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Green Port Industry to Support the Offshore Wind Sector: A Proposal Framework

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Abstract: In recent years, offshore wind power has become increasingly relevant as a key alternative for contributing to the global economy's decarbonization. Also, the accelerated technological development of the offshore wind turbine influences the increase in size and weight of its main components. This requires an appropriate port infrastructure to support the installation, operation, and maintenance and future decommissioning of offshore wind farms, and especially to serve as an area for manufacturing these components, addressing logistical challenges associated with land transport. This research aims to identify the factors that characterize a suitable port to support the offshore wind industry, also bringing the new green port industry concept. A systematic literature review was conducted via analyses of 126 documents, and a survey procedure was applied to validate the proposed model. As a result, a characterization model was proposed that includes 71 factors classified into 6 dimensions: physical characteristics, port layout, connectivity, port operation, port–farm performance optimization, and governance for sustainability, which is the main novelty of this study. The results contribute to the advancement of the offshore wind energy sector and can provide significant benefits for regional development and local communities with offshore wind potential.

Keywords: offshore wind; offshore wind support ports; port logistics; port infrastructure; green port; systematic literature review

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1. Introduction

The generation of energy from renewable sources is essential to neutralize carbon emissions into the environment and for countries to have a clean and renewable energy matrix [1]. That includes offshore wind energy, which is considered an important source in this global energy transition. It is necessary to deploy 2000 GW of offshore wind by 2050 to reach net zero. This requires a huge upsurge in installations, with 35 GW of offshore wind to be added annually in the coming decade, starting from a global total of just over 60 GW [2,3].

By the end of 2022, 64.3 GW of offshore wind capacity had been installed worldwide, with China leading the installed capacity, followed by the UK and other European countries [2]. In addition, new markets have emerged, for instance, in the USA, Japan, Taiwan, Vietnam, India, South Africa, and Brazil [4,5], as a result of cost reductions in the rapid technological development of turbines as well as due to improved logistics and supply efficiency throughout the offshore wind farm's lifecycle.

There is a tendency to continue the technological development of the offshore wind turbine and the consequent increase in the dimensions of its components to generate a greater energy quantum, better performance, and higher nominal power, as the increase in height and swept area consequently increases the capacity factor [6,7]. As examples of this evolution, in 2010 there were turbine models with 3 MW and in 2015 with 6 MW of nominal power. In 2018, a 12 MW model was launched by General Electric (GE), with a blade length of 107 m [8]. In 2020, Siemens Gamesa launched a 14 MW turbine, with sales projection for 2024, measuring 108 m in blade length [9]. In 2023, China Three Gorges Corporation had installed the world's first 16 MW offshore wind turbine, off the coast of Fujian, China, with a blade length of 123 m [10].

Consequently, this increase in dimensions and weight brought challenges for transport, handling, and movement of components, which creates the necessity for manufacturers of these large components, e.g., blades, to install their industries in a port area. This would make the role of port infrastructure essential in the development of offshore wind farms, as the main onshore support base throughout all lifecycle phases [11–13].

It was observed that turbines with a nominal capacity above 5 MW have severe restrictions on the transport of components by road or rail [12,13]. These bottlenecks can be mitigated by using ports with layout, connectivity, and physical characteristics [11,14] that add value to the entire chain, optimizing them, and creating an important link between land and maritime activities.

Thus, it is necessary to build or adapt the port infrastructure linked to the concept of the port industry as close as possible to the offshore wind site, so that it is possible to support not only the manufacturing, but also the installation, operation, and maintenance (O&M) of components, such as the blades, nacelle, tower, and foundation. In regions that have the potential to install more than 5 GW of OWF, the construction of a manufacturing port becomes viable and attractive to developers [15].

In addition to the technical factors, there must also be a concern for the sustainability elements to be linked to this port industry. Through the concept of green ports [16], one must be concerned not only with implementing operations to support the clean energy sector, but also with adding governance elements for sustainability, with actions and guidelines that promote this sustainability in these operations, contributing to the reduction of greenhouse gas emissions [16,17].

When analyzing existing studies around ports to support the offshore wind sector, it is noted that there are studies that identify the essential characteristics of a base port, whether it be for the installation or operation and maintenance phases. There is a study that described the port requirements for the offshore wind industry in the context of cooperation between ports in the North Sea, Germany, addressing the characteristics of base ports, and quick reaction/O&M and supply ports [18].

There is another study that addressed key port requirements to support offshore wind development in North America with a brief comparison of traditional ports versus offshore wind ports [19]. Another article proposed a project for a logistic port for offshore wind turbines in the United States and presented five critical elements that must be applied [20].

About the suitable ports, with the aim to rank the most suitable ports for installation and O&M, the authors of [11] evaluated and selected the most suitable port to support an offshore wind farm in the United Kingdom, using the analytic hierarchy process (AHP) method, in which 3 criteria and 15 sub-criteria were classified and prioritized.

Another study defined the optimized layout of an installation port to support an offshore wind farm, in which the port area was segmented into sub-areas: unloading, storage, preparation or assembly areas, and loading areas, in order to minimize the logistics transportation costs within the port [21].

The authors of [14] discussed the need for the supply chain to be ready for a green transformation regarding the challenges of offshore wind logistics and the role of ports.

In 2020, a review study was prepared by the authors of [22] about the installation of offshore wind turbines and, in this context, revealed some elements required of ports to meet this activity.

Therefore, although some countries are advancing in the development of studies, gaps were identified in the academic literature regarding the following: (i) research that systematically addresses the factors that characterize the port infrastructure necessary for the offshore wind industry, (ii) research that details and defines the concept of port industry for the offshore wind sector, and (iii) studies that address the ports in terms of not only environmental sustainability, linked to the concept of green ports, but also socioeconomics, performance optimization, and at the operational level, focused on serving this sector.

Thus, from these gaps, the research question arose: which factors should be considered to characterize an offshore wind support port? This article aims to identify the factors that characterize a suitable port to support the offshore wind sector.

The article is organized into six sections. Section 2 deals with the materials and methods. Section 3 addresses the literature review, with relevant concepts on the subject. Section 4 provides the results about the conceptual model and the proposal framework. Section 5 presents the main discussions. Finally, Section 6 considers the conclusions and recommendations.

2. Materials and Methods

The research is characterized as theoretical [23], with a qualitative–quantitative approach [24], as we used predominantly qualitative data but also quantitative data to analyze the results. We also used inductive logical argumentation [25], as new knowledge was generated from various factors, and a technical procedure for bibliographic research [26,27], as we used the systematic literature review (SLR) to obtain the conceptual framework as well as a survey procedure, applying a questionnaire to validate the framework.

The SLR consists of a systematic, rigorous, and holistic analysis of a given topic, based on scientific evidence, to reduce the bias associated with studies using non-systematic reviews [28–30]. Compared to the traditional review, the SLR declares the purpose of the review and performs a thorough search with combinations of keywords, in addition to being concerned with the possibility of replication [31,32]. Thus, it aims to generate structured knowledge to make predictions about a particular topic [33].

The research procedure included 6 steps, as shown in Figure 1.

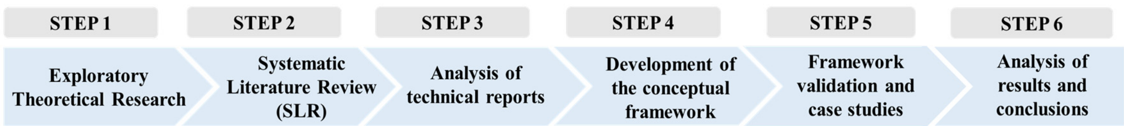

Figure 1. Steps of the research procedure.

First, we conducted exploratory theoretical research to contextualize the main topics about the offshore wind sector and related port infrastructure. In the second step, we started the systematic literature review (SLR), which was performed in four stages, as shown in Figure 2, including SLR planning, screening and selection of articles, detailed analysis of documents, and framework modeling.

In the first stage, after defining the research question, the combinations of keywords and databases used were defined. The 8 keyword combinations are described in Table 1, which were explored in 8 databases: Capes (www.periodicos.capes.gov.br, accessed on 3 February 2020), Scopus, Science Direct, Web of Science, Emerald, Semantic Scholar, NTNU, and CORE journals, which are known in the research theme. The total number of documents found was 1965.

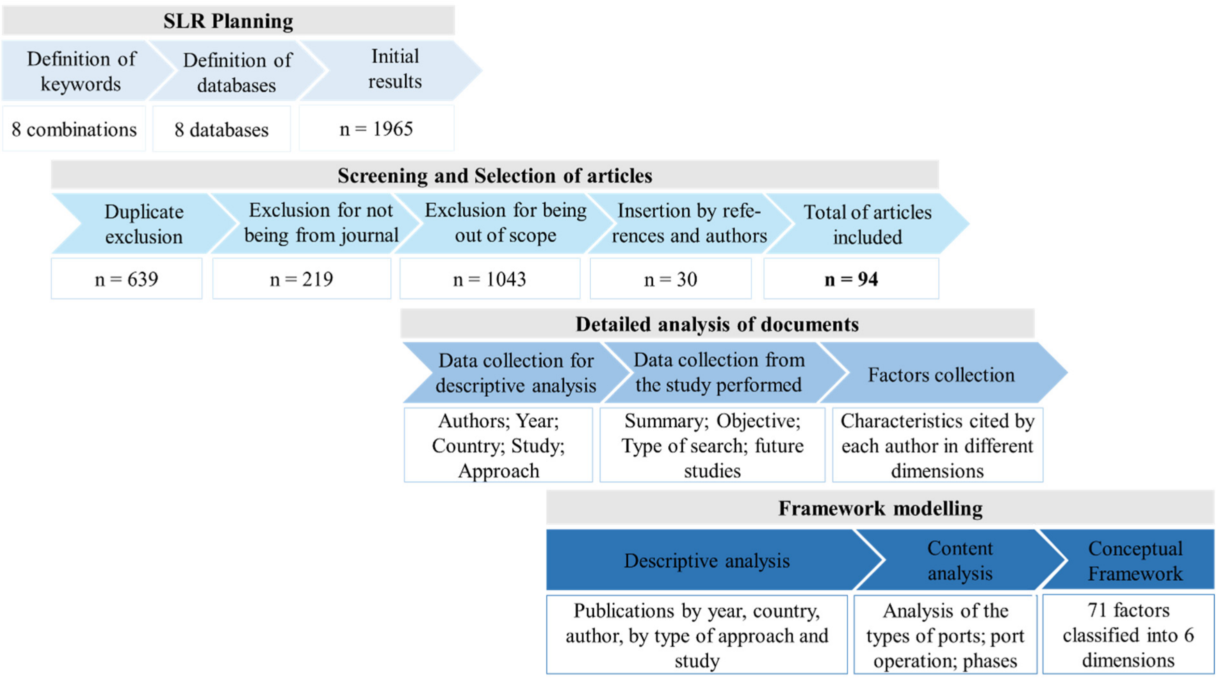

Figure 2. Stages of the SLR.

Table 1. Keywords and combinations included in the selection of the articles.

Combination	Title Search	Boolean Operator	Search on "All Options"	Results Included
1	Port	and	Offshore wind	27
2	Ports		Offshore wind	3
3	Requirement		Offshore wind port	1
4	Installation		Offshore wind port	15
5	Operation and maintenance		Offshore wind port	3
6	Decommissioning		Offshore wind port	4
7	Industry		Offshore wind port	4
8	Green port concept		-	7
			Reference articles	24
			Other publications by authors	6
			Total	94

Filters were not used to restrict the publication period, so it was between 2001 and 2021. For step 3 of this research procedure, 9 theses, 6 book chapters, and 17 technical reports were included in the SLR to enrich the research through the many factors also mentioned in the reports, totaling 126 documents. All data were catalogued and systematized using the affinity diagram.

Subsequently, in step 4, it was possible to elaborate the framework modeling on the dimensions and factors that a port must have to support the offshore wind sector. The modeling went through the elaboration, critical analysis, and improvement phases, with 5 repetition cycles until reaching the final version. The dimensions were obtained through the reading of technical reports.

After that, it was necessary to validate the developed framework (step 5) through the application of a questionnaire answered by experts in the field of offshore wind ports. The following were considered as specialists: authors with the largest number of publications, authors of the analyzed technical reports, speakers at international events on ports, port managers of the main ports that support the offshore wind sector, and experts in the study of the offshore wind sector. The population considered was 70 specialists, to whom the questionnaire link was sent in 5 rounds. The total period for this phase was 11 days. After this, the collection, description, and analysis of the responses obtained by the 15 respondents occurred, which corresponds to 21% of the population, and all these respondents came from 7 different countries: Germany, the United Kingdom, Denmark, the Netherlands, Belgium, the United States, and Brazil.

The tool used was Google Forms and the questionnaire was divided into eight sections: an introductory section, six sections, one for each dimension studied and their respected factors identified, and a final section on respondent identification data. In each section on dimensions and factors, the following were asked: a closed question with a scale ranging from 3 answers ("I agree", "I agree in parts", and "I disagree") to facilitate judgment, and two open questions about the justification of disagreement and suggestion of new factors.

Also in step 5, to validate and strengthen the proposal framework, case studies were conducted about three main ports to support the offshore sector in their countries: Port of Esbjerg, Green Port Hull, and Bremerhaven Port. With this inter-case analysis, it was possible to compare the factors and their requirements presented in the framework and the literature and discuss good practices in the operations of each port.

Finally, in step 6, it was possible to analyze the results, considering the knowledge obtained and validations carried out by experts, and propose a model for characterization of a green port industry to serve the offshore wind sector.

3. Literature Review

3.1. Logistics and Importance of Ports

The lifecycle of an offshore wind power plant comprises five main phases: (i) project, with information gathering, development, and concession; (ii) acquisition and manufacturing, with choice of suppliers to acquire and manufacture components; (iii) installation and commissioning, in which all plant components are installed, commissioned, and tested; (iv) operation and maintenance, which corresponds to the operationalization of the park and preventive and corrective maintenance; (v) decommissioning of part or the whole, such as turbines, foundations, cables, and substations [14,34,35].

Throughout this lifecycle, logistics is a fundamental factor, which facilitates the flow of resources needed to carry out the various activities during all phases of an offshore wind project [36,37]. It is, therefore, the storage and movement, on land and sea, of components, people, and equipment, safely and under variable weather conditions, inserted in a supply network with different chains, but seeking maximum efficiency [13]. Thus, three resources are indispensable in the logistical process: ports, vessels, and installation equipment [36].

The role of port logistics becomes increasingly important due two main factors: (i) The tendency to locate more manufacturing facilities and assembly operations in ports, near waterways, due to the size and weight of the turbine's components and, therefore, the logistical challenges associated with its inland transport [13], as they represent the interface between onshore and offshore operations [38–40]. (ii) Ports are also a critical part to bring efficiency during all offshore wind farm lifecycle phases and serve as a land base primarily to support installation, as well as the O&M and decommissioning phases [11,41].

Given not only the high cost of offshore operations but also the risk and uncertainty related to environmental conditions, it is important to carry out as much activity onshore as possible to reduce the number of offshore lifts, cost, and time [42,43]. A scenario projected by WindEurope predicted, by 2030, a total of 70 GW of installed capacity from offshore wind farms in Europe, where ports will have to service 10,000 wind turbines for O&M, install about 460 turbines/year, and decommission 600 turbines/year. Based on this, it is estimated that ports can contribute 5.3% of the total LCOE reduction, which is equivalent to a CAPEX reduction of EUR 185,000/MW. To invest in the construction or adaptation of ports, only 10–20% savings in CAPEX are needed, demonstrating feasibility in its use [44].

3.2. Ports for Offshore Wind: Types and Definitions

A port is a link in the transport chain that promotes economic development in a region through the flow of people and goods between the sea and land [45]. However, over time, ports have developed other features and, consequently, several types are found in the literature. Figure 3 presents some of the types of ports with their respective definitions, capable of supporting the phases of the lifecycle of offshore wind farms.

Port cluster	A cluster can be defined as a geographic region based on a relevant port location, incorporating most, if not all, of the necessary offshore wind energy value.
Port super hub	It is at the highest capacity level, whose function is to build, assembly, test and transport turbines and foundations, also as an interface for manufacturers.
Manufacturing port	Used during the farm construction phase. Its areas are needed to manufacture the main components and structures, so the value-adding activities can take place in the port.
Installation port	The main components are manufactured and then delivered to the installation port, to be then stored and pre-assembled, for subsequent transport to the offshore installation site.
Base port	Base ports has a wider managerial and organizational use. Also, some authors call those used for the production, storage of components and assembly.
Preparation port	Like installation ports but focussed on preparation or pre-assembly. Components can be shipped from the manufacturing port and prepared before transporting to OWF.
Transportable port	It can be used in several projects within a short distance of them. It is essential to have static stability and verification of movement response.
Assembly port	It has functions like to the preparation ports, focused on aiding the assembly, where large areas are usually designated to minimize offshore operations and lifts as much as possible.
Service port	The rapid reaction port differs from the previous one in that they are intended to support spontaneous and short-term maintenance operations, with quick access. It must guarantee the availability of spare parts and transfer 24 hours a day, 7 days a week.
O&M port	As Operation and Maintenance (O&M) is the longest phase of the cycle, it is necessary that the port is committed throughout this period, providing regular services and coordinating O&M activities, such as corrective and preventive maintenance, repairs and replacements. Its infrastructure requirements are less complex compared to the installation port.
Green port	It is the product of the long-term strategy aimed at sustainable and climate-friendly development of the port infrastructure. Environmentally responsible behaviour of all work structures, operations, equipaments and technologies. While many ports choose not to act beyond complying with existing environmental regulations, in many cases they have exercised their potential for addressing both social and environmental externalities.

Figure 3. Types of ports and their definitions. Source: adapted from [18,19,41,46–58].

Different port definitions have been provided to support offshore wind operations. In this article, a port industry as an offshore wind support port, from a point of view of all lifecycle phases, can be defined as an "industrial and logistical complex with features ranging from the manufacture of large components, their storage, assembly, and testing, as well as the support for the installation and operation and maintenance activities of offshore wind power plants, based on governance for sustainability of all its activities". Based on this concept, the factors that characterize this type of port will be described in the next sections.

4. Results

4.1. A Conceptual Model: Dimensions and Factors

A conceptual framework is presented in this section from the systematization of all the factors and characteristics identified during the SLR, with the main aim to characterize offshore wind support ports, including sustainability and organizational considerations, as important and necessary elements to make the port suitable. These elements were classified into six dimensions, as shown in Figure 4.

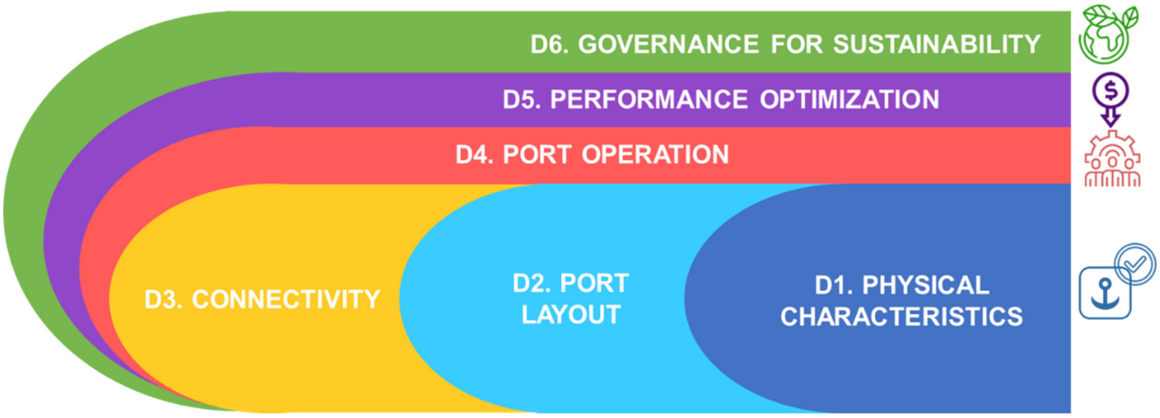

Figure 4. Conceptual framework of the dimensions for characterization of ports.

From the figure, the relationship between these dimensions can be seen. One is not superimposed on the other, but they are interconnected, complementing each other. The order from D1 to D6 means that in dimension D1, the factors are more tangible, technical, and quantifiable to analyze the port. But as the factors approach the D6 dimension, they appear to be more comprehensive and intangible, such as governance for sustainability, which is treated in a more global way.

The next topics describe, in detail, each of the factors collected in the SLR and the authors who cited them, divided into these 6 dimensions, pointing out the 71 systematized factors, in which there were 14 in physical characteristics, 17 in port layout, 7 in connectivity, 8 in port operation, 14 in performance optimization, and 11 in governance for sustainability. In the end, these factors will illustrate the proposed characterization framework.

4.1.1. Physical Characteristics

This dimension was defined to describe the physical structural port elements and availability of necessary equipment. In Table 2, the 14 factors are systematized, accompanied by the sources that cited them.

Table 2. Factors classified by the physical characteristics of a port industry.

Factors	Definitions and Importance	References
Port's depth	Height between the seabed and the water depth of the port, suitable to accommodate vessels. Must be more than 10 m.	[8,11,12,15,18–20,41,43,48,50,56,57,59–78]
Quay length	It is the available linear extension and must be longer than the total length of the vessel, more than 200 m is acceptable.	[8,11,15,18,19,39,41,46,50,57,59–61,64–68,73,75–80]
Quay width	It must be suitable for carrying components and for moving equipment. It must be wider than 70 m.	[18,64,69,70,73,80]
Surface loadbearing capacity	Measures the ability of the soil surface to support load, before failure occurs. Minimum 10 t/m^2.	[8,11,12,15,18–20,40,41,43,48,50,59,60,64–72,77–79,81–84]
Appropriate docks and shipyards	Used for unloading, assembly, and construction of components and foundations. Suitability in surface, length, and depth.	[46,56,63,80–82,85–87]
Seabed suitability	Ability of the bed to accommodate vessels, in terms of soil conditions and composition, to bring stability to lifting vessels, as the jack-up vessel.	[8,11,12,41,59,62,64,66,68,70,78,82]
Availability of component handling equipment	Defined and available for loading, unloading, pre-assembly, and internal offsets.	[15,38,40,51,64,65,68,71,88–90]

Table 2. *Cont.*

Factors	Definitions and Importance	References
Availability and capacity of suitable lifting cranes	They can be fixed, mobile, on tracks, gantry, and floating, with high load capacity, mainly for loading.	[8,11,12,15,19,20,39–41,43,46,48,50,56,59,61,64–70,72,73,75,76,78,80–83,85,86,90–98]
Availability of Ro–Ro and Lo–Lo	These are resources for integration to vessels that operate by rolling (Roll-on, Roll-off) and by lifting (Lift-on, Lift-off).	[11,15,41,46,59,65,66,68,78,88,99]
Availability of Self-Propelled Modular Transport Vehicles (SPMT)	Used to move the component in the port, with a superior flexibility and lower ground pressure compared to cranes.	[11,12,15,19,20,56,59,61,64,66,73,78,83,90,94]
Truck availability	For transporting smaller components, parts, and other resources.	[12,39,76,83,100]
Availability of floating pontoons	Two functions: manufacture of foundation by gravity and/or as a transport platform.	[22,59,61,82,88]
Appropriate port protection	Protection against cross currents, strong winds, storms, and waves. Loading bridges are essential.	[20,46,49,57,72,75,77,80,101]
Unrestricted air draft	Clear height with no overhead limitations, and no air current restrictions are required, especially for pre-assembly activity.	[15,19,48,49,56,57,59,60,64,66,67,73,75,77–80]

4.1.2. Port Layout

This dimension was chosen because the configuration of the port layout plays an important role in the efficiency of component installation operations. The response time can be reduced if the layout of the port is adequate; however, the opposite case will restrict all parts of the project [59]. Thus, in Table 3, the 17 factors are systematized.

Table 3. Factors classified into the port layout dimension.

Factors	Definitions and Importance	References
Component manufacturing facility availability	Large area for manufacturing installations of the main components. An average area of 15 hectares, depending on the number of factories and the space availability.	[11,12,14,15,19,20,40,46,48,50,56,57,59–62,64–68,73,78,79,81,96,102,103]
Component storage area availability	Large area to supply the manufacture and assembly of components, to take advantage a time-limited weather window. It can be open or covered, using racks/fork-lifts. Minimum of 13 hectares, depending on the availability and dimensions of components.	[8,11,12,15,18,20,21,39–41,46,48,49,52,56,57,59–70,73,75,76,78,79,81,83,84,86,88–90,94,96,104–116]
Spare parts storage area availability	Inventory storage for maintenance. May include components, handles, and tools.	[8,18,57,59,78,86,112,117–119]
Storage area for decommissioned components	Intended for storage, processing, and preparation for final disposal of decommissioned components.	[43,95,100,112]
Preparation/staging and assembly area availability	Intended to receive, prepare, pre-assemble, and load components before installation.	[11,12,14,15,18–21,39–42,46,48,50,54,56,58,61,62,64,67,68,70,71,73–79,81,86,90–92,94,96–98,103,105,107,109,112,115,116,118,120–125]
Area for testing of components	In addition to assembly, an area for testing turbines is required before installation.	[14,70,75]
Proximity of storage and assembly to the quay	Storage and assembly must be adjacent to the quay, looking for minimal handling and movement.	[18,19,46,66,69,116]

Table 3. *Cont.*

Factors	Definitions and Importance	References
Dry dock area availability	Used to manufacture foundations, especially gravity or floating types.	[15,22,48,56,59–61,66,67,73,78,82]
Appropriate space for handling or movement	Unhindered port layout for handling and internal movement of components between areas.	[46,64,66,78]
Potential for expansion	It is essential to have an area in the port reserved for expansion, in case there is a need for future expansion, due to the prospects of industry growth and technological advances.	[11,18,41,68,101]
Office facilities and control centers	Includes offices, social rooms, rooms for maintenance activities, control, and human resources centers.	[11,18,41,46,56,57,64,66,67,69,70,75,78]
Loading and unloading area available	Large area, located on the quay or pier, with lifting cranes and ramps installed. The unloading area can also be on the land side.	[12,14,20,21,40,42,46,49,50,52,53,56,58,65,66,77–80,89,93,94,96,97,106–108,112,113,126,127]
Workshop area	For maintenance activities, repair of broken/defective components, inspections, cutting, and painting.	[11,19,41,56,61,63,64,67,73,78,109,111,112,123,128]
Space to maneuver vessels	Enough space and depth to maneuver ships within the protected area of the port.	[46,101,108]
Heliport	Area for helicopter landing and technician transfer when the response time in O&M is critical.	[73,87,123]
Horizontal terminals	Organized as horizontally as possible, parallel to the pier for easy accessibility.	[18,67]
Onshore base green hydrogen and green ammonia	Base for the production, storage, and distribution of green hydrogen and ammonia to feed vessels, equipment, and factories. The space could also be used for fuel cell units.	[16,17,129,130]

The installation process requires the sequence of substructure, tower, nacelle, and blades and, therefore, storage at the port must follow this order, where support structures are closer to the pier and blades are stored further away, as they will be the last components installed [88]. In addition, each component must be transferred from the unloading area to the storage area, then to the preparation area, and finally to the loading area, to minimize the transportation cost [21].

4.1.3. Connectivity

The components, depending on size and weight, can be transported to the port by sea, road, and/or rail access [51]. In addition to multimodal connectivity, proximity to other key factors is also essential, hence the insertion of this dimension. Table 4 describes the seven factors.

Table 4. Factors classified into the connectivity dimension.

Factors	Definitions and Importance	References
Proximity between port and offshore wind farm	Key element for all phases because it significantly affects overall logistics strategy, time, and cost, being especially critical for O&M.	[11,12,14,18,19,21,39–43,46,56,57,59,63,64,67,69,72,73,77–79,81,82,85,86,91,94,96,97,105,107,110,112–114,117,118,121,123,126,131–133]
Proximity to the key component suppliers	Having regional suppliers of key components near or within the port area is an advantage.	[11,15,18,40,41,56,58,61,62,68,69,92,126,134]

Table 4. *Cont.*

Factors	Definitions and Importance	References
Proximity to heliports	Support for the O&M phase, when response time is critical.	[11,18,41,46,56,59,61,65,79,85,87,132]
Proximity to airports	To receive priority resources, with agility.	[18,19,46,56,61,64]
Proximity and access to road and rail networks	There must be road and rail connections for transporting and loading/unloading components and materials.	[8,11,15,18,19,41,46,48,51,54,56,59,61,64,67–70,72,73,75,77,78,83,90,95,100,111,112,116,133,134]
Appropriate maritime access	It must allow the transit of specialized vessels.	[12,19,20,46,48,49,51,54,56,73,80,90,98,108,112,116,120,126,132,135]
Wide navigation channels	Must be clear and direct, with a wide navigable entrance and adequate width, unrestricted horizontal and vertical clearance.	[12,46,48,56,57,62,64,66,72,73,75,78]

4.1.4. Port Operation

Port operation for this type of complex activity requires needs on the part of operators as well as the port management, justifying the choice of this dimension as part of the result. Table 5 describes the eight factors.

Table 5. Factors classified into the port operation dimension.

Factors	Definitions and Importance	References
Port operationalization, 24/7	The port must operate 24 h/day, 7 days/week, 365 days/year. In a marine environment, a maximum of 12 h/day.	[18,56,57,59,64–66,73,75,77,78,121]
Specialized workforce	Availability of specialized workers, mainly local, such as engineers, electricians, mechanics, and machine operators.	[15,18,46,58,59,73,75,78,79,86]
Sharing information	It is essential to have an installation schedule combined with the sharing of information about the port's storage capacity, weather forecast, and availability of vessels.	[12,38,59,65,84,103,105,107,126,129]
Team and supplier management	To avoid stockout situations. These skills are needed to ensure the efficient operation of the supply chain and logistics.	[40,49,77]
International port operation compliance	Ensure that cargo can be transported internationally, requiring an ISPS (International Ship and Port Facility Security) compliant port.	[15]
Occupational health and safety measures	Measures and strict requirements must be implemented to avoid riskiness and accidents on land and/or sea. Establish occupational health programs to protect everyone.	[58,59,61,65,136]
Facilities for first aid at the port	Provide emergency services and first aid facilities. The port must be sufficiently close to hospitals.	[56,136]
Training courses and research center	Port location with training courses and research in centers of excellence. Promote access to high-quality training and research expertise at the port facility or through courses and training elsewhere or centers of excellence near the port.	[18,75,102]

4.1.5. Performance Optimization

This dimension is essential because, on the one hand, there is a need to assign port resources very early in the lifecycle phase of the offshore wind farm and, on the other hand, an inadequate dimensioning of the ports can drastically interfere in efficient installations and incur additional costs. For that reason, each process in the performance is crucial to minimize costs, logistical inefficiencies, and waiting times [108,137]. The 14 factors are described in Table 6.

Table 6. Factors classified into the performance optimization dimension.

Factors	Definitions and Importance	References
Minimum port–farm distance	Impacts on port costs because it reduces transfer time, uses less fuel, expands the climate window, and decreases LCOE.	[8,11,18,41,42,52,64,66,69,76,78,85,87,88,97,100,110,122,123,125,127,133,138]
Port storage cost	It is included in the logistical costs. Corresponds to port fees for the storage of parts and facilities.	[90,118]
Port labor cost	Multiply the average working days required by the fixed daily work rate.	[65,66,87,118]
Annual rate	Paid to local authorities for the use of port infrastructure, berthing at the quay, and use of cranes.	[61,118]
Learning rate	It shows how agile the operations are. If the rate is high, then the shipping and installation cost is low.	[97]
Transport of complete structures	Included in the port cost. It aims to minimize offshore work and maximize pre-assembly onshore, simplifying operations, time, and costs.	[42,43,110,122,123,125,139]
Inventory control and targets	Port inventory control that synchronizes storage, production, and lead times to maintain capacity, avoid waiting times, and ensure supply.	[20,38,79,84,88,106,115,116,137,140]
Optimization of the required flow of inputs and outputs to components	It is essential to optimize the cycles or inflow and outflow of the turbines, to ensure replenishment and deliver components at a defined frequency, avoiding delays, additional costs, and low performance.	[137,140]
Potential activities and use conflicts management	Ports host a variety of activities other than offshore wind, which can conflict with each other directly or inadvertently, positively or negatively.	[78]
Loading time at port	Included in the port cost. This time depends on the configuration, how many turbines will be loaded, and the number of lifts.	[49,52,78,104,106,110,115,116,119,137,139]
Transport time from the port to the farm	This transport time depends on the number of turbines, vessel speed, and port-to-site distance.	[52,66,77,78,104,106,115,116,119]
Decommissioning cost	Means the transportation cost of the return and processing at the port of decommissioned components.	[110]
Choice of vessel type	This is a crucial decision when planning the installation, as well as choosing the loading mode and the base port.	[61,110,139]
Towing speed	Included in the port cost. Corresponds to the speed of the tugboat when transiting components from the port to the site. The higher the speed, the higher the performance.	[110]

4.1.6. Governance for Sustainability

Governance of ports is a very important issue that is often overlooked in many studies that only consider logistics characteristics. Therefore, this dimension was included because, as demonstrated by the literature analyzed in Table 7, sustainable development in port regions is necessary and is characterized by a complex decision-making process involving environmental, social, and economic issues [141].

Table 7. Factors classified in the governance for sustainability dimension.

Factors	Definitions and Importance	References
Storage and use of renewable energy	Use the port to store excess energy obtained from wind farms, using hydrogen. The port would function as a generator and energy consumer, being able to achieve 25% less emissions.	[16,57,129,142–144]
Use of OPS system	Port power supply, called onshore power supply (OPS). Allows the shutdown of auxiliary engines of vessels while they are berthed. Reduces adverse environmental effects, generating energy from renewable sources.	[129,130,142,145]
Monitoring of port environmental impacts	Fundamental in all phases of construction and operation, as dredging activities can induce aquatic impacts, and port operations can produce sewage and solid waste, leakage of harmful materials, and oil pollution.	[136,144]
Investment in green equipment	Equipment is less likely to cause pollution, such as engines from renewable sources and electric cranes.	[47,57,136,144,145]
Sustainability practices in the port operations and its entire chain	The entire supply chain at all stages must be concerned with following environmental criteria and sustainable business practices with equal weight to environmental, economic, and social decisions. It should include the efficient use of resources, quality of the natural port environment, waste management, waste reduction, and encouragement to reuse and recycle materials.	[47,57,64,65,144,146–148]
Clean and efficient shipping, transport, and logistics	The ship-building industry must implement strict liquid and solid waste policies and use electric power and alternative fuel engines. The "Clean Truck Program" consists of a ban on trucks manufactured in the port before 1989.	[144,145,148]
Fuel cells for operations and vessels	Green energy strategy for a system composed of hydrogen fuel cells, electromechanical cells, and offshore wind turbines. It provides a reduction in CO_2, NOx, and CO emissions from vessels, in addition to the economic impact of the application of this technology.	[16,17]
Inclusion of trees in the port area	It is a landscape inclusion that includes trees, with the objective of absorbing noise and reducing pollution, reducing the contributions of greenhouse gases and other emissions.	[144,147]
Monitoring composite sustainability indexes	Use of composite sustainability indexes, encompassing the three dimensions: economic (regional GDP, employment and unemployment rates, and employment generation mainly from manufacturing and O&M facilities), social (gender differences, life expectancy, rate of participation in education and training, and benefits to the local community), and environmental (air pollution and average annual exposure). Thus, it is possible to measure the positive impact of the sustainable development of the ports in a composite way.	[16,17,69,79,102,103,141,148]
Development and maintenance of highways and railways	The port as a driver in the development of highways and railways, mainly those connected to it.	[129,135]
Link with population centers	Connection and proximity of the farms to population centers is essential, because it will allow less tension in terms of accessibility and logistics of the network, promoting social development. This is primarily a "connectivity" issue but has also been placed here due to its sustainability implications.	[131]

Also, it is important to realize that the environmental impact of ports and the problems caused come from three main sources: the port activities, the activities of the ships that dock, and emissions from the intermodal transport chains that serve the interior of the port [129]. Thus, the negative environmental impact is a reality [142]. Hence, offshore wind support ports also contain these characterization factors, because minimizing negative environmental impact is necessary in order not to negate some of the positive environmental benefits gained by the transition to offshore wind energy. Equally, the economic and social benefits that an offshore wind port brings should be managed in a sustainable manner. Table 7 describes 11 factors covered, which show how the green port could be operated and managed.

4.2. A Proposal Framework: Factors for Characterization of a Green Port Industry

This section consists of validating the developed framework, through the results of the application of a questionnaire answered by experts in the field of ports for offshore wind. The following were considered as experts: authors with the highest number of publications (greater than or equal to three), the first two authors of the technical reports analyzed, speakers at international events on ports, port managers of the main ports that support the offshore wind sector, and experts in the study of the offshore wind sector.

Some of these respondents noted that the analysis of the exposed factors depends on the type of port that is intended to be analyzed, what the support is, and at what phase of the lifecycle, as there are many types, with different scopes of work and different requirements to be attended, consequently.

However, the objective of this study was to characterize a green port industry to support the offshore wind sector as a port capable of providing the necessary support, from the manufacture of components within the port area, through the subsequent support for installation, operation, and maintenance, and even its decommissioning. Because of this, the research systematized all factors found in the publications, not focusing only on factors corresponding to an installation port or an O&M port, for example, nor on supporting a specific lifecycle phase.

Regarding the dimension "physical characteristics", no factor needed to be removed, as most factors obtained 100% agreement. The factor "appropriate docks and shipyards" was disagreed on by some, as seen, but it was not removed due to its importance in the manufacture of foundations, mainly. Therefore, they are in fact not essential in the installation phase, as commented by experts, but they are essential in the manufacturing phase of fixed and floating foundations, as well as being a support point for unloading and assembly when necessary [56,85,86]. Likewise, the factor "availability of floating pontoons" was defended, as it supports the same function of building foundations, mainly of the gravity type [82].

The other factor also commented on with disagreements was "seabed suitability", but this factor was not removed, as it is important not only for the location of the farm, as justified by the specialist, but mainly to know the conditions and capacity of the seabed of the port to dock and accommodate certain vessels in order to stabilize them at the time of lifting for loading, as occurs with the jack-up vessel [11,12].

Regarding the suggestion of new factors, according to the experts, the inclusion of the factor "capacity and availability of energy substations" was considered, since it is really an important factor to be analyzed with a view to supplying sufficient energy resources for the operation of the port and execution of manufacturing, assembly, and loading, among others. The factor "wide evolution basins" was not considered as a new factor, as it is already included in the factor "wide navigation channels", in the dimension "connectivity". Likewise, the suggested factor "differentiation between SOVs and CTVs" was also not included, as it was already included in the factor "choice of vessel type", in the dimension "performance optimization".

When analyzing the results for the dimension "port layout", no factor was removed or added. The first factor that obtained disagreement was "dry dock area availability", with the justification that they are not essential in the port, but looking at an area suitable for manufacturing gravity and floating support structures (foundations), as well as their maintenance and repair [22,59], becomes an important factor to be analyzed, depending on the strategy adopted by the developer and stakeholders.

The "heliport" factor was also considered not essential for installation or manufacturing. However, it was not removed, as it is an extremely important factor for maintenance activities with a critical response time for resolution and high complexity [122], which can also occur in a port industry. The third and last factor with a percentage of disagreement was "onshore base for storage of green hydrogen and green ammonia", with the justification that it is not essential for the port, but for the green energy transition.

However, the port, according to good practices seen in countries such as Scotland, can serve as a viable and strategic base not only for storage, but also for the production, distribution, and export of green hydrogen, for example [16,17,129,130].

For the "connectivity" dimension, the results showed that the "proximity to heliports" factor remained for cases where there is no heliport in the port area. However, the "proximity to airports" factor, the second that had disagreements, was removed, as experts believe it is unnecessary in view of the other forms of existing connectivity. The other factors obtained 100% agreement and there was no addition of new factors for this dimension.

For the dimension "port operations", the factors remained unchanged. There were no justified disagreements or suggestions for new factors. Regarding the "performance optimization" dimension, the main result was the need to clarify the dimension and what it is about. The disagreement or agreement in parts was indicated by thinking that the dimension should only consider port assessment factors or those that directly involve port operations.

However, in fact, the dimension seeks to bring important decision factors regarding the interface between the port and farm, costs and fees that involve both sides directly and indirectly. Each of the factors considered is defined and justified in Tables 4 and 5. All have a direct or indirect influence on the port cost, such as towing speed, decommissioning cost, the minimum port-to-farm distance, and the choice of vessel type, as it influences the type of pre-assembly, time, and mode of loading operations, among other essential relationships. With this, the dimension, in its latest version, is now called "port–farm performance optimization".

Thus, none of the factors were excluded, the respondents' comments did not include plausible justifications for the removal of any factor. Regarding the suggestions for new factors, they were also not added, since the possible factor "rapid adaptation to bad weather conditions" is already considered in the factor "optimization of the required flow of inputs and outputs to components" in this same dimension, as it concerns precisely predicting production and demand and knowing how to deal in an optimized way in adapting to bad weather conditions through stocks and replenishment cycles, to avoid delays, additional costs, and poor performance [137].

In the "governance for sustainability" dimension, there was a comment about these sustainability factors and decisions still being in the research and discussion phase to be clearly determined, as achieving and maintaining greater sustainability is an important factor, but the location of the facility and the capabilities are even more urgent in practice. Through the results obtained throughout the study, this understanding is clear, but the novelty of the research was to fill precisely the existing gap on the discussion of sustainability factors and how this governance could occur in the port environment and which paths could be followed.

Thus, some factors disagreed. The factor "fuel cells for operations and vessels" was not removed, as it is known that the use of combustion engines can still be more economical and efficient, but the use of fuel cells will be a viable and extremely necessary option in the near future, as a green energy strategy that can significantly reduce CO_2, NOx, and CO emissions from ships, in addition to the economic impact of applying green energy technologies [16,17].

The factor "monitoring composite sustainability indexes" was also not removed, as in addition to the disagreement not having been justified, this factor brings together a number of important factors for achieving sustainability and green port policy, which seeks to encompass the three dimensions' analysis: economic, environmental, and social [103,141].

The factor "inclusion of trees in the port area" was removed, as the experts' justification was plausible: there are other more important factors with better academic basis to be considered, regarding the mitigation of environmental impacts and promotion of green ports, which go beyond this concern for the port's landscape.

In addition, the insertion of a new factor "presence of recycling companies" was suggested, but it was not added to the proposed model, as it is already being considered in the factor "sustainability practices in the port operations and its entire chain" in the same dimension.

Therefore, some factors were added and removed after the validation and discussions step, as explained. Thus, the proposed new model is illustrated in Figure 5. There were 71 factors, where 2 factors were excluded (proximity to airports, in the connectivity dimension, and inclusion of trees in the port area, in the governance for sustainability dimension) and 1 factor was included (capacity and availability of power substations, in the physical characteristics dimension).

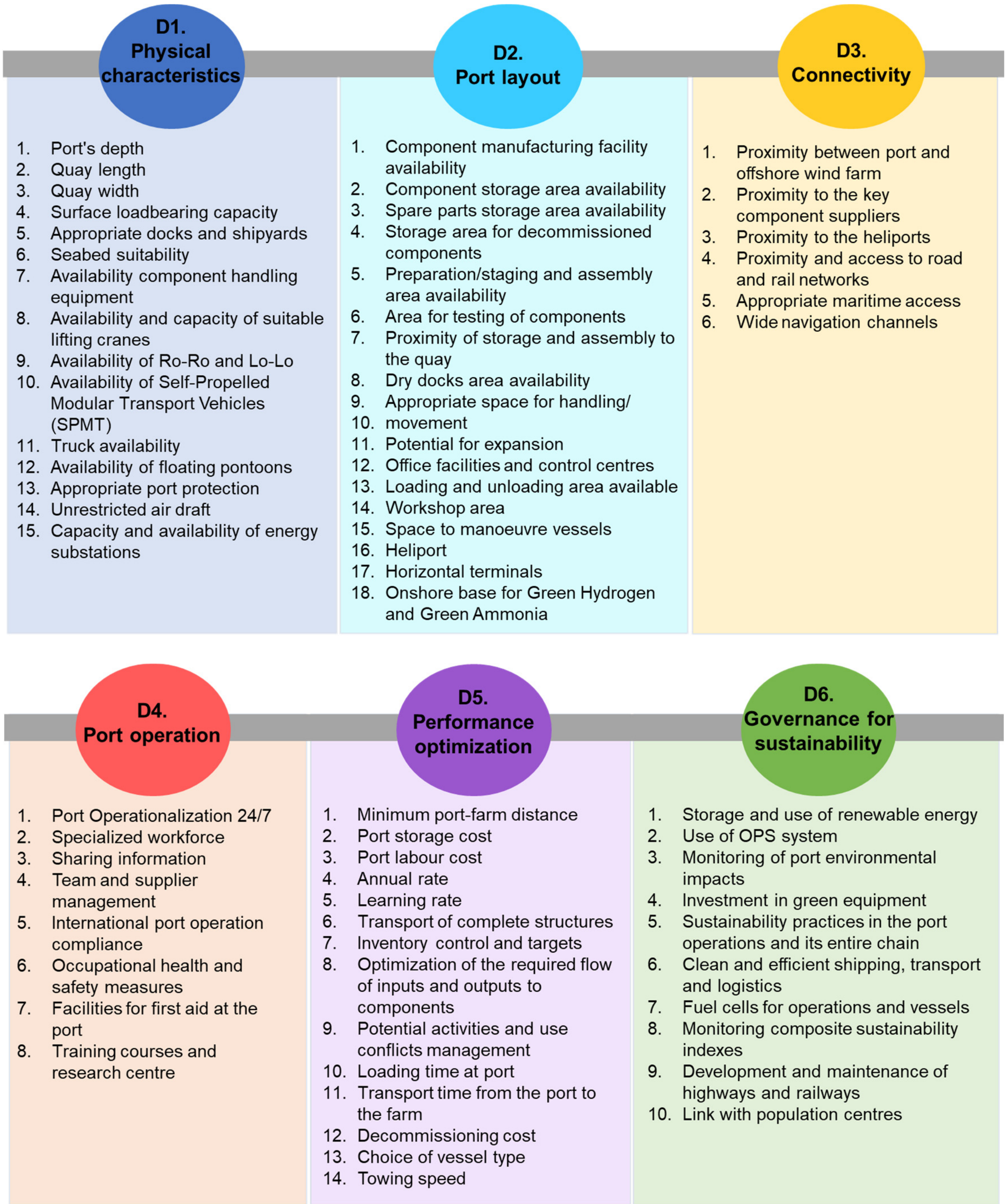

Figure 5. Proposal characterization framework.

4.3. Case Studies on Existing Ports: Strengtheing the Proposed Framework

This section consists of strengthening the proposed framework through comparison and analysis of existing ports to validate some factors and characteristics already identified, especially the quantitative ones. The studied ports were (1) the port of Esbjerg in Denmark, (2) the port of Hull in the United Kingdom, and (3) the port of Bremerhaven, Germany. The port of Esbjerg was selected as the reference port in support of the offshore wind sector and helped to implement the largest installed capacity of offshore wind farms. The port of Hull was studied due to its experience of including the blade industry in the port, having preparation areas for the installation of offshore wind farms in the UK, as well as being considered a green port and industry port. The port of Bremerhaven was chosen for its expertise and experience with the offshore wind industrial cluster.

Table 8 shows the three ports in terms of physical characteristic factors, port layout, connectivity, as well as some governance aspects for sustainability, which demonstrate the main aspects of a green port industry to support the offshore wind sector, for the manufacturing operations, installation, and operation and maintenance of plants, also linked to the implementation of green port strategies.

Table 8. Characterization factors for the ports of Bremerhaven, Esbjerg, and Hull.

Factors	Bremerhaven	Esbjerg	Hull
Port type	Port industry, as well as a base for assembly, installation, and O&M.	Base port for installation and O&M.	Port industry, as well as a base for installation and O&M.
Operations/ Activities	Manufacture and assembly of foundation, tower, and nacelle, manufacture of blades, as well as storage, transport with suitable load capacity, and heavy forklifts. Also included the export of components.	Manufacturing, storage, assembly, testing, loading, unloading, and transport.	Manufacturing, storage, preparation, loading, and transport.
Supporting farms	25	55	20
Area (offshore wind)	More than 25 ha (OTB); 10 ha (ABC); 25 ha (containers 1)	450 ha (total)	58 ha (Alexandra Dock)
Port's depth	14.1 m (OTB); 10.5–11 m (ABC); 12.5–15.5 m (containers 1)	9.4–10.5 m	8.3 m (Alexandra Dock)
Quay length	500 m (OTB); 900 m (ABC); 450 m (containers)	14 km	4.082 m (Alexandra Dock)
Surface loadbearing capacity	10–50 t/m^2 (OTB); 20 t/m^2 (ABC)	15–30 t/m^2	20 t/m^2 (Alexandra Dock)
Crane capacity	30–400 t	308–448 t	180–420 t
Storage area	Approx. 100,000 m^2	Approx. 1,000,000 m^2	70,000 m^2—Covered 650,000 m^2—Open
Manufacturing area	Yes (blades, foundations, towers, cables)	Yes (MHI Vestas)	Yes (Siemens Gamesa, 40,000 m^2)
Assembly/ preparation area	Yes	Yes	Yes
Testing area	Yes (blades and nacelles)	Yes	No
Heliport	No	Yes	No
Dry dock	Yes	Yes	Yes
Expansion area	Approx. 200 ha	Approx. 100 ha	Approx. 183 ha

Table 8. *Cont.*

Factors	Bremerhaven	Esbjerg	Hull
Horizontal terminals	Yes	Yes	Yes
Proximity and access to road and rail networks	Yes	Yes	Yes
Proximity and access to airports/ heliports	Yes (58 km from Bremen International Airport)	Yes (8 km from Esbjerg Airport and heliport)	Yes (28 km from Humberside Airport, which houses the second largest heliport in the country)
Wide navigation channels	11–12.2 m (depth); 498 m (width)	10.3–11.6 m (depth); 200 m (width)	7.9 m (depth); 167.7 m (width)
Port operation 24/7	Yes	Yes	Yes
Specialized workforce/ jobs	Yes (many training centers and generation of 3000 jobs)	Yes (generation of 10,000 jobs in the offshore wind and oil and gas sector, with specialties of blacksmiths, electricians, welders, and engineers)	Yes (12,000 overall and over 3500 in the offshore wind chain)
Training centers/ universities	Fraunhofer (IWES); Deutsche WindGuard GmbH; k-wind: University of Bremerhaven; ISL Institute for Shipping Economics and Logistics; Wind Energy Agency (WAB)	Offshore Academy; Energy Innovation Cluster	HETA; HOTA; Hull Training; HFR Solutions; Universidade de Hull
Distance to the farm	Up to about 320 km	Up to about 600 km	Up to about 300 km (12 h of navigation to wind farms of the third round)
Governance for sustainability and benefits for the local community	PERS certification; ESI Index; recycling system; use of terrestrial energy with renewable energy sources; air quality indicators; CO_2 footprint analysis; sediment management; defined compensation and protection measures; city development; highway development; incentive to local companies; employment and income; measures to disseminate to the public (observation facilities, guided tours, and events).	Yellow containers for garbage collection; recycling station; effective waste disposal system; port waste treatment plan; city development; development of rail and road access; employment and income; opportunity for young people.	Biomass handling facility; Energy Works Project; Chowder Ness; noise barrier; opportunity for young people and women; Humber Coastal Half Marathon.

Source: adapted from [149–179].

From this systematized table, it is possible to compare with the minimum or ideal values established in Section 4.2 to conclude if what is discussed in the literature and technical reports can be proven in the reality of existing industrial ports. For examples, the verification and comparison for each requirement follow:

(a) The surface loadbearing capacity was established with at least 10 t/m^2. In the studied ports, it appears that this requirement is being met, as shown in Table 8.

(b) The capacity of the cranes was observed with the ideal of 400 t to 1000 t. In the studied ports, all identified cranes reached 400 t, which, added to the capacity of other cranes, working together, can exceed 1000 t.

(c) The quay length established as the minimum acceptable was 200–300 m, as an average value found, considering the technological and dimensional advances of the vessels and components. The case study ports exceeded this limit in their terminals and wharves, which proved compliance with this requirement and full conditions for berthing vessels.

(d) The minimum depth of the port industry was established at 10 m, as a minimum acceptable average for suitability for receiving vessels. The case studies showed that two ports were following this requirement, Esbjerg and Bremerhaven, while the port of Hull was at 8.3 m, the smallest depth among the three.

(e) The significant use of SPMTs and Ro–Ro ramps was proven in the literature and in the conceptual framework. It was also identified as good practice in the case studies, since all ports make these tools available in the execution of their operations.

(f) Layout areas, as noted in the systematic literature review, vary greatly depending on the availability of area in each port. However, some values perceived as usual were 20 to 40 ha for the storage and assembly area, up to 40 ha for manufacturing facilities, and an average area of 4000 m^2 for offices and control centers. In the case studies, this information was not available for the most part, but the storage areas found were within compliance, if compared to this information.

(g) Factors established as important in a port industry, such as expansion area, testing area, presence of dry docks, heliport in the port area, and horizontal terminals, were verified in the case studies and were compliant, showing that they are also able to use these good practices.

(h) Another requirement that was also met by the three ports studied was proximity and access to road and rail networks, as an essential factor for unloading raw materials for manufacturing and small components.

(i) The port operation in the 24/7 regime was also a factor attended by all the studied ports, as a good practice, mainly in the operation and maintenance phase. In addition, the specialized workforce, training centers, and partnerships with research and development centers were proven as important factors and were also part of the practices established in the three ports of the case studies.

(j) The distance between the port and farm has an average requirement of 150 km to support O&M activities and an average of up to 400 km to support plant installation activities, as verified in Section 4.2. The studied ports complied with these requirements mainly regarding installation activities, with the port of Esbjerg being the one with the greatest reach in terms of service to the farms.

(k) All ports in the case study can also be considered green ports, as a good practice identified in the SLR, meeting numerous governance factors for sustainability and the consequent benefits to the local community.

5. Discussion

In addition to the direct relationships that the factors establish within each dimension by affinity, it is also possible to extract from the framework factor relationships between different dimensions, such as the following: the close relationship between the specialized workforce and the generation of employment and income; the need for access to roads and railways and their consequent regional development; the need to install factories with the disposal of suppliers close to or within the port area; the depth of the port and the close connection with the suitability of the docks, seabed, and the choice of vessels; the areas for handling and movement with the respective availability and capacity of handling, lifting, and transport equipment; the existence of training centers with an increase in the learning rate; the relationship of the information sharing factor with the control factors and inventory targets, management of suppliers and teams, as well as the promotion of a sustainable chain, among other interconnections.

It was also noted that the systematization globally sought all the factors that can characterize a support port for the offshore wind sector, regardless of the phase it serves or the target activity it is willing to offer, designing an ideal port that encompasses industry at all stages and is sustainable, although more factors have been found for the manufacturing and installation phases.

In addition, although the factors have been systematized qualitatively, some factors have quantifiable requirements, mainly the factors of the dimensions "physical characteristics" and "layout". It was also proven by the case studies described in the last section.

Depending on the conditions of the port area, meeting one requirement to the detriment of another will result in a better or worse cost–benefit, which proves, once again, the close relationship between the factors and the impact of each one on the cost, performance, and consequently, on the decisions. For example, if there is an area to build a port with a shallow seabed depth, there will be the cost of dredging to reach the minimum height of 10 m. If there is another area with an adequate depth, but without a sufficient coastline length and width for berths and quays, there would be this cost for the potential increase in available coastal area. This is a multicriteria decision based on the conditions of each port area analyzed.

Therefore, this research can be seen as the advancement and implementation of a more holistic and systematized operational and sustainable analysis, in which 71 characterization factors were identified and classified into 6 dimensions, thus providing a novel, detailed, 6-dimension systematic analysis of the literature pertaining to ports that support the offshore wind sector. In addition to the structured dimensions and factors validated with experts, the novelty of this article is also the new port concept presented, which combines not only installation and operation support activities, but also component manufacturing activities as an industrial cluster, in a port environment with green technologies and management.

6. Conclusions

The accelerated technological development of the offshore wind turbine requires that the traditional function of the port be expanded from a logistical port to a port with manufacturing, assembly, and testing facilities. Also, the concern for the sustainability of the planet requires that ports adopt strategies involving the concept of a green port and actions of governance for this sustainability in all the operations and management. Thus, new requirements, factors, and characteristics are needed to have suitable ports to support the offshore wind sector.

Because of the above, this study was conducted based on the following research question: which factors should be considered to characterize an offshore wind support port? And this article was achieved with the main objective being to identify the factors that characterize a suitable port to support the offshore wind sector. This was reached using SLR and the conceptual framework proposal as a result, with 71 characterization factors classified into 6 dimensions, not only related to technical feasibility, but also to infrastructure and operational factors, optimization and organizational, and especially sustainability elements, which are able to assess what a port could have.

The proposed framework was strengthened by case studies on existing ports, which identified a list with the minimum requirements of a port capable of this level of support, as well as described other good international practices at these specific ports, which also contributed to and reinforced the characterization of a green port industry.

Therefore, the identification of these factors contributes not only to the state-of-the-art, but also to the offshore wind energy sector and the port sector, because they can promote less risk in manufacturing, installation, and O&M operations, as well as influence the increase in competitiveness of both ports and project developers. Linked to this, the research can promote benefits for other port economic activities, as well as for regional development and local communities. There is a vision not only of the importance of ports for offshore wind, but also the benefits of offshore wind as a competitive advantage for ports.

Thus, the choice, adequacy of ports, and projection of new port infrastructure will be a focal point of analysis for the projects, the developers, the port authorities, and other stakeholders involved, as well as for formation and discussion of public policies, due to the accelerated and continuous evolution of this industry and this technology. Also, the results of this research are essential to decision-makers about how to invest in adequacy of ports or construction of new ports to support this sector, being able to take this study as a guide of factors and characteristics to be analyzed and prioritized.

The results highlight the importance of this research, although it faced some limitations, mainly about the difficulty of keeping in touch with experts and the sample size obtained in the study.

For future research, it is recommended to analyze what minimum or ideal requirements are necessary so that it is suitable for the dimensions of the components of the next generations of turbines. Furthermore, how can the identified factors be analyzed and classified according to the level of criticality, so that the priority factors are listed? What multicriteria decision models can be developed from the identification of these factors? What mathematical models can be developed to evaluate the performance of these ports in supporting offshore wind? What paths should decision-makers, port authorities, and governments follow to secure investments in ports? How could a technical, economic, and environmental feasibility study be conducted for this type of port?

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