions from Ships which aims to phase out GHG emissions from ships as soon as possible in this century and reduce them by at least 50% by 2050 (compared to 2008). The Strategy states that its goals can only be reached when alternative fuels and energy sources are used (IMO, 2018). The Organization is currently debating several candidate measures aiming to accelerate the fuel transition.

In the FuelEU Maritme proposal as part of the Fit for 55 package, the European Commission has proposed that ships reduce the GHG intensity of the fuels used on voyages to and from EU ports, which will require an increased use of alternative fuels over time (EC, 2021c). At the start, the goals can be achieved by using low-GHG fossil fuels like LNG and LPG, as well as biofuels, as shown in Figure 1. Over time, the stringency of the regulation increases and by 2050, many ships will probably need to switch to biofuels or e-fuels.

Figure 1 - Proposed GHG intensity pathway of marine fuels and default intensity values of selected fuels in the FuelEU Maritime proposal



Source: (EC, 2021c), Article 4, Annex II.

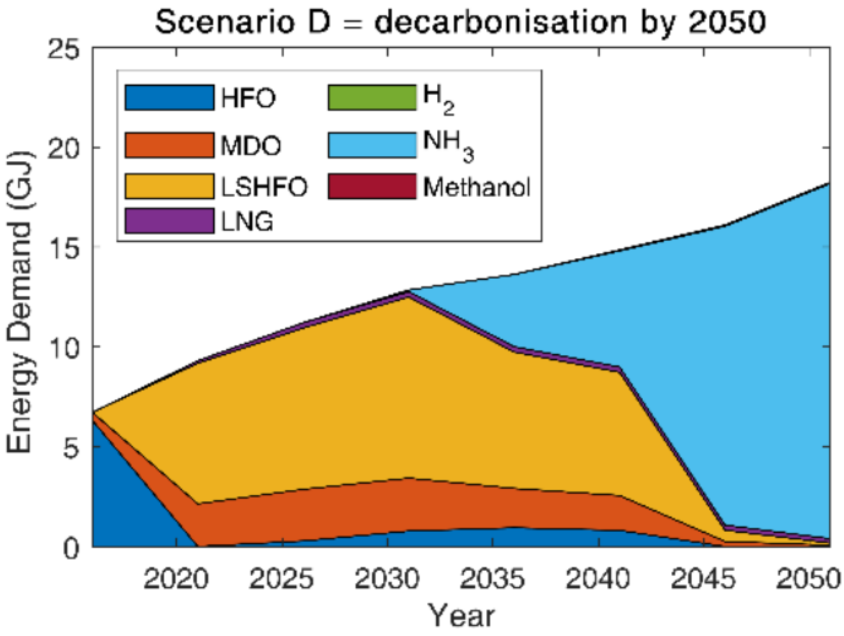
In a separate proposal (a revision of the Renewable Energy Directive), the European Commission proposed to require that the GHG intensity of fuels sold to the transport sector (road transport, aviation, maritime and rail) from the jurisdiction of EU countries should be reduced by 13% in 2030, on average (EC, 2021a). Minimum shares of 2.2% of advanced biofuels and 2.6% of non-biological renewable fuels should contribute to reaching the reduction in GHG intensity.

1.4 Fuel transition of maritime transport

Future European and IMO regulations will likely drive a fuel transition. Several studies have modelled what such a transition would entail for the fuel choice in the next decades. Although different studies show differences in fuel mix over time, it is generally expected that fossil fuels, and especially petroleum-based fossil fuels, will give way to fossil fuels with lower emissions (e.g. LPG and LNG), biofuels (e.g. biodiesel and biomethanol), and synthetic fuels (e.g. ammonia and methanol), either based on green hydrogen or on hydrogen from steam reformed methane in combination with CCS. The results of four recent studies are presented to demonstrate the variety of forecasts in the future maritime fuel mix.

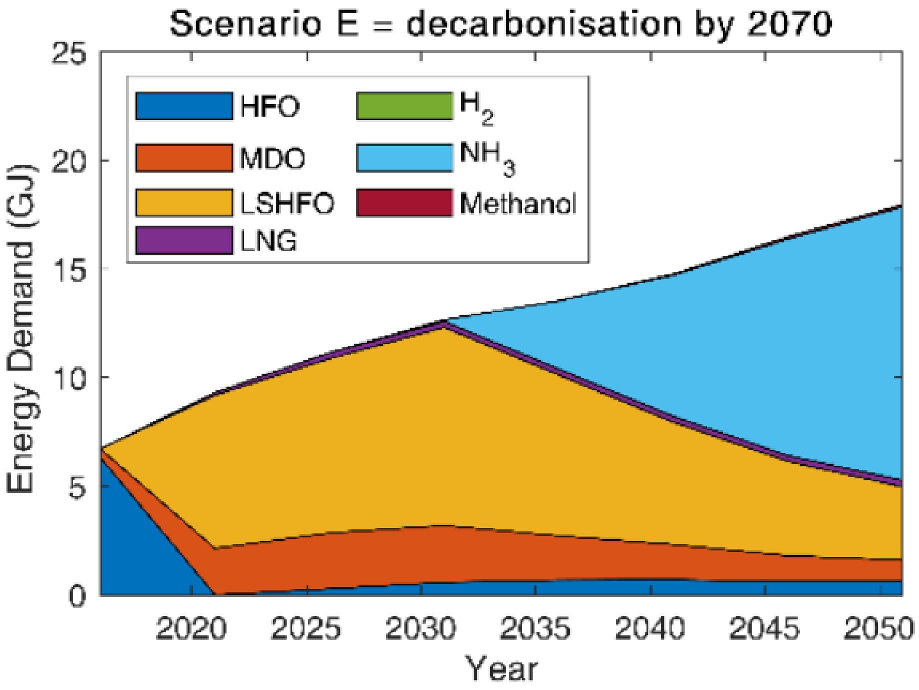
The first study presented here is Raucci et al., (2020) who have developed two scenarios which result in decarbonisation of the shipping sector by 2050 and by 2070, respectively. In both scenarios, the use of petroleum-based fuels increases until 2030, after which it is gradually or rapidly replaced by ammonia. Methanol, hydrogen and LNG have minor roles in these scenarios. Figure 2 shows the most ambitious of the two scenarios, Figure 3 the less ambitious one.

Figure 2 - A fuel scenario for the decarbonisation of shipping by 2050



Source: Raucci et al., (2020).

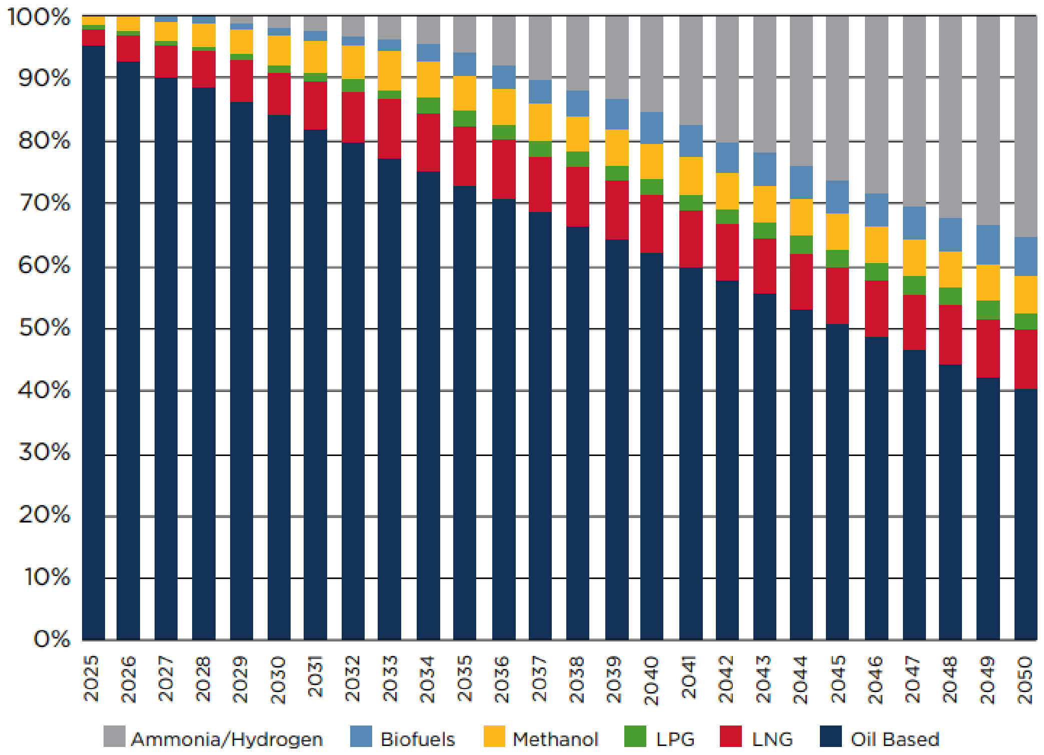
Figure 3 - A fuel scenario for decarbonisation of shipping by 2070



Source: Raucci et al., (2020).

The second scenario presented here is (ABS, 2020), who have developed a scenario which reduces shipping emissions by 50% by 2050, relative to 2008, in line with the minimum level of ambition of the Initial IMO Strategy to Reduce GHG Emissions from Ships (IMO, 2018). In their scenario, shown in Figure 4, the share of LNG increases rapidly between 2025 and 2030, after which year it stabilizes. Further reductions in emissions are caused by an increase in the share of methanol between 2025 and 2035, and, especially after 2035, an increase in the share of biofuels, ammonia and hydrogen.

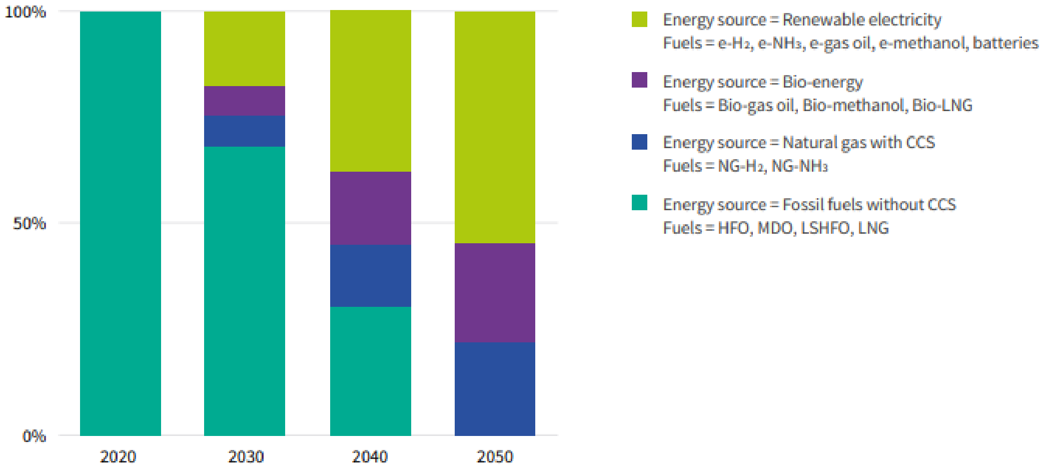
Figure 4 - A fuel scenario for a reduction of shipping emissions by 50% by 2050



Source: ABS, (2020).

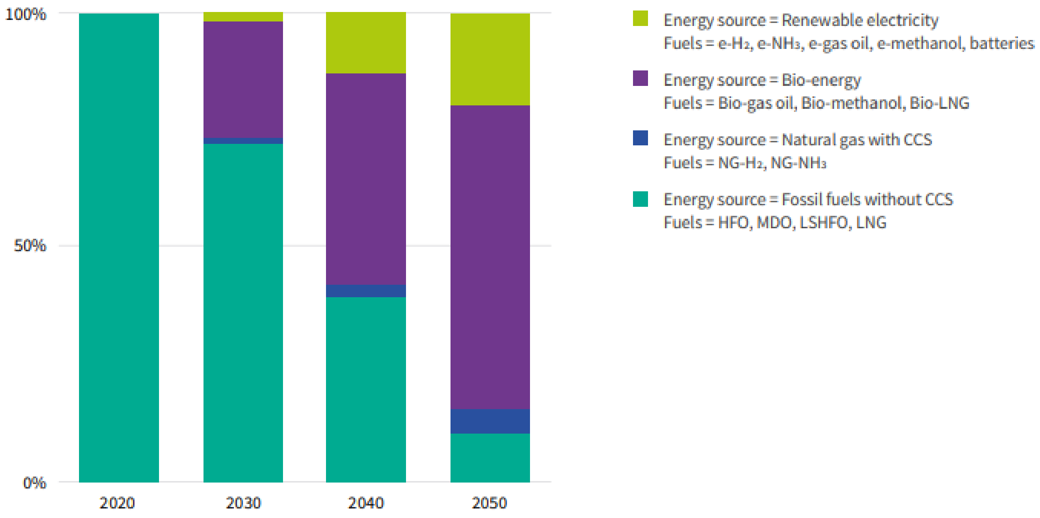
The third scenario is Lloyd's Register and UMAS (2019) who have developed three scenarios, all achieving full decarbonization by 2050. One is dominated by e-fuels produced with renewable electricity (Figure 5), one by biofuels (Figure 6), and the third one is a mix of the other two (Figure 7). In all three scenarios, fossil fuels are rapidly replaced by low-GHG alternatives as from 2030.

Figure 5 - A fuel scenario for the decarbonisation of shipping by 2050 in which e-fuels dominate



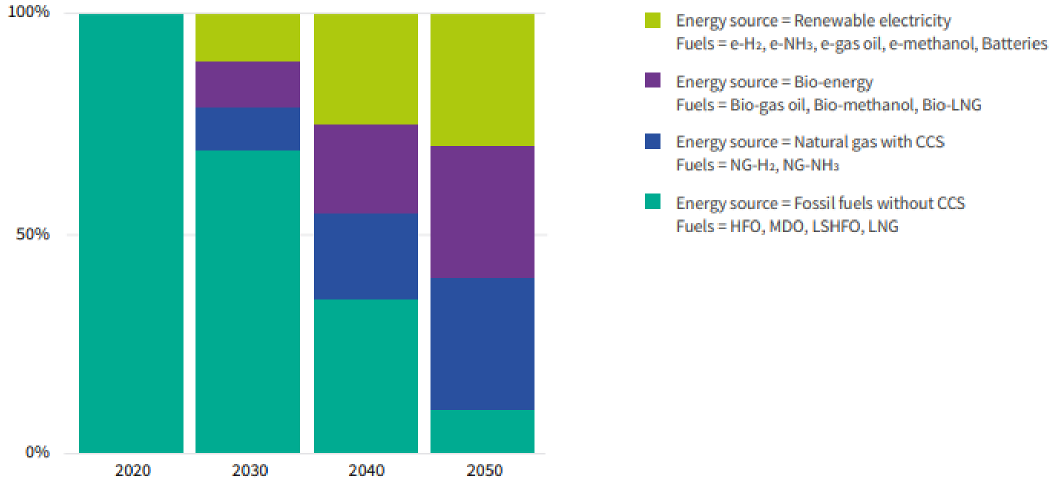
Source: Lloyd's Register & UMAS, (2019).

Figure 6 - A fuel scenario for the decarbonisation of shipping by 2050 in which biofuels dominate



Source: Lloyd's Register & UMAS, (2019).

Figure 7 - A fuel scenario for the decarbonisation of shipping by 2050 with a balanced e-fuel/biofuel mix



Source: Lloyd's Register & UMAS, (2019).

Finally, the fourth scenario, DNV, (2021) project a rapid increase of fossil LNG until 2030 or 2040, depending on the ambition of the climate regulation. Carbon neutral fuels like ammonia and bio-based methanol are expected to pick up in the late 2030s to mid-2040s, reaching between 60 and 100% of the fuel mix in 2050, again depending on the regulation.

All scenarios, except for Raucci et al., (2020), have in common that the dominance of a single fuel type (residual petroleum fuels) is replaced by a broad range of different fuels. Only Raucci et al., (2020) project a replacement of petroleum-based residual fuels by e-ammonia. In the other scenarios, the dominant fuels of the future are expected to be e-ammonia, biomethanol, biodiesels and ammonia from natural gas with CCS.

The scenarios project that by 2040, between 20 and 70% of marine fuel will be fossil fuels (either petroleum based or natural gas). The high end of this range corresponds to scenarios envisaging a 50% reduction in GHG emissions by 2050; the lower correspond with scenarios which project a full decarbonization by 2050. A conclusion that is common to all studies is that a share of the fleet will still sail on fossil fuels by 2040, and still have internal combustion engines, so that by 2040 OPS will have lower air pollutant emissions and often also lower GHG emissions.

2 The concept of shore power and electrification of shipping

Ships at berth generally require electricity for a number of purposes, such as conditioning crew quarters, pumps, cranes and other cargo handling equipment, heating or cooling of cargo, et cetera. The power demand at berth varies significantly over ship type, size, type of cargo, location, et cetera. Typically, passenger ships, liquefied gas carriers, oil tankers and container ships consume more electricity at berth than other ship types (Faber et al., 2020).

Ships have basically two sources of electricity: they can generate it on board or acquire it from shore. Traditionally, ships have been equipped with auxiliary engines and generators to generate electricity from fuel, or, in the case of diesel-electric ships, with generators and electric motors. From 2004, an increasing number of ports along the Pacific costs of North America offered ships the opportunity to connect to power from shore and from about 2010 onwards, an increasing number of European and Asia ports followed suit (Notteboom et al., 2022).

This chapter provides an overview of the ways in which ships at berth can be powered and what the drivers for the costs of powering ships are. Section 2.1 presents the technical concept of onshore power supply and Section 2.2 its economics. Sections 2.3 and 2.4 present the technical and economic aspects of self-generated electricity.

2.1 The technical concept of Onshore Power Supply

An Onshore Power Supply (OPS) to a berthed marine vessel needs to comply with stringent technical and operational requirements, as well as being economically viable.

The OPS comprises of a central substation that houses the necessary electrical components for delivering the desired frequency and voltage level to the vessel. OPS systems can typically deliver 50 and 60hz power at low voltage (440–690V), or medium voltage level (6.6 or 11kV). A substation can serve multiple vessels, but each vessel needs to be galvanically separated using an in-line transformer and dedicated switchgear. The capacity of the substation needs to be able to cater for the peak load of the vessel(s) to avoid a power trip and blackout. The reliability of the substation is typically very high but there will be some downtime in the maintenance of the main components like the frequency converter.
The frequency conversion also consumes power (estimated to be around 5-10%) that dissipates as surplus heat via the substation cooling system.

The connection between the vessel and shore is established via the cable management system (CMS) and is typically the most critical component of the overall system. The CMS needs to be sufficiently flexible to cater for the variety of vessels that may utilise the quay, both in terms of the safe and reliable power transmission as well as the physical handling to ensure that a connection can be made efficiently and safely. The larger the variety in vessels and berth patterns, the more complex the CMS becomes. For a ferry in a fixed berth pattern, the CMS can be fully automated and kept relatively simple. However, for a deep sea container terminal or bulk terminal, where the vessels can berth anywhere along the entire quay length and have variable power demand, the CMS concept is more challenging and can become significantly more expensive.

The interplay between the local shore power system and the vessel's electricity system is very refined, and as such vessels will have to be specifically commissioned for the first time use of an OPS system at the quay.

2.2 The economics of Onshore Power Supply

For the ship, the costs of OPS comprise the depreciation of the OPS equipment, the cost of electricity and the cost of the crew required to connect the ship to the power supply.

The cost at which the onshore power can be supplied to the vessels will depend on a number of variable cost components (like the electricity price, transport costs and the connection costs) and some fixed cost elements for the depreciation, operation and maintenance of the OPS facilities and infrastructure. Depending on the local situation, the infrastructure costs may also include upgrades of the capacity of the grid to allow for the transport of the electricity required by ships.

A commonly used commercial model between the company that provides the OPS services and the vessel owner assumes a 'pay-by-use' model, also to allow for a direct comparison with self-generated power using the vessel's auxiliary engine and available marine fuels. As the auxiliary engine will typically have a significant operational range, the vessel can cater for a large ratio between peak demand and average demand. But for the OPS facility the peak to average ratio is a very important technical and commercial component, as the facilities will need to be designed for the peak rate and also the transport fee with the grid operator is typically driven by the peak capacity demand and not by averages. Therefore, the OPS owner might need to settle the cost based on peak capacity. However, its income is based on the average power volumes supplied to the vessel. Given pay by use model, the vessel owner has very little incentive to flatten its demand profile when using OPS.
As example, if the peak to average rate was 4:1, then even a fully utilised OPS system (time based), would only see a capacity utilisation of just 25%. This situation would improve if multiple vessels are connected to the central OPS system simultaneously and the peaks can be balanced out better. When more ships connect to OPS, it will be possible to improve the utilisation rate of the central facility, although this depends on the terminal and port lay-out.

In order to improve economic viability, it would be preferred that the OPS system will not have to be designed for the worst case demand situation and that a more probabilistic approach with a smart power management system is to be sought. The current international OPS standards[2] do not cater for this and is very much designed from the perspective that the vessel is given maximum certainty and reliability with regards to the shore power capacity availability. That might be optimized in the future when more ports advance their OPS designs.

The business case for the vessel owner constitutes of the difference between the cost incurred with auxiliary engine use within the governing regulation, and the cost for the OPS power. The cost and operational complexity for establishing the OPS connection will be an important consideration in the comparison, especially for the lower power demands. Counterintuitively, a low voltage connection is not necessarily much easier to establish given that the cables are considerable thicker for transporting the same amount of electrical power, and more cables may be needed. The thicker cables will be more difficult to handle and also more expensive.

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[2] IEC/IEEE 80005-1, IEC/IEEE 80005-2, and IEC/IEEE 80005-3.

It is anticipated that future vessels will increasingly use hybrid propulsion systems, where electrical thrusters are combined with (renewable) fuel driven generators. These vessels will typically also have a battery pack onboard to manage the short-term peaks and ensure a more continuous and stable load on the generators. The on-board power concept is then very much in analogue to hybrid cars. This provides significant upside for the OPS business case when the on-board batteries can be used for peak shaving and can also be charged during the berth stay, thereby significantly increasing the OPS utilisation and ability for system balancing.

2.3 Self-generated electricity

Electric power on board ships are commonly generated either by a shaft generator; by a turbine supplied with steam produced in a waste-heat boiler; or by generators driven by auxiliary engines. Since the main engine is usually switched off at berth, the two former options are not available and electricity is generated by running auxiliary engines.

Zero-emission alternatives to using generators are either using fuel cells or batteries. Fuel cells have been used in submarines since the 1960s. The interest has increased in recent years due to their potential to reduce GHG emissions and a few dozen demonstration projects have been conducted in marine vessels, with power output capacity ranging from 10 to 500kW (Xing et al., 2021). However, major barriers to their wider application remain their relatively high cost, the high cost of the fuels which are not usually supplied to ships and which need to be very pure, and reliability.

Batteries are used in full electric ships (mostly ferries) and in hybrid ships. While they provide clean energy, they are not commonly used because the integration of a battery in a ship’s power system is costly. The price of a marine battery was estimated to be USD 500 per kWh by a major supplier in 2019 (MAN Energy Solutions, 2019). However, in several cases their use could be economical and there have been multiple announcements of new ferries with batteries so the number of ships equipped with batteries could increase in the future (Brittany Ferries, 2022, Stena Line, 2021)

The amount of fuel used at berth varies over ship types and sizes. In order to get a perspective, ships that reported to the EU MRV consumed 6% of their fuel at berth and the remaining 94% at sea and manoeuvring (CE Delft & Ecorys, 2021). Auxiliary engines emit pollutants to the air when they generate electricity. In the EU, approximately 2% of NO_x is emitted by ships at berth, as well as 0.2% of $PM_{2.5}$, 0.2% of SO_2 and 0.1% of NMVOC (CE Delft & Ecorys, 2021).

2.4 The economics of self-generated electricity

From the perspective of the ship, the costs of self-generated power are determined by the fuel costs, which are determined by the fuel price, the fuel usage of the auxiliary engines used at berth, conversion losses (SFC), maintenance costs, and, where applicable, taxes.

3 Comparison of onshore and self-generated power

This chapter compares the costs of onshore power, generated in an increasingly decarbonized way, with the costs of decarbonised self-generated power. It presents two comparisons. First, a comparison of the variable costs, which are relevant when investments in CAPEX are considered sunk costs (e.g. because they are required by the regulator or because the investments have been written down). Second, case studies of the business case for investing in OPS equipment, which takes the costs of financing the assets into account.

Note that the calculations presented here have been made in 2021 and prices reflect the prices and price projections of that year. In 2022, prices have increased as a result of disruptions of the energy system. We have decided not to update the calculations because of the high current volatility and uncertainty about future prices.

Section 3.1 presents a comparison of variable costs in order to analyse how costs of zero-GHG electricity delivered via OPS compare with unit costs of zero-GHG self-generated electricity, and how will this comparison evolve over time. Section 3.2 presents case studies in order to analyse under which conditions there is a positive business case for investing in OPS – even when such investments are not mandated.

3.1 Variable costs comparison

All costs have been estimated for 2030, 2040 and 2050. Estimates for later years have a larger uncertainty than estimates for earlier years. Section 3.1.2 presents the estimates for 2040, which is towards the end of the economic life of OPS installations that are installed in the next few years and towards the end of the economic life of ships built now. Results for other years are included in Annex A.

3.1.1 Methodology

The variable costs of OPS are defined as the average price of electricity. In Europe, we have taken the projected average electricity prices in the impact assessment of the European Reference Scenario (E3M-Lab et al., 2021) and of the European Green Deal (EC, 2020a). In the US, we have used the projected electricity prices from the Annual Energy Outlook of the U.S. Energy Information Administration (EIA, 2022). All prices are average prices of grid electricity which currently emit carbon. The European Green Deal foresees full decarbonization by 2050, resulting in increasing prices, while prices in the other two scenarios are more or less stable over time.

The final consumer prices include the costs of power generation and transport. Since alternate current in Europe has a frequency of 50Hz, and ships require 60Hz, the current has to be transformed to a different frequency. It has been assumed that the associated losses are 5%. Costs of investments in transformers are not included here.

The variable costs of self-generated electricity is determined by the cost of the fuel and the efficiency of the auxiliary engine/generator set. Assuming that ships are obliged to connect to OPS unless they generate power without local emissions, a zero-emission fuel has been

selected in combination with a fuel cell. As for fuel, Ammonia has been selected as a fuel because it is projected to have the lowest cost of e-fuels (CE Delft & Ecorys, 2021).
The costs of e-ammonia are based on (IRENA, 2021). Because of the uncertainty about the technological progress, a low, middle and high price projection have been used. These can also be interpreted as the costs for producing ammonia in regions with low, medium and high costs of renewable electricity. As the IRENA prices do not include bunkering costs, we have assumed that the bunkering costs of liquefied ammonia amount to USD 2/GJ of fuel.

It has been assumed in the calculations that the efficiency of the fuel cell is not determined by the type of energy carrier, and that the electrical output is 45% (average efficiency) or 60% (future high efficiency technology) of the lower calorific value of the energy carrier. These are representative values for fuel cells, taking into account that they do not operate at optimal load and are subject to ageing (Xing et al., 2021).

3.1.2 Results

The comparison of variable costs is relevant for cases in which the capital expenditures for OPS installations are not included in the price of OPS power. This can be because the OPS installations have been subsidized, or because they have been installed in order to comply with legal obligations, or because the investments are considered as sunk costs[3] and will therefore not determine the decision to supply or not.

Table 1 presents the price difference between variable OPS costs and variable costs of power generation on board of a ship in 2040 for a number of electricity price projections. Depending on the projected electricity price and the price of fully renewable fuel, the variable costs of OPS are between 0.01 and 0.23 USD per kWh cheaper than the variable costs of self-generated power, when the fuel cell has an efficiency of 45%. This implies that when OPS prices are based on variable costs, it is economically rational for ships to connect to OPS.

Table 1 - Price difference between onshore power and self-generated fuel cell power in 2040 (USD/kWh)

	Lower price projection of NH_3	Middle price projection of NH_3	Upper price projection of NH_3
EU Reference scenario grid price	-0.04	-0.11	-0.17
EU climate target scenario grid price	-0.01	-0.08	-0.15
US Annual Energy Outlook 2022 reference case grid price	-0.10	-0.17	-0.23

Note: negative values denote that the marginal costs of onshore power is lower than the marginal costs of self-generated power. The EU Reference scenario projects an overall reduction in GHG emissions in the EU of about 60% by 2050 (E3M-Lab et al., 2021). The EU climate target scenario models an energy mix which achieves a 90% of reduction in CO_2 emissions by 2050 **(European Commission, 2020)**. US AEO Reference case projects an emission intensity improvement of about 2% between 2021 and 2050 (E3M-Lab et al., 2021). The cost-price of self-generated power assumes the use of green ammonia in a fuel cell with 45% efficiency. Ammonia costs include bunkering costs and are based on IRENA (2021). Note that energy taxes have not been included in the comparison.

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[3] Economic theory is that, once an investment has been done, the decision whether or not to supply is determined by whether the price equals the marginal (=variable) cost of production. The investment costs are called ‘sunk costs’, because they do not affect the decision whether or not to supply.

The costs of self-generated electricity in 2040 range from 0.20 to 0.33 USD per kWh (see Annex A). Hence, a cost saving of USD 0.10 per kWh on average is a significant share. For a large container ship with a power demand of 1.4 MW and eight hours at berth, the average savings amount to USD 1100 per port call. For a cruise ship with a power demand at berth of 10 MW, remaining twelve hours at berth, the savings amount to USD 12,000.

3.2 Total cost comparison

In contrast to Section 3.1, this section analyses the business case for investments in OPS. Therefore, both investments and variable costs are taken into account. Such comparisons are relevant for a situation in which ports are not required by law to supply OPS and ships are not required by law to connect to OPS. The section analyses whether in those cases, investments in OPS are profitable.

A number of cases have been identified to allow for a comparison of OPS with renewable fuels, shown in Table 2.

Table 2 - Overview of the different use cases for terminals

Case	Power demand at berth	Voltage level	Quay Flexibility (CMS cost)
Ferry terminal (two ferries)	2 MVA	11kV/ 60 hz	low
Cruise terminal (one cruise vessel)	10 MVA	11kV/ 60 hz	medium
Deep sea container terminal (multiple vessels)	8 MVA	6.6kV/60 hz	High
Bulk terminal (multiple vessels)	1 MVA	440V/50hz	High

Source: Port of Rotterdam Authority.

Case 1
The first case describes a typical ferry terminal, with two berths/linkspans.
The OPS system is designed for 2 mega Volt-Ampères (MVA) with the ability to supply peak power to one vessel and average power to both vessels (the average power intake is 1 MVA, and the peak approximately 1.5 MVA).

Case 2
The second case looks at a cruise terminal with one cruise ship berthed at the time. Because of the power demand of cruise ships, the OPS system is designed for 10 MVA but upgradable to 16 MVA. The CMS flexibility needs to be higher since every cruise ship will come with its own unique OPS connection design. Typically a (fully autonomous) trolley system is used to cater for that variability.

Case 3

The third case looks at a deep sea container terminal, with 1 km of quay length, divided into four zones of 250 m each. The container vessels will come with their own cable management system pre-installed on board, but the quay needs to be able to have the power sockets sufficiently spread over the quay (or facilitated via an automated system) to ensure that the operational flexibility is not compromised and there are not dead zones on the OPS coverage. The lateral displacement of the cable over the quay is typically very limited (max. 25 m). The capacity is 8 MVA.

Case 4

The final case is looking at a bulk terminal, where the vessels will require much lower power loads (typically around 500 kW) and the system will be designed to cater for two vessels at a quay of one km and have a capacity of 1 MVA.

3.2.1 Cost and demand estimates

Table 3 provides an overview of the capital cost estimates for the four use cases. These figures are derived from quick scan studies conducted by the shore power program team of the Port of Rotterdam Authority during 2020 and 2021. They are typically based on a budgetary market quote from relevant suppliers and consultant. The costs include the socialised cost for the grid connection, but exclude the actual cost that may be incurred by the grid operator.

Table 3 - Capex costs estimates for each of the four cases

Case	System design	Central system	CMS cost	Overall Capex	Cost per MVA
	(MVA)	(Million USD)			
Ferry terminal (two ferries)	2.0	1.37	0.23	1.60	0.80
Cruise terminal	10.0	11.42	2.28	13.70	1.37
Deep sea container terminal	8.0	6.85	4.57	11.42	1.48
Bulk terminal	1.0	1.14	0.69	1.83	1.83

Source: this report.

The fixed cost of these cases will be driven by the capex depreciation and market compatible return (assumed to be 6% for infrastructure), the local grid operator tariffs for the capacity & power transport and the cost for operating & maintaining the facility. Table 4 provides the assumptions based on the Rotterdam situation.

Table 4 - Fixed annual cost estimates for each of the four cases

Case	System design	Grid connection	O&M costs	Capex deprecitation and return	Total fixed annual costs
	MVA	1,000 USD			
Ferry terminal (two ferries)	2 MVA	132	78	126	336
Cruise terminal	10 MVA	628	320	1.073	2,021
Deep sea container terminal	8 MVA	503	274	893	1,670
Bulk terminal	1MVA	69	82	143	294

Source: this report.

The variable costs are largely driven by the green electricity supply, the margins for the energy provider and the losses in the OPS system (primarily the frequency conversion). It has been assumed that the electricity losses as a result of frequency conversion amount to 5%%.

The demand profile for each of the use cases (Table 5) is based on some real-life examples and feasibility assessments conducted in Rotterdam. The data is taken from the satellite tracker (AIS) of the sea going vessels that occupy the berth and validated with questionnaires to the foundation customers (on the actual power profile) and terminal datalogs. The capacity utilisation is the ratio of the expected power output and the maximum power output. The utilisation is always lower than 100% because a berth is not continuously occupied and because systems are designed at peak power capacity.

Table 5 - OPS demand and system utilisation for the base case

Case	System design (MVA)	average demand (MW)	berth time/ visits	Annual berth time total (hrs)	Energy total (MWh)	System capacity utilisation
Ferry terminal (two ferries)	2	1,2	8 hrs/2 daily	5844	7013	40%
Cruise terminal	10	9	24 hrs/100 times per year	2400	21600	25%
Deep sea container terminal	8	2,5	16 hrs/400 per year	6400	16000	23%
Bulk terminal	1	0,4	30 hrs/200 per year	6000	2400	27%

Source: this report.

3.2.2 Business case results

With the assumption from Section 3.2.1, the levelised cost of energy can be derived for the various use cases. These are the costs that the ship owner will need to pay per kWh in order for the terminal to make a reasonable market conform (6%) return on their investment. In this evaluation a 114 USD[4] connection fee has been taken into consideration. The international shore power standard requires for every unique ship - shore power installation to be fully commissioned once before operation. This is a one-off cost and in the future may become a less labour-intensive process (e.g. using blockchain technology). The one-off commissioning fees are not included in the business case.

The results are presented in Table 6. For the four used cases analysed, the base OPS costs vary between USD 270 and USD 322 per MWh. A comparison with the unit costs of self-generated electricity shows that when renewable fuels are expensive, the OPS LCOE is lower than the variable costs of self-generated electricity. When the price of renewable fuels is low, self-generated power is less expensive.

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[4] This is based on the indicated 100 euro connection fee by Port of Rotterdam. A higher connection fee would increase the LCOE of OPS.

Table 6 - Levelised cost of electricity results from the base evaluation (USD/MWh)

	OPS LCOE	Self-generated electricity		
	Base	**Low NH_3 price**	**Medium NH_3 price**	**High NH_3 price**
Typical ferry terminal (two ferries)	270	200	270	340
Cruise terminal	280			
Deep sea container terminal	294			
Bulk terminal	322			

Note: grid prices based on the EU Reference scenario, which projects an overall reduction in GHG emissions in the EU of about 60% by 2050 (E3M-Lab et al., 2021). OPS LCOE will be higher with EU climate target scenario grid prices and lower with grid prices from the US AEO 2020 Reference Case.

3.3 Conclusions

This chapter has compared the costs of OPS with the costs of self-generated green electricity onboard ships for 2040, both on a variable cost basis and on a total cost basis.

The variable costs of OPS are lower than the variable costs of self-generated electricity in all price projections. When the projected costs of electricity are high and the costs of the e-ammonia is low, the differences are almost negligible, but in all other cases, the variable costs of OPS are lower, on average by a third. Note that when electricity is taxed, the conclusions could be different.

For ships with a relatively high power demand at berth, such as ferries, cruise ships and container ships, the total costs of OPS electricity are close to the costs of self-generated power under medium price projections of ammonia. When renewable fuel prices are low, self-generated power is cheaper; when renewable fuel prices are high, OPS is cheaper. This means that for these ship types, the investments could yield a return. However, when OPS electricity would be taxed, the costs of OPS would increase.

4 Conclusions

This report has analysed the economics of onshore power supply in order to assess the risk of onshore power supply units becoming stranded assets when the shipping sector undergoes a transition from fossil fuels to zero-GHG fuels. After all, when ships sail on zero-GHG fuels, which often also have significantly lower emissions of air pollutants, the benefits of OPS become smaller, which may result in exemptions from requirements to connect to OPS. When ships are not legally required to connect to OPS, they will only do so if it is more cost-effective to buy electricity from shore than to generate it on board.

The analysis focusses on 2040, because this is near the end of the economic life of both OPS installations and ships which are built today.

The report finds that there are several reasons which make it unlikely that OPS becomes a stranded asset.

First, shore power is projected to be cheaper in Europe than electricity generated on board with a green fuel on a variable cost basis, even when the fuel is produced and bunkered in regions with very low renewable electricity prices, as long as both bunker fuels and electricity are exempt from energy taxes.

Second, ships that sail on fully renewable fuels may still have air pollutant emissions, especially when the renewable fuels are used in internal combustion engine with a pilot fuel. Depending on the precise regulation, these ships may not be exempted from an obligation to use OPS.

Third, in all scenarios of decarbonization of shipping, a significant share of maritime fuels will still be fossil by 2040. Depending on the projection, the share ranges from 20 to 70%, with lower percentages associated with scenarios that model full decarbonization by 2050 and higher percentages with scenarios that model decarbonization at a later date. Ships sailing on fossil fuels are likely to still be legally required to connect to shore power at berth.

For ships with a relatively high power demand at berth, there is a positive business case for investing in OPS. The total costs of OPS electricity are not comparable to the costs of self-generated power under medium price projections of renewable fuels.

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A Full overview of comparison of variable costs

This annex presents the comparison of variable costs for all years, as well as the price projections for ammonia and electricity.

Table 7 - Green ammonia cost projections USD/MWh

Bound	2030	2040	2050
Lower	113	85	67
Middle	147	115	91
Upper	180	145	114

Source: (IRENA, 2021) (see Figure 4 on page 15 of this source).

The efficiency of self-generated electricity with green ammonia in a the fuel cell is assumed to have an electrical efficiency of 45%. Therefore the costs in Table 7 have to be increased to 100%. The following formula is used to calculate the values of Table 8: (costs Table 7 + bunkering costs)/45*100/1.000.

Table 8 - Variable costs of self-generated electricity with green ammonia in a fuel cell with an electrical efficiency of 45% [USD/MWh]

Bound	2030	2040	2050
Lower	270	200	160
Middle	340	270	220
Upper	420	340	270

Note: the assumed costs for bunkering are 2 USD/GJ LCV of ammonia or 7.2 USD/MWh.

Source: this report.

The efficiency of self-generated electricity with green ammonia in a the fuel cell is assumed to have an electrical efficiency of 60%. Therefore the costs in Table 7 have to be increased to 100%. The following formula is used to calculate the values of Table 9: (costs Table 7 + bunkering costs)/60*100/1000.

Table 9 - Variable costs of self-generated electricity with green ammonia in a fuel cell with an electrical efficiency of 60% [USD/MWh]

Bound	2030	2040	2050
Lower	200	150	120
Middle	260	200	160
Upper	310	250	200

Note: the assumed costs for bunkering are 2 USD/GJ LCV of ammonia.

Source: this report.

Table 10 - Electricity price projections (consumer prices excluding energy taxes) USD/MWh

Source	2030	2040	2050
EU Reference scenario	159	158	159
EU climate target scenario	182	184	237
US Annual Energy Outlook 2022 reference case	106	105	102

Source: (E3M-Lab et al., 2021, EC, 2020b, EIA, 2022).

Explanation values EU reverence scenario:

- Source: E3M-Lab et al., (2021).
- From this source Figure 65 on page 100 is used.
- Total costs - excise tax and VAT on electricity - tax on fuels and ETS payments.
  This give a price in euro's per MWh. This is scaled (via HICP) to price level 2020 and from Euro’s to USD.

Explanation values EU climate target scenario:

- source: EC, (2020a);
- from this source figure 87 is used;
- used the values of the years 2030 and 2050;
- 2040 scaled from 2030 and 2050;
- decrease the value with tax (see the tax in the EU reverence scenario);
- scale (via HICP) to price level 2020 and to USD.

Explanation US Annual Energy Outlook 2022 reference case:

- source: EIA, (2022) Table: Table 8. Electricity Supply, Disposition, Prices, and Emissions;
- use price for all sectors average in dollar cent per kWh;
- calculate dollarcents to dollars;
- calculate to MWh.

Explanation calculation Table 11

- convert value 2nd row of Table 10 to kWh;
- add 5% energy loss:
  5% = 50 kWh loss per MWh. 50 kWh costs: 50 * value 2nd row of table 12/1,000;
- subtract this with the value of Table 8.

Table 11 - Price difference between onshore power and self-generated fuel cell in EU reference scenario (USD/MWh), assuming 45% electrical efficiency of the fuel cell

	Lower price projection of NH_3	Middle price projection of NH_3	Upper price projection of NH_3
2030	**-100**	**-180**	**-250**
2040	**-40**	**-110**	**-170**
2050	**0**	**-50**	**-100**

Source: The efficiency of self-generated electricity with green ammonia in a the fuel cell is assumed to have an electrical efficiency of 45%. Therefore the costs in Table 7 have to be increased to 100%. The following formula is used to calculate the values of Table 8: (costs Table 7 + bunkering costs)/45*100/1.000, assuming a 5% energy loss for conversion of 50Hz to 60Hz.

Table 8, Table 10 assuming a 5% energy loss for conversion of 50 to 60HZ.

Explanation calculation Table 12: see explanation of Table 11, but use the 3rd row of Table 10 instead of the second.

Table 12 - Price difference between onshore power and self-generated fuel cell in EU climate target scenario (USD/MWh), assuming 45% electrical efficiency of the fuel cell

	Lower price projection of NH_3	Middle price projection of NH_3	Upper price projection of NH_3
2030	**-80**	**-150**	**-220**
2040	**-10**	**-80**	**-150**
2050	**80**	**30**	**-20**

Source: The efficiency of self-generated electricity with green ammonia in a the fuel cell is assumed to have an electrical efficiency of 45%. Therefore the costs in Table 7 have to be increased to 100%. The following formula is used to calculate the values of Table 8: (costs Table 7 + bunkering costs)/45*100/1.000, assuming a 5% energy loss for conversion of 50Hz to 60Hz.

Table 8, Table 10 assuming a 5% energy loss for conversion of 50 to 60HZ.

Explanation calculation Table 13: see explanation of Table 11, but use the 4th row of Table 10 instead of the second.

Table 13 - Price difference between onshore power and self-generated fuel cell in US AEO2022 reference case (USD/MWh), assuming 45% electrical efficiency of the fuel cell

	Lower price projection of NH_3	Middle price projection of NH_3	Upper price projection of NH_3
2030	**-160**	**-240**	**-310**
2040	**-100**	**-170**	**-230**
2050	**-60**	**-120**	**-170**

Source: The efficiency of self-generated electricity with green ammonia in a the fuel cell is assumed to have an electrical efficiency of 45%. Therefore the costs in Table 7 have to be increased to 100%. The following formula is used to calculate the values of Table 8: (costs Table 7 + bunkering costs)/45*100/1.000.

Table 8, Table 10.

Explanation calculation Table 14: see explanation of Table 11, but use Table 9 instead of Table 8.

Table 14 - Price difference between onshore power and self-generated fuel cell in EU reference scenario (USD/MWh), assuming 60% electrical efficiency of the fuel cell

	Lower price projection of NH_3	Middle price projection of NH_3	Upper price projection of NH_3
2030	**-30**	**-90**	**-310**
2040	**10**	**-40**	**-90**
2050	**40**	**0**	**-40**

Source: Table 9, Table 10, assuming a 5% energy loss for conversion of 50Hz to 60Hz

Table 15 - Price difference between onshore power and self-generated fuel cell in EU climate target scenario (USD/MWh), assuming 60% electrical efficiency of the fuel cell

	Lower price projection of NH_3	Middle price projection of NH_3	Upper price projection of NH_3
2030	**-10**	**-60**	**-310**
2040	**40**	**-10**	**-60**
2050	**120**	**90**	**50**

Source: Table 9, Table 10, assuming a 5% energy loss for conversion of 50Hz to 60Hz

Table 16 - Price difference between onshore power and self-generated fuel cell in US AEO2022 reference case (USD/MWh), assuming 60% electrical efficiency of the fuel cell

	Lower price projection of NH_3	Middle price projection of NH_3	Upper price projection of NH_3
2030	**-90**	**-150**	**-310**
2040	**-50**	**-100**	**-150**
2050	**-20**	**-60**	**-100**

Source: Table 9, Table 10.