




## Article

# Iberian Ports as a Funnel for Regulations on the Decarbonization of Maritime Transport

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**Abstract:** We are currently seeing how new marine fuels are being introduced, such as Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), hydrogen, ammonia, methanol, batteries, etc., for the propulsion of the world fleet with the aim of complying with the increasing IMO emissions regulations. The frenetic effort made by shipping companies to decarbonize maritime transport must be followed by an unstoppable adaptation of ports from the historical supply of only fuel and diesel to covering the demands of new fuels, ensuring their renewable origin; onshore power supply (OPS); or even the storage of captured CO<sub>2</sub>. This article compiles the current environmental regulations applied to maritime transport to provide an analysis of the current situation and a link between vessels' requirements to comply with such regulations and port environmental infrastructure. This work demonstrates that technological development is growing faster onboard vessels than at ports. It is demonstrated that except for the case of LNG, the theoretical shipping fuel world demand of each type of alternative fuel cannot be absorbed by current world production, where we found big gaps between supply and demand of up to 96.9%. This work concludes that to speed up this process, ports will need European aid as well as private investment. It is proposed that for the next steps, the port system needs to provide the required infrastructure to vessels on time, which inevitably means improvements in competitiveness and governance to promote the blue economy and the concept of smart ports, attracting main international shipping lines with a complete decarbonization hub on their routes by taking advantage of the geostrategic role of the Iberian ports. At the same time, the port governance model must be more flexible in the decision-making process, anticipating changes in maritime regulations with the challenge of coordinating public and private interests, serving as a link, once again, between ship and society.



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## 1. Introduction

Spain, one of the world's main tourist destinations, is the focus of the cruise market due to its geographical position in the western Mediterranean, the Atlantic coast, and the Canary Islands. This tourist attraction is the main engine of the Spanish economy, and for this reason, our port system is aware of and invests in the necessary infrastructures to attract cruise ships and a greater number of tourists to our territory. The impact of tourism reached around 8% of the country's gross domestic product in 2021 [1], with part of its economy being sustained by the service sector, with development and excellence unparalleled among hotel and transport offers.

Maritime transport is the most efficient means of transport in terms of g.CO<sub>2</sub> per t-mile sailed. On the other hand, exhaust gas emissions from shipping are significant contributors

to global atmospheric emissions and to local pollution in harbour areas. The reason is because the activity carried out by maritime transport is very large, moving more than 80% of the world's trade volume [2] and will keep increasing annually at an average rate of 3.5% [3]. The total emission from shipping in the European Union measured in 2018 was 25% compared to other sources [4]. It is expected that in 2022, the maritime transport sector will emit 851 mt of CO<sub>2</sub>, 2.3% of the world total [5].

This issue is receiving a lot of pressure not only from regulators but also charterers, cargo owners, shipyards, non-governmental organizations (NGOs), or even financiers, as well as other stakeholders. To revert the increase in emissions from the transportation sector, a number of new regulations with huge impacts on economics, technology, infrastructure, and the supply chain have been taken into effect.

The maritime environment is also aligned with this emission reduction strategy, to the point that the financial sector is organizing itself around what is known as the Poseidon Principles, which currently have some 30 signatories. Their objective is to have portfolios made up of assets that meet the double achievement of zero net emissions and a 50% reduction in CO<sub>2</sub> emissions by 2050 [6]. As a result, the Poseidon Principles enable financial institutions to align their ship finance portfolios with responsible environmental behavior and promote responsible environmental stewardship in the maritime value chain. The four principles (assessment of climate alignment, accountability, enforcement, and transparency) include new requirements for banks and owners. Banks will now present an annual report collecting data emissions from borrowers, including KPIs. An independent entity will score a given portfolio against the Poseidon Principles' requirements. Owners will also need to share a statement of fact documenting fleet performance against the requirements of the Poseidon Principles.

For decades, there has been talk that global warming will have catastrophic consequences for humanity: that is why the Paris Agreement was signed in 2015—to reduce climate change. Its main objective is to limit the increase in global temperature to 1.5 °C from preindustrial levels. Currently, and despite a massive buildout of renewables in the coming years, a rise of 2.4 °C is forecasted by 2050.

Technology, policy, and social change have the power to reduce emissions and create a clean energy future. The use of less energy in the construction, transport, industrial sectors is the least expensive way to reduce carbon emissions. For this, it is commonly accepted in the international community that the energy transition will be based on three pillars: renewable energies, energy networks, and efficiency in the use of energy.

To contribute to this transition, maritime transport must begin a path of decarbonization in this decade, which it will require new technologies and fuels. At the same time, new regulations will control and incentivize this emission reduction from 2023.

Of course, this decarbonization will have costs for transport. So, there are three clear risks to achieving this energy transition: new regulations that will appear, future energy and fuel prices, and the effect on world transport demand. Fuel costs are part of the voyage expenditure (VOYEX) costs related to a vessel's voyage that are proportional to its use. Bunkers share between 50% and 60% on average of the total operational cost of a ship [7]. To use an example, the bunker component for 2 mn bl very large crude carriers (VLCCs) on the US Gulf Coast–China route reached 33 pc of the 15 November 2021 freight rate of USD 5.7 mn, compared with 16 pc of roughly the same freight rate on 6 July 2020 [8]. With vessels carrying over 80% of the global trade volume, higher fuel costs and consequently higher significant shipping costs will increase the maritime transport price. The United Nations Conference on Trade and Development estimated that, in particular, higher grain prices and dry bulk freight rates in early 2022 contributed to a 1.2 percent increase in consumer food prices [9]. Therefore, the shipping industry is willing to reduce its emissions but also fuel consumption due to higher fuel prices, social pressure on environmental impact, and the resulting mandatory emission control regulations globally [10].

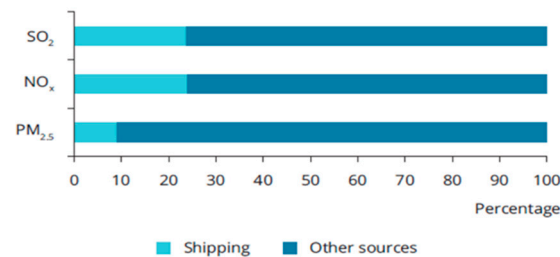
This work is divided into the following sections: Section 3 describes the consequences for the maritime traffic of the regulations, updated in Section 2, and the current alternatives

taken by vessels to comply with them; Section 4 provides the current developments being implemented by ports; Section 5 entails the analysis and discussion; and finally, Section 6 summarizes the conclusions.

The goal of this work is to provide an answer as to whether port infrastructures are growing enough to support the new alternative fuels required by new maritime propulsions to achieve the decarbonization required by the new international regulations. For this purpose, this work analyzes current developments carried out by vessels and ports in the Iberian Peninsula and the production available for alternative fuels to establish if they are enough to provide vessels the required port infrastructure and volume.

## 2. Regulation Updates

The main air pollutants emitted by ships to the atmosphere are sulfur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), particulate matter (PM), and carbon monoxide (CO). In 1998, as shown in Figure 1, the proportion of emissions produced by the maritime transport sector in Europe, including international, domestic, and inland, was represented by 24% of NO<sub>x</sub>, 24% of SO<sub>x</sub>, and 9% of PM<sub>2.5</sub> (PM with a diameter of less than 2.5 µm) of the emissions from all the sectors considered [4]. When the world maritime sector is taken into account, 13% of global SO<sub>2</sub> emissions come from shipping [11].



**Note:** NO<sub>x</sub>, nitrogen oxides, PM<sub>2.5</sub>, particulate matter with a diameter of less than 2.5 µm, SO<sub>2</sub>, sulphur dioxide.

**Figure 1.** Total emissions in the EU by means of transport. Source: EMSA, 2021.

Seeing these values, sulfur particles were considered as the main contributor of air pollution by the regulators, and for this reason, initial sulfur emissions limit rules were imposed. The new changes to Annex VI of MARPOL 73/78 (International Convention for the Prevention of Pollution from Ships), confirmed in 2016 by the International Maritime Organization (IMO), declared that world fleet emissions from burned marine fuels cannot exceed the limit of 0.1%S (in mass sulfur content) in Emission Control Areas (ECAs) and 0.5%S in the rest of the world, and limited the amount of nitrogen oxides. Sulfur dioxides (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) emitted into the atmosphere and transported by wind and air currents are considered the main producers of acid rain [12]. Many scientific studies have shown evidence of a relationship between SO<sub>2</sub> and some heart attacks and effects on lung function [13]. As per research carried out by the Marine Environment Protection Committee (MEPC), over 570,000 premature deaths due to SO<sub>x</sub> emissions are predicted due to a delay in world sulfur limit regulations from 2020 to 2025 [14]. In addition, NO<sub>x</sub> emissions also contribute to a reduced ozone level, which is also harmful to human health.

Greenhouse gas (GHG) emissions, including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), expressed in CO<sub>2</sub> of total shipping (international, domestic, and fishing) have increased from 977 million tons in 2012 to 1076 million tons in 2018 (9.6% increase). In 2012, 962 million tons were CO<sub>2</sub> emissions, while in 2018, this amount grew 9.3% to 1056 million tons of CO<sub>2</sub> emissions. The share of shipping emissions in global anthropogenic emissions increased from 2.76% in 2012 to 2.89% in 2018 [15].

On 1 January 2023, a new set of rules entered into force with the aim of reducing CO<sub>2</sub> emissions from maritime transport. The target is to reduce greenhouse gas (GHG) to limit temperature rises to 1.5 °C, one of the main agreements of the UN Climate Change Conference (COP16) in 2021.

The Initial IMO GHG strategy, adopted on 13 April 2018 (see RESOLUTION MEPC.304-72), envisages a reduction in carbon intensity of international shipping (to reduce CO<sub>2</sub> emissions per transport work), as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008. In July 2023, during the MEPC80, a newly revised GHG reduction strategy was adopted. One main target and three indicative checkpoints were assumed. The principal ambition agreed was to reach net-zero GHG emissions from international shipping close to 2050. Three indicative checkpoints were defined: Firstly, carbon intensity of international shipping should decline by at least 40% by 2030, compared to 2008. Secondly, the total annual GHG emissions from international shipping should be reduced by at least 20% by 2030 and 70% by 2040, compared to 2008. Finally, international shipping should derive at least 5% of its energy usage from zero or near-zero GHG emission technologies, fuels, and/or energy sources [16].

To achieve the GHG IMO strategy, new indexes have been included as part of regulations. Effective as of 1 January 2023, an Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator (CII), and Ship Energy Efficiency Management Plan (SEEMP) is required for existing vessels.

EEXI is the coefficient between CO<sub>2</sub> emission rate (affected by main engine design, specific fuel oil consumption (SFOC) calculated as 75% of MCR power, and design of the shaft) and the transport power (affected by capacity, speed, and Dead Weight Tonnage (DWT)). See Equation (1). It is a measure of the vessel that must be certified by an independent party with an International Air Pollution Prevention (IAPP) certification. As mitigation actions to comply with the EEXI, an engine power limitation (EPL), which reduces vessel speed; propulsion optimization using computational fluid dynamics (CFD); or engine NO<sub>x</sub> optimization can be used.

$$EEXI = \frac{e_{CO_2}}{P_t} \left( \frac{g \cdot CO_2}{t \cdot nm} \right) = \frac{EP \cdot C \cdot f_{CO_2}}{S \cdot DWT \cdot \Delta} \quad (1)$$

where:

EEXI = Energy Efficiency Existing Ship Index;

$e_{CO_2}$  = CO<sub>2</sub> emission rate;

$P_t$  = transport power;

EP = engine power;

C = fuel consumption;

$f_{CO_2}$  = CO<sub>2</sub> factor;

S = reference speed;

DWT = dead weight tonnage;

$\Delta$  = correction factors.

The operation of a ship heavily influences the fuel consumption and the amount of emissions. Main factors are operational speed [17], power management [18], and propulsion control [19]. To account for these influencers, the SEEMP and CII have been included as part of the GHG rules. They measure how a vessel is operated and introduce mandatory annual reduction targets for operational emissions. CII is the coefficient between annual fuel consumption affected by the CO<sub>2</sub> factor, the annual distance sailed, and capacity. See Equation (2). Each ship must achieve level C or higher and maintain it. It has rolling requirements every year. Correction factors are being developed. To reduce CII, it is necessary to modify the CO<sub>2</sub> factor by using low-carbon fuels like LNG, LPG, hydrogen, methanol, or electrification. Annual consumption can also be reduced by improving vessel hydrodynamics, implementing machinery improvements, or modifying the logistics and utilization of a vessel by digitizing vessel operations and port connection.

$$CII = \frac{C_a}{D_a} \cdot \left( \frac{f_{CO_2}}{C} \right) \cdot \Delta \quad (2)$$

where:

CII = Carbon Intensity Indicator;  
 $C_a$  = annual fuel consumption;  
 $D_a$  = annual distance traveled;  
 $f_{CO_2}$  =  $CO_2$  factor;  
 $C$  = capacity (DWT or GT);  
 $\Delta$  = correction factors.

SEEMP Part III, or the Ship Operational Carbon Intensity Plan, will serve as the implementation plan for achieving the required CII and will be subject to verification and company audits. In their SEEMP, owners have to include a 3-year implementation plan documenting how the required CII will be achieved over the next three years, with yearly targets and procedures for self-evaluation and improvement.

The European Green Deal, approved in July 2021 by all 27 EU Member States, committed to turning the EU into the first climate-neutral continent by 2050. To achieve this, they pledged to reduce emissions by at least 55% by 2030, compared to 1990 levels. The European Green Deal will also improve our takeout from the COVID-19 pandemic consequences. One third of the EUR 1.8 trillion investments from the Next Generation EU Recovery Plan and the EU's seven-year budget will finance the European Green Deal [20].

To comply with these new maritime regulations, the world fleet is being challenged to use new maritime propulsion, low- and zero-carbon fuels, and energy efficiency tools.

### 3. Route Sailed

#### 3.1. Trilemma to Comply with SOx and NOx Rules

Since 2015, to comply with the first set of regulations under MARPOL Annex VI, vessels have been faced with a trilemma. The first choice is to forgo large-scale capital investments. Here, vessels have three options: burning Marine Diesel Oil (MDO), Very Low sulfur Fuel Oil (VLSFO) or biofuels. MDO is much more expensive than the heavy fuel oil used over the last 100 years, with a price difference of 258 USD/t using PLATTS historic series 2010–2020. In some ports, vessels also have the option to burn a new VLSFO with a maximum of 0.5% sulfur content and with discount compared to the world average MGO between 12% and 35%, which means that VLFO is be quoted at between 118 and 409 USD/t cheaper than MGO when taking the historical series of 2020–2023 in [21], as shown in Figure 2.

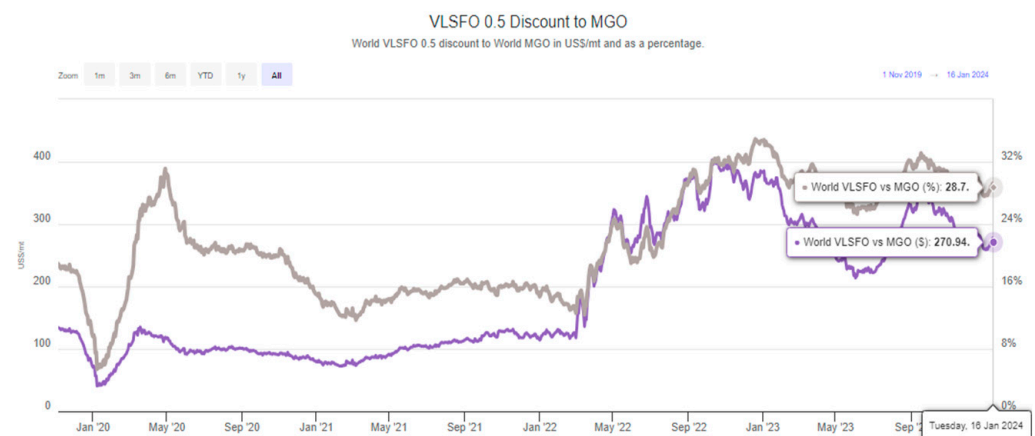
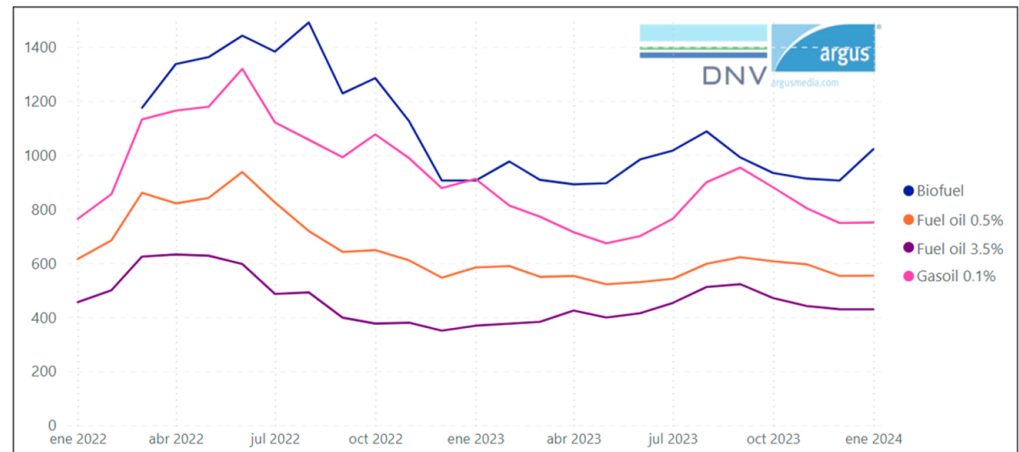


Figure 2. VLSFO 0.5 discount to MGO 0.1. Source: Bunker Index, 2023.

Finally, the last option is the use of biofuels, which, since the first quotation in markets in February 2022, are between 50 and 200 USD/MDO equivalent more expensive than MDO, as per data from [22], as shown in Figure 3.



**Figure 3.** Bunker prices alternative to Gasoil. Source: AFIDNV, 2023.

Regarding the biofuel offer and demand, if shipping is to decarbonize primarily using biofuels with other energy efficiency measures in 2050, 250 Mtoe will be needed yearly. The DNV's white paper estimates that the global sustainable and economical supply of biofuels could reach 500–1300 Mtoe per year by 2050 [23]. This means that between 20 and 50% of global biofuel production will be used by shipping. Considering the demand from a range of other sectors like aviation and road transport, shipping cannot rely on biofuels as the only solution to achieve its decarbonization requirements. Therefore, the maritime industry will have to continue to explore other options to reach net zero emissions.

In any case, this means that vessels have been able to sail through this first set of environmental regulations related to SO<sub>x</sub> but have been paying more in fuel price compared with the heavy fuel oil used in the past.

As an alternative to the MDO, scrubbers or Liquefied Natural Gas (LNG) as fuel are available as the main choices for complying with the new regulations.

Scrubbers can clean the exhaust gases from sulfur content before going into the atmosphere, which allows for vessels to comply with the MARPOL regulation while burning high-sulfur fuel. However, this alternative only complies with SO<sub>x</sub> restrictions, so it must be combined with others to comply with NO<sub>x</sub> and GHG regulations. This system uses an open or closed loop if it uses seawater or fresh water, respectively. The hybrid loop has both circuits. The majority of the currently installed equipment is open loop, 3778 of 4679 [22]. The equipment must be installed inside the funnel of the ship, and due to technical, operational, and economic reasons, the vessels that have chosen this alternative are large vessels with high demand of autonomy. Bulk carriers, containerships, crude oil tankers, and oil/chemical tankers are the types of vessel that have selected this choice. Until now, retrofits have been more numerous, 3273 of 4679, than newbuilt.

LNG-powered vessels require a bigger investment as well as a new cryogenic system onboard to maintain the LNG. The segments of vessels choosing this alternative are small newbuilt containerships, small tankers and cruise ships, Ro-Ro cargo ships, car carriers, and passenger ferries. The main reason is their deadweight (DWT), low requirement of autonomy, and, especially, because they sail regular routes. This new fuel requires a very different port infrastructure; therefore, these vessels need to ensure a supply port infrastructure on their routes.

We counted 261 LNG-fueled ships in operation and 435 ships mainly using a dual-fuel engine on order as per the DNV.

We need to see the values of vessels using alternative fuels as a percentage of the world fleet to see how deep the adoption of these new technologies is. If we count alternative fuels—LNG, LPG, methanol, and hydrogen—only 0.56% of the world fleet currently uses alternative fuels; however, including vessels on order and new orders for 2023, this value increases to 23%.

There are many works that have studied which alternative fuel is the most suitable for a specific type of vessel, and many of them have arrived at the conclusion that the main challenge for any of those alternative fuels is the reduction in autonomy due to the limited space onboard to install tanks for these new fuels with less volumetric energy density than the HFO or MDO. Therefore, with current technology, to comply with the new environmental regulations, owners will need to choose between reducing autonomy or sacrificing space dedicated to payload [24].

Additionally, 25% of the fleet has energy-saving technologies (EST) including propellers with nozzles, rudder bulbs, Flettner rotors, and air lubrication systems, to which other types of retrofits such as Ballast Water Management (BWMS) [25].

### 3.2. Alternative Fuels to Comply with Greenhouse Gas (GHG) Rules

To comply with GHG IMO ambitions and the EU Green Deal, which wants a climate-neutral Europe by 2025, including shipping, it is not enough just to change to a low sulfur content fuel. The world fleet needs to use low- and zero-carbon fuels and energy efficiency tools. To achieve better energy efficiency for maritime transport, not only equipment but also digitalization is needed. The work carried out by [26] states that although maritime transport is the backbone of world commerce, its digitalization lags behind significantly when we consider some basic facts. Ports is the sector that offers great opportunities for studies given that it needs to interact with inland transport, which is highly digitalized.

New technologies are being developed to provide vessels new alternative fuels like hydrogen, methanol, ammonia, LPG, or batteries. The figures here are more modest than for LNG or scrubbers, as the technology is still under research. But even so, as of February 2022, there were 553 vessels sailing with batteries (397 in operation and 156 on order), 97 with LPG as fuel, 51 burning methanol, and 7 burning hydrogen.

But we need to keep in mind that even though these new alternative fuels have virtually no emissions when used to generate electricity onboard, the environmental impact of the entire supply chain needs to be evaluated to also take into consideration how they are produced and even transported. So, we see how for complete decarbonization of the maritime sector, black (or brown), gray, blue, and yellow hydrogen must be avoided [27].

The first conclusion from the values in Table 1 is that we do not see a predominant technology or maritime alternative fuel that marks a way to meet the challenging goal for decarbonization the maritime transport. Neither the IMO nor any other organization has indicated the right path. Therefore, most shipowners are evaluating and developing their own solutions based on the current technologies.

Two of the main shipowners in the maritime container market are leading early solutions to meet CO<sub>2</sub> requirements. In March 2022, Maersk confirmed strategic partnerships around the world with six companies to produce green methanol (bio-methanol and e-methanol) on a large scale until 2025 [28]. Total production of green methanol is expected to reach 700,000 tons by 2025 and 1.2 million tons beyond 2025. The total energy demand for shipping burning only on methanol should reach 777 million tons. Therefore, this production will only offer energy demand for a small number of vessels. MSC presented its plan to reduce CO<sub>2</sub> emissions to satisfy the European Green Deal and achieve net decarbonization by 2050. MSC has highlighted a combination of fuels and believes that bio and synthetic Liquefied Natural Gas (LNG), synthetic and bio-methanol, and green ammonia may become fuel choices. In parallel, energy efficiency measures will have a core role in progressively reducing its carbon intensity while also improving vessel performance and optimizing all voyages [29].

Research conducted by Grzelakowski et al. [30] proposed a possible scenario for the mix of alternative fuels that could be used by maritime transport to achieve the required reduction in CO<sub>2</sub> emissions in global shipping.

**Table 1.** Current uptake (February 2022) of alternative fuels and technologies in shipping. Number of vessels (in operation or on order). Note: Adapted from AFI DNV, 2023.

Type of Vessel	Scrubber	LNG	Battery	LNG Ready	Methanol
Bulk carriers	1665	63	11	46	
Containers vessels	1004	149	2	89	21
Crude oil tankers	658	87	6	27	
Chemical tankers	574	69	6	31	25
Cruise vessels	221	33	20		
Ro-ro	195	15	20	8	
Gas Tankers	118	15			2
General cargo	103	17	2		
RoPax	95	33	7	12	1
Car Carriers	56	63			
Passenger ferries	13	51	234	4	
Other activities	7	22	121	1	
Offshore vessels	2		21		1
Fishing vessels			17		
Offshore supply			69		
Tugs			17		1

#### 4. Port Side Development

The Fit for 55 package proposed by the European Commission on 14 July 2021 revised the Alternative Fuels Infrastructure Regulation and included shoreside electricity and LNG in TEN-T core network ports by 2030 (electricity) and 2025 (LNG) (Directive 2014/94/EU).

The Spanish port system, since 1992, is made up of 46 ports of general interest managed by 28 Port Authorities, whose coordination and control corresponds to the Public Entity Puertos del Estado, which is a body dependent on the Ministry of Transport, Mobility, and Urban Agenda, which is responsible for the execution of the government's port policy, all of them under a landlord model [31].

Under this model, the Port Authority maintains ownership of the port, while the infrastructure is leased to private operating companies. The Port Authority's responsibilities as owner include economic exploitation, long-term development of the land, and maintenance of basic port infrastructure, such as access roads, berths, and wharves. Private operating companies that lease from the Port Authority provide and maintain their own superstructure and purchase and install their own equipment.

Port infrastructures have been picking up the need to adapt to emission reduction and environmental protection regulations in different ways, depending on the traffic they always serve as a priority and financing capacity.

The regulation that limits their decisions is based on a set of measures and certifications that allows them to optimize the adaptation of their facilities to the premises led by the Eco-Management and Audit Scheme (EMAS), following the European Sea Ports Organization (ESPO) guide, which represents the interests of European ports before the institutions of the European Union and which proposes the following tools:

- Self-Diagnosis Method (SDM): list of environmental management items for ports that facilitates internal control of compliance with regulations;
- Port Environmental Review System (PERS): the only specific environmental management standard developed for the port sector by the ports themselves;

- Environmental Management Index (EMI): commitment index of ports with environmental management.

According to the ESPO itself, as of 2022, 75% of the ports in the EU and Norway have an Environmental Management System (EMS) certificate, be it ISO, EMAS, or PERS; up to 90% have implemented policies and have an environmental control program; and 88% of them have defined environmental improvement objectives [32].

The EMI marks ten priorities that ports should focus on in environmental matters (Figure 4), based on which a formula is generated that allows for measuring the environmental performance of a port from 0 (without environmental management) to 10 (excellent environmental management) [33]. It is expected that this value will reach the level of 8 points in 2025, which has almost already been achieved since its evolution in 2013, when it stood at 7.25, as it has been trending upwards to position itself at 7.98 in 2022.



**Figure 4.** The 10 environmental priorities for European ports in 2020. Source: ESPO, 2021.

In Spain, in 2018, according to Puertos del Estado, 7 port authorities have an EMAS, 16 with ISO 14001 certification, plus another 2 in the implementation phase, and 8 have a PERS [34], which have been recently joined Ceuta. According to the ESPO database, of the 13 Spanish ports that have joined this network, 9 have a PERS, 12 have an ISO 14001 certificate, and 7 have an EMAS, of which 5 have all three certificates: Algeciras, Barcelona, Cartagena, Ceuta, and Vigo; another 5 have two of them: Bilbao, Huelva, Melilla, Seville, and Valencia; while the rest have only one: Castellón, Tenerife, and Vilagarcía [35]. With these data, Spain is at the head of the European port system in terms of the degree of commitment acquired together with the United Kingdom and Germany; doubling France, the Netherlands, and Denmark; and leaving the rest of the countries far behind.

When we look at the environmental priorities of the ports, it turns out that practically all the objectives are limited to the land side. We find on the seaside only the improvement in water quality, dredging of ports, and support for the removal of garbage from ships. This fact leaves only one item directly linked to support for the needs of ships (Figure 5), and as of yet, none related to energy support for ships, provisioning, regulation of port taxes, or development of the port have appeared to cover the loading and unloading of goods and people from ships. This despite the fact that since 2008, shipping companies and shipowners have been pressured with continuous and increasingly strict regulations that are difficult to comply with if the ports are not prepared.

	1996	2009	2013	2018	2019	2020	2021	2022
1	Port development (water)	Noise	Air quality	Air quality	Air quality	Air quality	Air quality	Climate change
2	Water quality	Air quality	Garbage/Port waste	Energy consumption	Energy consumption	Climate change	Climate change	Air quality
3	Dredging disposal	Garbage/Port waste	Energy consumption	Noise	Climate change	Energy efficiency	Energy efficiency	Energy efficiency
4	Dredging operations	Dredging operations	Noise	Relationship with the local community	Noise	Noise	Noise	Noise
5	Dust	Dredging disposal	Ship waste	Ship waste	Relationship with the local community	Relationship with the local community	Relationship with the local community	Water quality
6	Port development (land related)	Relationship with the local community	Relationship with the local community	Port development (land related)	Ship waste	Ship waste	Water quality	Relationship with the local community
7	Contaminated land	Energy consumption	Dredging operations	Climate change	Garbage/Port waste	Water quality	Ship waste	Ship waste
8	Habitat loss/degradation	Dust	Dust	Water quality	Port development (land related)	Garbage/Port waste	Dredging operations	Garbage/Port waste
9	Traffic volume	Port development (water)	Port development (land related)	Dredging operations	Dredging operations	Dredging operations	Port development (land related)	Port development (land related)
10	Industrial effluent	Port development (land related)	Water quality	Garbage/Port waste	Water quality	Port development (land related)	Garbage/Port waste	Dredging operations

Figure 5. Details of the 10 environmental priorities for European ports from 1996 to 2022. Source: ESPO, 2021.

Although it is true that in these years the level of commitment of ports to these priorities has been increasing, gradually increasing the degree of commitment from levels of 35 to 67% in 2013 to a current range in 2022 of 45 to 82%, the percentage of ports that are considering adapting their infrastructure continues to oscillate at the 75% level, which, while being high, does not inform us of the extent to which these adaptations are going to materialize or the reasons why they have not been carried out yet.

Regarding the so-called green services to shipping, the ESPO highlights the supply of electrical energy from land (Onshore Power Supply, OPS), LNG supply facilities, and reduced port taxes. This monitoring was implemented in European ports in 2016 but it was not until 2021 that it was consolidated. These three developments are in line with the mandate of the Green Deal.

On the sea side, one of the first choices taken by vessels was to burn LNG, for which a big transformation must be carried in port infrastructure. We see that the first fast attempt has been to supply LNG by truck. This supply method is obviously not enough to supply more than 150 m<sup>3</sup> without delaying the average port call of a vessel. LNG supply by barge is growing very slowly. In Table 2, we see that only three LNG barges are in operation, in Huelva, Barcelona, and Algeciras. Even if we go beyond to 2025, there will only be three additional LNG barges in Iberian ports as per information provided by the AFI of the DNV. In the case of European ports, we see 19 LNG barges already operating, all of them in the ECA. Outside Europe, the situation is even worse, mainly because their ECAs started later than the European one. We count three in Asia, three in the US, one in Brazil, one in Jamaica, and two in an unknown location. Therefore, there was total of 44 LNG barges worldwide operating in 2023. If we extend the margin until 2025, there are 27 additional future projects, 65% of them in Europe and Asia, which forecasts an even slower development speed in America.

**Table 2.** Status of LNG bunker vessels projects in Portugal and Spain. Note: Adapted from AFI DNV, 2023.

Vessel Name	Port	Status	Delivery/Capacity (m <sup>3</sup> )	Operator
Oizmendi	Huelva	Operation	2018/600	Cepsa
Bunker Breeze	Algeciras	Operation	2018/1200	Cepsa
Unnamed	Portugal	Discussion	2025	Galp
Levante LNG	Algeciras	Operation	2023/12,500	Peninsula
Haugesund	Barcelona	Operation	2022/5000	Shell
Net Zero	Canary Islands	Decided	2025	

The second core action for the development of infrastructures for the use of alternative fuels in the transport sector is the OPS. While in motion (navigating or maneuvering), a vessel needs all the equipment onboard switched on, and the main engine's energy demand is high. When a vessel is docked, most of the equipment is off and there is lower energy demand from the auxiliary engines [36]. If a port has an OPS infrastructure, it allows for the vessel to switch off its auxiliary engines and connect to the land network, which supplies the necessary electrical energy to the vessel. The objective is zero emissions at port, and noise and vibrations eliminated. Regarding the sources of CO<sub>2</sub> emissions from port activity, one of the most important is the time spent by ships during their port call. Gibbs et al. [37–39] demonstrated with a UK case that emissions generated by ships during port calls are far greater than those generated by port activities. Consequently, ports might have more impact through focusing their efforts on reducing shipping emissions.

It was estimated during 2016 that the potential of OPS, also called cold ironing, for the reduction in externalities in the 46 Spanish ports is EUR 440 million [40]. It is combined overall external costs from both local and global effects of shipping emissions from berthed vessels. Martinez-Lopez et al. [41] showed that feeders achieve greater environmental improvement by using port mitigation than Ro-Pax vessels because of the high impact of the short port calls of Ro-Pax. They also stated the need for ensuring the sustainability of onshore grids, especially in insularity frameworks, with an electricity generation mix that offers few renewable sources. Therefore, it is a necessity that the development of the OPS grows in parallel with the renewable energy in ports.

In the case of Portugal, the work carried out by Nunez et al. [42] showed higher externalities for Sines and Setubal ( $2.0 \times 10^2$  million), followed by Leixoes ( $1.8 \times 10^2$  million), and Viana do Castelo (6.3 million). Although Setubal port showed higher performance than Viana do Castelo port based on the economic data, when social and environmental aspects were considered, the results changed. This shows the importance of performing a more comprehensive analysis using social and environmental indicators. If the in-port emissions in these four ports would have been considered as part of the total emissions reported by the Portuguese Environment Agency, emissions of NO<sub>x</sub> and SO<sub>2</sub> would have increased 16% and 28% in 2014 [42]. Therefore, there are several works where it is stated that emissions from vessels during port calls are an important source of air pollution, mainly regarding NO<sub>x</sub> and SO<sub>2</sub>.

The “OPS Master Plan for Spanish Ports” project has as its objective the drafting of a master plan for the supply of electrical energy to ships mooring in Spanish ports. As a result, three OPS installations have been deployed as pilot in the ports of Santa Cruz de Tenerife, Palma de Mallorca, and Las Palmas. Another twenty installations will be set up between 2022 and 2024 in Spanish ports.

Recently, two EU regulations have entered into force, one on the deployment of alternative fuels infrastructure [43,44] published in the *Official Journal of the EU* on 22 September 2023, which will require that ports have OPS facilities that allow for OPS to provide shore-side electricity supply for at least 90% of the total number of port calls of seagoing containerships, Ro-Ros, ferries, and cruises above 5000 gross tons each year from 2030.

And the other on the use of renewable and low-carbon fuels in maritime transport [45] published in the *Official Journal of the EU* on 13 September 2023, which establishes a limit on the greenhouse gas (GHG) intensity of energy used on board by a ship arriving at, staying within, or departing from ports under the jurisdiction of a member state; and an obligation to use onshore power supply (OPS) or zero-emission technology in ports under the jurisdiction of a member state. Therefore, From 1 January 2030, a ship moored at the quayside in a port of call which is under the jurisdiction of a member state shall connect to OPS and use it for all its electrical power demand at berth. This obligation shall apply to containerships and passenger ships.

In December 2021, Spain published a plan for the progressive installation of dock electrification systems. As of 2022, only eight Spanish ports can provide electricity to ferries and Ro-Ros as part of a pilot project. We will not see ports ready with OPS for containers and cruises in Algeciras, Barcelona, Bilbao, Valencia, and Alicante until 2024, as per data provided by [46].

Finally, up to 60% of the ports have differentiated rates, and another 33% plan to put them into operation soon, for ships that adhere to strict compliance with regulations on various issues, among which are segregation and handling of ballast water (58%), reduction in polluting gases (58%), reduction in greenhouse gases (42%), noise reduction (24%), and environmental certificates (47%).

Ports have to play a key role in the road to decarbonization in maritime transport and need now to choose for which type of fuel they develop the port infrastructure. But at the same time, shipowners are struggling to find a single solution for each vessel on their fleet, and as seen, there are now many options to comply with new environmental regulations. LNG is currently the main alternative for HFO and MDO. Methanol is becoming more attractive due to its clean combustion and good source of supply. Ammonia and hydrogen are promising, but still have not reached technological maturity. This uncertainty can be reduced by closer cooperation between shipowners and ports [47].

## 5. Results and Discussion

### 5.1. Decarbonization in Maritime Transport: The Current Situation

As we have learned, more than 6000 vessels worldwide have already included a type of alternative fuel or technology. Almost 800 vessels already use LNG as fuel or will use it in the coming year. This contrasts with only 35 LNG bunker barges in operation worldwide, 19 of them in Europe. Only two in Spain and none in Portugal are in operation in 2023.

If we assume that the complete fleet calling at Iberian Peninsula ports would change to LNG for fueling their ships, a great amount of LNG (6.3 million tons) will be needed to supply vessel demand [48]. This amount was calculated by analyzing all vessel calls in the Iberian Peninsula in 2014. If the results of the LNG potential demand are analyzed, the ports that would suffer the greatest impact of new IMO regulation are Algeciras, Valencia, Barcelona, and Las Palmas in Spain and Lisbon and Sines in Portugal, which represent an average of 65% of the demand of all vessels calling Spain and Portugal in recent years. It is necessary to analyze ships in more depth by type, since smaller ships (Ro-Ros, cruises, ferries, etc.) are more suitable to burn LNG because of the return of the investment. In this regard, Algeciras with 3607 Ro-Ros, Valencia with 1273, Barcelona with 1614, and Lisbon with 265 comprise almost the whole Ro-Ro and ferry sector of the Iberian Peninsula.

We conclude that the only two LNG barges operates in Huelva and Algeciras and none in Portugal are definitely not enough to cover the potential LNG demand. We see also that the LNG barge located in Huelva could have bigger potential demand in other Spanish ports. The results above are also proof that the LNG barges operating or decided (Table 2) are located in the right ports (Algeciras, Barcelona, and Lisbon) and there is still room for market development in Valencia and Las Palmas. Ports have the challenge to adopt various measures to facilitate vessels' emission reductions, but the current incentive is still limited for shipping and ports [49].

How the change from the current bunker demand based on fossil fuels to low-carbon fuels be achieved? To establish a real comparison between alternative fuels, it is necessary for energy storage in HFO tanks to be the same as those using any other alternative fuel to maintain a vessel's autonomy. To take this topic into account, a comparison between Equivalent Energy Capacity (EEC) for each of the alternative maritime fuels vs. HFO should be considered. We calculate EEC using the following Equation (3):

$$EEC = (D_{HFO} * LHV_{HFO}) / (D_x * LHV_x) \quad (3)$$

EEC = Equivalent Energy Capacity

$D_{HFO}$  = HFO density ( $\text{kg}/\text{m}^3$ );

$D_x$  = alternative fuel density ( $\text{kg}/\text{m}^3$ );

$LHV_{HFO}$  = HFO Lower Heating Value (LHV) (MJ/kg);

$LHV_x$  = alternative fuel Lower Heating Value (LHV) (MJ/kg).

The results are included in Table 3. Note that additional volume for tank insulation is included for the following types of fuels: ammonia 1.15; LNG 1.6; hydrogen 2.0.

**Table 3.** Equivalent Energy Capacity for main alternative maritime fuels (own elaboration).

Type of Fuel	LHV	Density	EEC	EEC *
HFO	39	940	1	1
MGO	43	840	1.015	1.015
Biodiesel	37.2	880	1.120	1.120
Methanol	22	794	2.099	2.099
Ethanol	28	789	1.660	1.660
Ammonia	18.6	682	2.890	3.324
LNG	50	460	1.594	2.551
Hydrogen	120	71	4.303	8.606

\* Additional volume included when tank insulation is needed.

The bunker demand for marine fuels is forecasted for 2023 in approximately 370 million tons/year with a LHV of 42.7 MJ/kg (according to ISO standard for fossil fuels derived from crude oil). To meet the same energy demand as in 2023 and taking above values, the equivalent amount of each type of fuel is shown in Table 4.

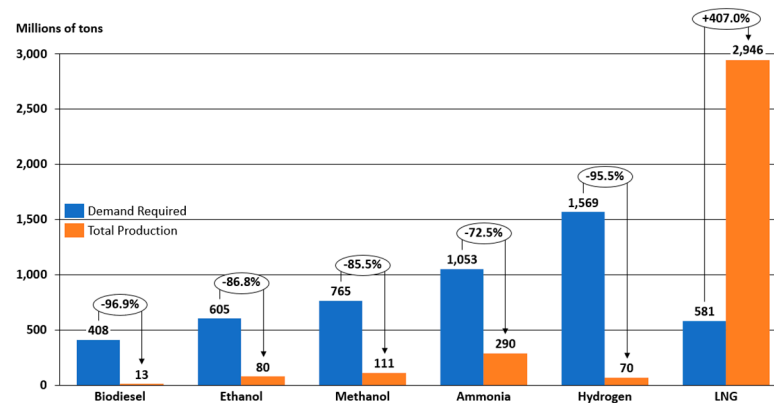
**Table 4.** Comparison of theoretical shipping fuel world demand in 2023 vs. world production for each type of fuel in 2023 (own elaboration).

Type of Fuel	Shipping Demand (Millions of tons)	World Production (Millions of tons)
MGO	370	
Biodiesel	408	12.5
Methanol	765	111
Ethanol	605	79.6
Ammonia	1053	290
LNG	581	2946
Hydrogen	1589	70

LNG required would be 581 million tons, methanol would be 765 million tons, ethanol would be 605 million tons, and ammonia would be 1053 million tons. It is important to note that global ammonia production in 2023 was only about 290 million tons and it is primarily

produced from natural gas. The carbon dioxide emissions from ammonia production accounted for approximately 1% of the global total emissions.

We conclude that except in the case of LNG, the theoretical shipping fuel demand of each type of alternative fuel cannot be absorbed by the current world production, where we find big gaps between supply and demand of up to 96.9%, as shown in Figure 6. This fact demonstrates that to reach the decarbonization of the shipping industry, a mix of alternative fuel types will be required due to shortages in manufacturing, commercialization, and supply of low- and zero-emission fuels to the shipping market.



**Figure 6.** Gap between alternative fuel theoretical demand 2023 and current production. Source: Own production.

### 5.2. The Role of the Ports in the Decarbonization of Shipping Transport

Two roles are required for ports: first is the role of low-carbon fuel providers for shipping during port calls; second is the role of allowing for vessels to switch off their auxiliary engines when docked at berth by providing onshore power supply. Both are keys to reducing emissions from vessels. If we follow the needed supply chain of shipping to obtain energy, it is obvious that the provision of port reception facilities is crucial for the effective implementation of MARPOL, the IMO GHG strategy, and the EU Green Deal in shipping. Thus, the port system, under the name Green Ports, has moved from the implementation of certificates to assess the adequacy of pollution measures and the capacity to manage waste towards the implementation of structures that help the maritime port system to establish itself as a decarbonization hub.

But as we have seen, the limitations generated by the division of roles between local administrations and the port authorities themselves, added to the lack of incentives for local operators and port concessionaires, have hampered the channeling of resources towards improving port infrastructures, undermining the ability of the fleet to adapt if among its assets it does not have priority commercial agreements with the ports at which it loads/discharges or does not participate directly in the shareholding of the same, among other possibilities of propping up the most suitable for the maritime sector.

Two possible ways to adapt ports to the needs of ships are clearly observed: the use of regulations that promote the adoption of the necessary infrastructures to provide the corresponding service, and the movement forced by the incorporation of ships to those that serve the chosen technologies, to avoid losing traffic. The movement derived from the impulse given by the “early adopters” of a certain technology does not produce any movement in the port sector, since those ships will have their survival somehow assured, via provisioning or specific agreement in the ports where most calls are foreseen.

However, ships that later join the technological change, the so-called “followers”, will be able to take advantage of the existence of these already equipped ports in the first instance, which will cause a domino effect in the other ports where they call frequently so as not to lose competitiveness, accelerating the port adaptation process. If we follow this scenario, the ports will be towed by the ships, so in this context, it is very probable that it

will not be possible to achieve the speed of change required to comply with environmental requirements on time. Complementarily, the mobilization observed after the implementation of a regulation has the particularity of taking place in parallel in both sectors, maritime and port, so neither of them should wait for the other to advance, thus reducing the risks for early adopters such as the progress times of the maritime–port system to comply with emission regulations.

That ports must adapt their infrastructures to the fuel consumption needs demanded by ships is, after more than one hundred years of heavy fuel oil consumption, an obligation that requires administrative flexibility, favorable regulation, and regulations that afford security to facilities and supply operations.

That ports should be the driver of change is a *sine qua non* condition, since they must not only facilitate the possibility of incorporating the required infrastructures, but they must also facilitate economic mechanisms through public–private structures that resolve the extremely high cost of deploying supply infrastructure on a global scale.

Whether the ports can do so under the conditions required by these rules and regulations is another matter, since the situation of many of the ports in environmentally protected areas, near or within cities or without physical expansion possibilities, can greatly condition the appropriate pace of advance.

It is recommended that the ports of Algeciras, Valencia, Barcelona, and Lisbon focus on LNG port development, and there is still room for market development in Las Palmas. Together, these ports comprise 90% of the total number of Ro-Ro port calls, which are the main potential LNG consumers together with cruise vessels and other small ships with less autonomy required. The same ports should invest in the alternative fuel decided by the big consumers, containerships. The rest of the medium–large-size fleets will follow the alternative fuel and probably the bunker port chosen by big consumers.

The second role of ports as electrical energy providers at docking during loading and unloading operations is also crucial because a very significant percentage of marine pollution from shipping occurs at ports, affecting both their surroundings and inland areas. It is estimated that up to 70% of the pollution from ships penetrates up to 400 km beyond the coast, which for the purposes of the Iberian Peninsula implies practically affecting 60% of its geography [50]. The immediate surroundings of the ports, which are usually very crowded cities, suffer especially from this situation of localized pollution due to the activity of ships in port. Pollution measurements and control are key to identifying the major pollutants, NO<sub>x</sub> and SO<sub>x</sub>, and their ability to reduce them through the solutions implemented. In ports where the pollution of ships has been measured, the route in the internal waters of the port until the berth produces significant emission of pollutants [51]. The size and capacity of the ships is more important than the time they spend at port [52]. Port pollution of the 24 largest ports compared to total road pollution throughout China is 30% [53]. There are ships that clearly determine the air quality in each port, such as cruise ships in Las Palmas; oil tankers, bulk carriers, and containerships in Kaohsiung (Taiwan); or containerships in Busan (Korea). The list of references with studies on port pollution from ships is endless. Since 2008, the data provided by the different measurements carried out at ports have been examined from multiple perspectives, firstly verifying what theories and studies from other places affirmed about the most important pollutants, their levels, and scope, as well as their importance for the environment and public health, to subsequently discriminating pollution by type of ship and operation or by times and moments of the scales.

### 5.3. Port System Challenges

There is therefore no doubt about the negative impact and externalities that occur in ports, which in 2014 the OECD estimated at EUR 12 billion per year for the 50 largest ports and a direct impact on approximately 230 million people, in addition to damage to buildings and materials, crop losses, and loss of biodiversity [54].

Therefore, a new environment is being created in the port sector produced by:

1. Changes in the supply and demand environment;

2. Concentration of shipping companies;
3. Larger ships;
4. New technologies and the need to supply alternative fuels.

These changes have also affected the distribution of functions between the public and private sectors in the port environment and there has been a transition in port governance models, moving from a model highly centralized by the public sector, which generally acted through a single institution, to another with greater private participation and with the involvement of different institutions belonging to different levels of the public sector (supranational, national, regional, and even local). This new model is much more complex than the previous one due to the increase in the number of public and private institutions that participate in the different levels of decision-making.

Coordinating public and private interests with the common objective of obtaining efficient, effective, and competitive ports can be defined as one of the greatest challenges of the port system.

Regarding governance, the current model of Spanish port governance is the so-called landlord port. The challenge here will be to evolve out of necessity towards a new model based on the corporatization and public–private management of Spanish ports of general interest.

## 6. Conclusions

The EU and national authorities are still far off the IMO target for reduction in emissions, but the technological progress is extraordinary. We are living through the biggest disruption in maritime propulsion of the past 100 years, since vessels changed from coal to fossil fuels.

The original contribution of this paper is to focus on the need for ports to act immediately to adapt to current environmental regulations.

Over the next few decades, it is likely that the energy mix for shipping will be compounded by a much greater degree of diversification than seen today. Natural gas will soon be an established fuel type, probably only as a transition energy, while liquid biofuels could gradually replace fossil-based fuels. Electricity from the grid will be increasingly used to charge batteries for ship operations in ports, but also for short sea propulsion. Renewable electricity could also be used to produce hydrogen that can be used to power fuel cells. Fuel cells can be connected to the existing power grid without major issues and do not require much space onboard. This makes this technology particularly suitable to retrofit small vessels like ferries, Ro-Ros, or Ro-Paxes in coastal regions, especially where battery propulsion cannot be implemented due to a lack of port infrastructure [55]. Other types of fuel, such as methanol or ammonia, will be used in certain geographical areas and ship segments, and given the right conditions, may develop to play a major role in the future.

The low-carbon energy sources and technologies needed to achieve fast and in-depth decarbonization exist today, but as we demonstrated in Section 5 and Table 4, the challenge is to produce them at a pace and scale with no precedent. There is not only one solution for all cases and the final selection will be based on the type of vessel, usual routes, and more importantly, their usual ports on their routes. If there is no port supply infrastructure for a new fuel, that new technology will be forgotten by the owner of the vessel.

Maritime industry has begun its decarbonization and digital transformation, with the pandemic accelerating the transition. Nevertheless, this high speed of development requires harmonization between supply chain, regulatory system, and ports that should offer the best soft and hard infrastructure.

We believe that vessels are sailing beyond the ports, which must be developed to supply new fuels like LNG or hydrogen, provide electricity, or receive new residues like sulfur from scrubbers. Ports, maritime cities, and clusters should generate strategies to cope with these global transformations. To succeed in this, ports should receive both public and private investment, as, contrary to a vessel, a port will never recover, for example, an investment in an onshore power supply (OPS).

Iberian ports must improve their governance and competitiveness to sail with vessels as smart ports and boost the blue economy. Our ports should take advantage of their strategic geography in international seas to be selected as decarbonization hubs by owners. Governance models should be more flexible in decision-making to be able to anticipate changes in climate regulation and to coordinate both public and private interests.

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