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Review

Design, Sizing, and Energy Management of Microgrids in Harbor Areas: A Review

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Abstract: Energy efficiency and low-carbon energy systems are increasingly taken into account in seaports, due to climate change challenges and the evolution of environmental regulations. Thus, technological breakthroughs must be brought to numerous systems in harbors, such as harbor cranes, seaport vehicles, or the power supply of berthed vessels. These aspects may require the establishment of a microgrid in the harbor area. Microgrids have been subjected to a wide development on the mainland and islands, mostly for domestic loads. However, these are still scarce in harbor areas. Their development in such places faces several challenges, such as high power requirements, monitoring and management of a wide range of loads, energy policy framework, etc. Moreover, the establishment of a microgrid involves a study of sizing and of energy management, to avoid prohibitive costs and to verify load requirements. This paper provides a literature survey related to the development of microgrids in seaport areas. Firstly, the main components that occur in harbor microgrids are listed, and then a review of studies dealing with sizing and energy management is proposed. Finally, from this survey, innovative concepts and barriers are listed, with an up-to-date review of microgrid development in seaports worldwide.

Keywords: microgrid; harbor; seaport; renewable energy; storage; sustainable development; energy management; sizing

1. Introduction

Maritime transport plays a key role in international exchanges, as it is estimated that 90% of the volume of goods traded worldwide transit by the sea [1]. However, most vessels use fossil fuels for their energetic needs, leading to the emission of pollutant gases, particulate matter and greenhouse gases (GHG) [1,2]. Thus, some environmental issues arise [3] along with health problems [4,5]. To reduce the air pollution and follow international environmental regulations, in 2011 the International Maritime Organization set a target for the reduction by 50% of GHG to be emitted by vessels in 2050 [6], despite increases in the transport of goods and passengers by this same date. To reach the environmental goals, several major changes must be brought to the maritime transport sector, both for the vessels and for the harbors. Since the 2000s, several alternative fuels have been considered for vessels, such as liquefied natural gas (LNG), methanol and hydrogen [7]. Moreover, all-electric ships appeared recently, with the launch of the first fully electric car ferry in Norway in 2015 [8,9]. In this kind of vessel, electrical energy can be generated by renewable sources and the use of storage systems is often considered, such as batteries [8,9], supercapacitors [10,11], and hydrogen [8]. To limit the use of fossil fuels as

much as possible, the electrical supply of berthed vessels provided by the onshore grid is increasingly considered, and details of this can be found in the literature under the terms of cold-ironing [9], shore-side electricity supply [12] or shore-to-ship power [13]. The supply of electricity to vessels at berth avoids the use of diesel generators in vessels. However, it faces technical challenges such as the high power and voltage requirements of vessels and the diversity of vessels that can arrive at a harbor [13]. This involves an obligation to take into account the compatibility between a vessel and onshore grids. To reduce the carbon footprint of vessels cold-ironing and avoid the use of electricity generated by fossil fuels in the main grid, the use of renewable energy sources such as solar panels and wind turbines, and storage solutions, have been increasingly taken into account in seaports [14,15].

To manage all these elements, the development of microgrids in harbor areas has been increasingly taken into account over the last decade [15,16]. A microgrid consists of the connection of different elements (sources, storage solutions, and loads) at a local scale, and their management to ensure that the load demand can be met at all times. Indeed, the power generation from renewable energy sources is non-dispatchable and can present severe fluctuations, according to different time scales [17]. Although microgrids have been widely developed worldwide in different kinds of territories (cities, remote communities, islands, etc.) [18], they remain scarce in harbor areas. This can be explained by the diversity of loads in a seaport (reefer containers, quay cranes, vessel cold-ironing, buildings, etc.). This diversity can involve challenges related to energy management, difficult load forecasting ability, and power requirements of several megawatts [16]. In addition, the development of microgrids involves heavy investments due to the use of storage solutions and renewable energies, leading to questions of investment cost sharing between authorities, port owners, etc. [13], and the management of the microgrid from business and energy points of view [16,19,20].

Thus, the development of microgrids in harbors seems to be a challenging task due to the diversity and complexity of the elements to be considered. It cannot be done without a rigorous study of the energy management system, and an optimization of sizing to avoid prohibitive costs. Several articles published in recent years deal with some systems that can be found in a harbor, such as shore connection (also named 'cold-ironing') [12,13], the vessel's electrical power system itself [8,9], the quay cranes [21], etc., by studying their control, sizing, and sometimes integration into a microgrid. Few reviews exist in the field of energy efficiency actions in harbors [14,15,22,23]. However, no study has proposed a review of the sizing, and energy management at the harbor microgrid scale, as their full-scale development is still limited worldwide. The sizing and energy management can be a challenging task as many criteria have to be considered, such as pollution, costs, and reliability. These criteria can be conflicting, which requires an optimization to meet the requirements as much as possible. Thus, it is necessary to know which facilities and criteria have to be considered before the development of a harbor microgrid project, which appears to lack in the literature.

In this paper, we propose an up-to-date review of the sizing and energy management of microgrids in harbor areas to foster their development at full scale and to help in their design by identifying the possible criteria. Firstly, an overview of the current situation from a literature point of view is given, to identify the number of studies, their origins, and their motivations. In Section 3, the main components which can be found in a seaport microgrid are listed, with sources, storage solutions, and loads. Then, the sizing and energy management aspects are analyzed in Section 4 thanks to a review of scientific papers, to point out the most used criteria and methods. Finally, in Section 5, the innovative concepts are highlighted and an overview of the microgrids development in harbor areas is proposed. The main barriers to the development of such microgrids and challenges are also identified.

2. Analysis of Studies Published in the Literature

Several research articles dealing with the design, sizing and management of a harbor microgrid have been published in recent years. To illustrate this trend, a search concerning the articles existing in the literature has been conducted with the Scopus database [24], using the following

query: (TITLE-ABS-KEY(size OR sizing OR design OR electrification OR control OR management OR ems)) AND (TITLE-ABS-KEY(electric* OR energ*)) AND (TITLE-ABS-KEY (grid* OR microgrid*)) AND (TITLE-ABS-KEY(harbor* OR harbor* OR "port area" OR seaport)). The results obtained are given in Figure 1 and show an increasing number of papers since 2007, and especially since 2018. This trend can be explained by the regulations set by the European Commission and the International Maritime Organization in the 2010s for GHG reduction and cold-ironing of vessels [1,25,26]. Thus, many challenges related to these subjects need to be answered. Moreover, most countries which these articles come from correspond to those directly involved by harbor evolution, as they are the location of the major harbors of the world: USA, Italy, China, Denmark, Germany, Taiwan, Finland, Greece, Spain, etc. Some harbors located in these countries have been used as application cases for research articles, for example: Long Beach (USA) [27,28], Houston (USA) [29], Copenhagen (Denmark) [30], Taiwan [31], Sardinia (Italy) [32].

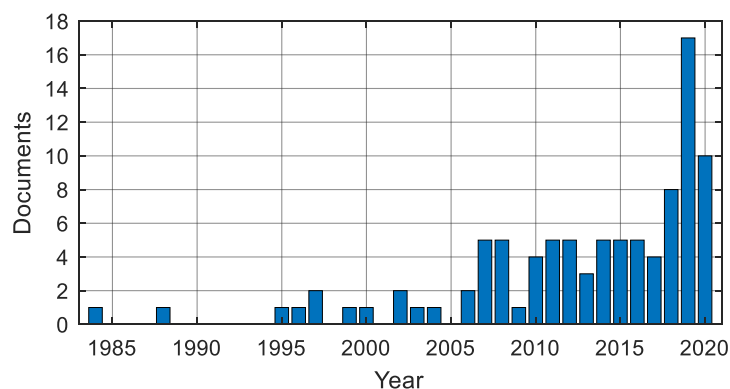


Figure 1. Number of publications dealing with the design, sizing and management of harbor microgrids over the years, according to the Scopus database (results of 15 September 2020).

These publications are reviewed in Sections 3 and 4. They are motivated by different aims:

- **Pollution reduction**, to meet the regulations set by the European Commission [25,26], for example by replacing fossil energies by renewable energy sources, stopping the engines of vessels during berthing, electrifying systems based on fossil energy (quay cranes for example) [33];
- **The adaptation of harbors to the technological evolution of vessels and to shore-to-ship requirements.** Fossil fuels are intended to be totally or partially replaced by electrical solutions (electrical machine and storage systems) such as in all-electric ships [9,34–36]. Also, vessels can be connected to an onshore power supply during berthing, but some technical challenges exist, related to the power supply, the compatibility between onshore and vessel power systems, and demand management [9,12–14,20,25,37,38]. Furthermore, the electrical vessels are sometimes considered as potential actors to provide load and ancillary support during berthing (compensation of power fluctuations in the electrical grid, stability management, voltage and frequency regulation, etc.) [39];
- **The harbor changes required to meet the needs of the forthcoming years:** increasing maritime exchanges and maritime traffic, extension of harbor areas, development of electrical transport (vehicles, boats), etc. [27,32,37]. The existing harbor grids are often undersized to be able to meet the future energetic needs. The development of multi-energy harbor grids has also been investigated [40]. Moreover, the requirement for a peak demand reduction is discussed in several publications. For example, several peak shaving solutions are investigated for port cranes [41–43] and for reefer containers [44–46]. These loads represent approximately 80% of the annual electrical energy demanded in seaports [47];
- **The harvesting and use of fatal energy sources that exist in harbor areas**, but are rarely exploited: renewable energy sources such as solar photovoltaic energy or wind energy [30,32,33,37,40,48],

the kinetic energy of harbor equipment (quay cranes [49,50] and gantry cranes [21,28,42,51,52]), or even the energy stored in electric cars or boats [14,15];

- **The need for an adapted energy management system and the related policy**, taking into account the diversity of loads, the power supply reliability and costs [23,29,32,38,53]. A technical and economic compromise must be found between electricity generation from local sources and its purchase from the main grid [29,30,40]. Some research has studied the feasibility of demand-side management (DSM) in harbors, but the diversity of loads (reefer containers, quay cranes, vessels, etc.) involves the definition of adapted strategies [29,40,54–56].

Thus, the motivation for the development of microgrids in harbor areas covers a wide diversity of facilities, such as sources, storage solutions, and loads. The possible components of a microgrid in harbor areas are analyzed in the next section, according to the articles that exist in the literature.

3. Elements of a Harbor Microgrid

Publications dealing with the design, sizing, and energy management of a harbor microgrid consider different kinds of power generation sources, and some storage solutions. Furthermore, they take a wide range of loads into account. These publications are summarized in Table 1 according to the elements considered and sizing and energy management aspects. Based on this survey, the following sub-sections propose a summary of the main elements which can be integrated into a harbor microgrid, according to the microgrid designs proposed in the reviewed publications.

Table 1. Summary of the publications dealing with the energy management and the sizing of microgrids in harbor areas.

| Ref. (year) | Harbor/Loads | RES | ESS | Cold-Ironing | Energy Management Aspects | Design and Sizing Aspects |
|----------------|---|-----------------------------|--|----------------------------------|---|--|
| [48] (2012) | Bayonne Tarnos (France) Cranes, warehouses, lighting (E = 96 MWh/year, P _{max} = 126.6 kW) | PV (150 kW) WT (50 kW) | Redox battery (800 kWh) | No | Analysis of the dynamic behavior during the transients (fluctuations of the RES power) and the effects on the requested power from the cranes | Sizing of RES according to renewable energy resources availability and local needs |
| [27] (2016) | Long Beach (USA) Container terminal (E = 150–200 MWh/y, P _{max} = 140 MW) | PV, WT | No | Cargos | Power supply of critical loads in emergency situations (service continuity) | Comparison of microgrid architecture (radial and open-loop) and the placement of the power generation systems allowing service continuity to be ensured |
| [33] (2017) | Mytilene (Greece) Vessels cold-ironing (E = 22 MWh/day, P _{max} = 900 kW) | PV (5 MW) WT (6 MW) | No | Ships, tankers, bulk carriers | - Surplus of renewable power generation: fed into the island grid for the power supply of others loads, without storage solution. - In case of low-RES power: the main grid provides the energy required for cold-ironing | - Sizing of PV and WT in order to cover the power demand of vessels at berth - Pollution reduction thanks to shore-to-ship: 63% for PM and 77% for CO ₂ |
| [20] (2017) | Vessels cold-ironing (P _{max} = 2 MW) | PV (1 MW) WT (3 MW) | Batteries | Vessels | Batteries are charged in the harbor, then moved into the vessel during the berth (exchange with the onboard discharged batteries) | Design allowing the supply of the vessels at berth and the charge of the vessel's batteries at the harbor (exchange during the berth) |
| [30] (2018) | Copenhagen (Denmark) Ship cold-ironing (E = 38 MWh/day, P _{max} = 5.2 MW) | PV (200 kW) WT (4.95 MW) | Lead-acid batteries (465 MWh) | Ships | The RES power is used for cold-ironing, then battery charging and if an excess exists, it is sold to the main grid. | Optimization of the quantities of PV, WT, and batteries minimizing the life cycle cost Constraint: available area for PV |
| [28] (2018) | Long Beach (USA) Quay cranes (P _{max} = 5.5 MW) | No | Flywheel | No | - DSM: group of 10 quay cranes - Minimization of the peak power of a quay cranes group (thus the purchased electricity) thanks to the coordination between cranes operation (ex: one crane is in hoisting when one is in lowering), and the use of a flywheel to store regenerative energy from the cranes | Choice of flywheel: fast response and high specific power, adapted for the severe power fluctuations of quay cranes |
| [32] (2019) | Sardinia (Italy) Commercial and tourist ports | PV, WT | Batteries and supercapacitors in boats | Electric boats | - DSM: shops, offices, industrials loads, EV, EB. - The EMS is based on a distributed control, with a multi-agents system in order to control the distributed sources and the active customers (EV, EB, flexible loads). | The EB and EV are used in bidirectional way: as a customer during batteries charging, as a distributed source during discharge on the grid with the possibility to provide ancillary services. |
| [35] (2019) | Vessel batteries charging and cold-ironing (P _{max} = 5 MW) | No | Batteries (6 MWh) | Ships (electric and hybrid) | Batteries of vessels can be charged either directly on the vessel during the berth, or onshore to be exchanged with the onboard discharged batteries. | Comparison of the architectures for the vessels' batteries charging, considering fast or slow charging configurations |

Table 1. Cont.

| Ref. (year) | Harbor/Loads | RES | ESS | Cold-Ironing | Energy Management Aspects | Design and Sizing Aspects |
|----------------|--|---|---------------------------------------|---|--|--|
| [23] (2019) | Kyllini (Greece) Vessels cold-ironing, lighting, quay cranes, reefers ($P_{\max} = 18$ MW) | PV, WT | Batteries (12 MWh) | Ships | <ul style="list-style-type: none"> - DSM: reefer containers. - Optimization of the reefer containers operation by minimizing the costs (purchased electricity), considering the internal temperature evolution. - Optimization of the cold-ironing operation by minimizing the costs and considering an upper limit for the pollution emitted by the auxiliary engines. | <p>In addition to the vessels cold-ironing by an onshore power supply, the auxiliary generators of the vessels can operate during the berth, but a limit related to the emitted pollution is set.</p> <p>Batteries can be used for the peak shaving of the quay cranes load power.</p> |
| [38] (2019) | Container seaport in Southern China ($P_{\max} = 10$ MW) | WT (until 8.5 MW) | Batteries (until 15 MWh) | Containers ships | <p>Minimization of the operation cost, considering several constraints: power balance, storage capacity limitations and emitted pollution (60,000 tons of CO_2/y). The loads are supplied in priority by wind turbines, then if necessary by batteries and finally conventional sources of the main grid.</p> | <p>Sizing of wind turbines and storage capacity allowing the load power to be met at each time, considering a minimization of the investment costs (wind turbines, storage and on-shore power supply).</p> |
| [37] (2019) | Cartagena (Spain) Vessels cold-ironing ($E = 314$ MWh/day, $P_{\max} = 13.1$ MW) | PV (until 9.7 MW) WT (onshore: 36.3 MW, offshore: 16 MW) | No | LNG and oil tankers, container ships, bulk-carrier ships and cruise ships | <p>The cold-ironing of vessels from an onshore power supply and the use of RES could reduce the CO_2 emission of 10,000 tons/year, thanks to stopping the auxiliary engines of the vessels at berth.</p> | <ul style="list-style-type: none"> - The sizing of the onshore power supply and the RES must be sufficient to cover the needs of different kinds of vessels: LNG tankers, oil tankers, container ships, bulk-carrier ships and cruise ships. - The number of calls and the time spent at berth must be taken into account. - The available area is considered for the sizing of PV. |
| [54] (2019) | Commercial harbor Reefers and vessels cold-ironing ($P_{\max} = 30$ MW) | WT (20 MW) | No | Ships | <ul style="list-style-type: none"> - DSM: Reefer containers, shore-to-ship power supplies. - Objective: Minimize the operation cost, the emission of pollutants and the wind power fluctuations. - Fuzzy logic is used for the control of reefer containers. | <p>A real-time DSM system is proposed, using multi-agents system (reefer containers, ships at berth, wind turbines, port manager). Thus, communications lines are required between agents.</p> |
| [29] (2020) | Barbours Cut terminal, Houston (USA) Container terminal ($P_{\max} = 20$ MW) | PV, WT | Yes (no specific solution is defined) | Container ships | <ul style="list-style-type: none"> - DSM: critical loads, high priority loads, low priority loads - A multi-objective optimization is done according to several criteria: unmet demanded energy by taking into account the loads priority, use of RES, emitted pollution and power outages. - Constraints: Operation cost (purchase and revenue of electricity) lower than available budget, power balance, power limits, storage's state of charge limits, load curtailment. | <ul style="list-style-type: none"> - Sizing of the dispatchable sources, non-dispatchable sources and storage capacity by minimizing investment costs. - Constraint: load demand satisfaction. |

Table 1. Cont.

| Ref. (year) | Harbor/Loads | RES | ESS | Cold-Ironing | Energy Management Aspects | Design and Sizing Aspects |
|----------------|---|--------------------------|--------------------------------|---|--|--|
| [34] (2020) | Aland Islands (Finland) Electric ferries charging and cold-ironing | PV (33 MW) WT (30 MW) | Lithium-ion batteries (35 MWh) | Electric ferries | <ul style="list-style-type: none"> - Batteries are used to store the energy generated by RES, to be used later for the supply of electric ferries during berthing - Batteries must be located carefully in the meshed grid to avoid line congestion | <ul style="list-style-type: none"> - Sizing and allocation of the onshore batteries in an archipelago, according to the battery charging needs of the electric ferries in many ports and a significant integration of RES in 2030. - Constraints: Lines congestion, battery power and capacity limits. - The optimization of the batteries capacity sizing allows the expansion of grid transmission lines to be avoided. |
| [40] (2020) | Seaport in China Loads: quay cranes, vessels cold-ironing, onshore electrical, cooling and heating loads ($P_{\max} = 80$ MW) | WT (23 MW) | Gas | Bulk ships, containers and cruise ships | <ul style="list-style-type: none"> - DSM: Transferable, shiftable and curtailable loads - Optimization of the operation costs by minimizing costs related to: investment, purchase of electricity and gas, maintenance, DSM application and wind energy curtailment. - The cheapest configuration is when DSM and energy hub interconnection are considered | Design of a multi-energies hub in a harbor area considering electrical and natural gas networks and several systems: CCHP unit, Power-to-Gas unit, air conditioning, gas boiler and gas storage solution. |

CCHP: Combined Cooling Heating and Power unit; CO₂: carbon dioxide; DSM: Demand-Side Management; EB: Electrical Boat; EMS: Energy Management System; ESS: Energy Storage System; EV: Electrical Vehicle; DSM: Demand-Side Management; PM: Particulate Matter; PSO: Particle Swarm Optimization; PV: solar photovoltaic panels; RES: Renewable Energy Source; WT: Wind Turbine.

3.1. Electrical Energy Generation

Electricity can be generated in a harbor microgrid thanks to different sources:

- **Main grid:** the harbor microgrid is connected to the national main grid, where electricity is mostly generated by conventional energy sources (thermal, nuclear, etc.). The purchase of electricity on the main grid is sometimes limited thanks to an optimized energy management system to minimize the operating cost [29,30,40]. Moreover, the power limits of transmission lines must be taken into account to prevent electrical network congestion [29]. However, the purchase of electricity from the main grid can involve environmental issues, since the electricity can be generated using fossil fuels.
- **Use of local energy sources.** Electricity can be generated in the harbor area thanks to:
 - **Renewable energy sources:** the most frequently considered renewable energy sources are solar photovoltaic panels and wind turbines [30,32,33,37,40,48,57], as these present an advanced technology readiness level. The installed power amounts to several megawatts. Although harbors are located in coastal areas, the use of marine renewable energies such as tidal energy, wave energy, osmotic energy or ocean thermal energy are not considered, due to their low technology readiness level [14,17]. Nevertheless, several wave energy pilot projects are cited in [14], for the ports of Naples [58] and Civitavecchia [59]. It can be noted that harbor breakwaters may be suitable for the installation of wave energy converters [60]. Also, some alternative renewable energy sources are not considered in publications dealing with the sizing and management of harbor microgrids, but they can be found in several industrial developments. For example, a geothermal plant (Thassalia) was built in 2016 in Marseilles [61,62]. The harvested energy from the Mediterranean Sea was then used for heating and cooling. Also, biomass projects have been described for several harbors (Rotterdam, (Netherlands), Koper (Slovenia) [14]), considering different materials (wood pellets, vegetables, cereals, etc.) and different uses (heating, hot water production, biofuels and biogas production, etc.).
 - **Energy harvested from harbor systems:** several publications deal with harvestable energy from quay cranes [23,49,50] and gantry cranes [21,28,42,51,52,63]. When a crane lifts a container down, the potential energy of the container can be transformed into electrical energy through an electrical machine (regenerative braking) [49]. To prevent this energy from being dissipated in resistor banks, the harvested energy can be fed back to the microgrid or to the main grid [23]. Otherwise, this energy can be stored, for example in flywheels [28,42,49,50], supercapacitors [41,42], or batteries [23,64,65]. Flywheels are often considered as they present a fast response time (several milliseconds), a high energy density and a long lifetime [28,42]. A flywheel can be used for one [51] or several cranes [28,52]. Several industrial projects integrating flywheels in harbor cranes have been developed in recent years: the Konecranes Noell RTG gantry crane made by Konecranes [66], the PowerStore flywheel developed by ABB in Kodiak seaport (Kodiakin, AK, USA) [67], and the ProwESS system developed by Cress Systems, installed in Felixstowe (Darlington, UK) [68].

The electrical energy generated by local sources is often used for the supply of local loads. This energy can also be fed to the electrical main grid or stored in storage solutions. However, the energy generated can be used under other energy vectors [14,15]:

- **Gas:** The energy can be transformed into hydrogen or LNG, to be used in land or sea transport;
- **Heat:** The harvested energy can be used to heat buildings or water;
- **Biofuels:** These can be produced from renewable energy sources such as biomass, as for example in Rotterdam harbor where the harbor wastes have been used as a renewable energy source for the production of biodiesel and bio-ethanol [69].

3.2. Storage Solutions

As the energy generated from local sources does not always correspond to that demanded by loads at the requested time, some storage solutions can be integrated that allow energy to be used later, acting as an energy buffer. Several storage systems have been considered in reviewed papers:

- **Batteries:** These are the most widely-used storage solutions, with several battery technologies: lithium-ion [34,64], lead-acid [30], and redox-flow [48]. Due to their high energy density, they can provide several hours of electrical energy, for example when the power generated by the renewable energy source is low or when the purchase cost of electricity is high [23,30,34,38]. Batteries can be placed in harbors to supply onshore loads and ships at berth [20,23,30,38,48]. Also, some publications describe the investigation of the exchange of charged batteries at the seaport with onboard discharged batteries during berthing, to limit shore-to-ship charging requirements [20,35]. Furthermore, onboard batteries can be used during berthing as an electrical power supply for onshore loads and they could provide ancillary services (boat-to-grid concept, also called B2G) [32,36,39]. Also, the use of batteries on a larger geographical scale can be considered. In [34], J. Kumar et al. have investigated the sizing and location of lithium-ion batteries in several harbors of the archipelago of the Åland Islands, allowing the expansion of transmission lines to be avoided and peak load demand to be reduced.
- **Flywheels:** These are used in quay cranes and gantry cranes, to store the energy generated when the container is lowered [28,41,42], as described in the previous section. Due to their high power density, flywheels can absorb the crane peak load power. Moreover, the stored energy can be used later as a peak shaving solution during lift up operations [42]. This allows the purchase of electricity to be reduced.
- **Supercapacitors:** This storage solution is considered in boats [10,11,32] or in harbor cranes [15,41,42]. Their role is very similar to flywheels. They are used to compensate the steepest power fluctuations and to reduce the power peak, allowing the energy consumption cost to be reduced.

3.3. Demand

A wide range of load power values can be seen in existing publications, from several megawatts to 100 MW. The load power of a harbor area depends on the facilities and activities of the seaport: the kind of terminal (reefer containers, oil, gas, containers, passengers, etc.), the size of warehouses, the presence of fishing activities, facilities for the electrical power supply of berthed vessels, the presence of quay cranes, etc. Thus, the loads of a harbor area can be classified into the following categories [15,16,47,70]:

- **Harbor facilities:** these depend on the activities of the harbor. The main facilities in terms of energy demanded are the quay cranes used for the loading and unloading of cargos at the berth, the gantry cranes used to stack containers (rail-mounted gantry cranes and rubber-tired gantry cranes), and the refrigeration of the reefer containers. These loads represent 80% of the annual energy demand of a seaport [47]. In addition, the refrigeration and air conditioning for fishing activities can represent significant energy consumption [57].
- **Shore-to-ship facilities:** the energy demanded depends on the kind of vessel (cargo, oil tanker, reefer cargo, passenger vessel, etc. [71,72]), the onboard systems operating during berthing and the presence of people onboard.
- **Harbor area buildings:** warehouses, technical buildings, industries, port authorities' buildings, etc.
- **Charging of batteries** (electrical vehicles and boats).
- **Lighting;**
- **Residential loads:** depending on the city and the harbor area, residential loads can be taken into account for the development of the harbor microgrid [57].

Moreover, the power demanded by a harbor fluctuates over the year, depending on maritime traffic (quantity and kinds of vessels, time spent at berth [37]), the quantity and weight of the containers,

the air temperature influencing the power required for the container cooling, etc. [15,73]. Moreover, the electrical energy demanded in harbor areas is expected to change in forthcoming years, due to the electrification and decarbonization of some systems, the electrical power supply of berthed vessels, the increase of maritime exchanges, etc. [15,32].

3.4. Energy Management System

From the review presented in the previous sections, an overview of the possible facilities in a harbor microgrid is shown in Figure 2. Amongst the wide variety of systems that can be used, some of them present a stochastic behavior, such as the power generation from renewable energy and the power demand of some harbor loads (berthed vessels, cranes).

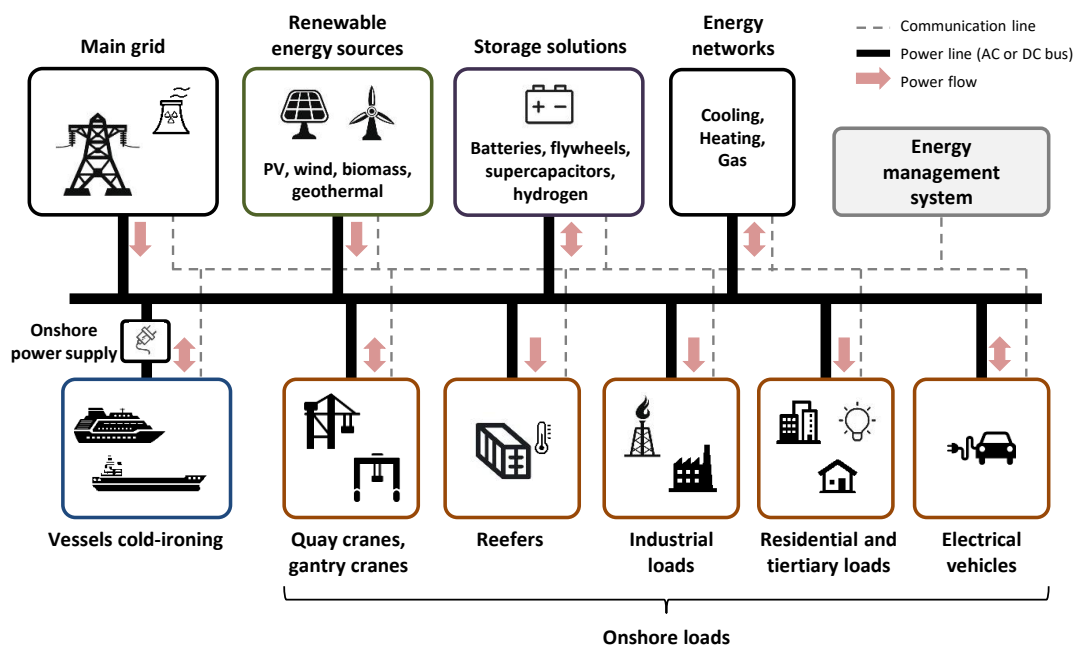


Figure 2. Overview of possible harbor microgrid facilities.

Service continuity must be ensured for critical loads (for example, reefer containers and quay cranes). Thus, a smart energy management system must be implemented, so as to monitor and control the sources, storage solutions and loads (Figure 2). The energy management system aims to determine the power setpoint of each facility of the harbor microgrid thanks to measurements [74]. It also aims to reduce the energy consumption by implementing energy efficiency measures and optimized energy management strategies [75]. A forecast of the power generation and of the load demand can improve the management of the storage solutions [74]. Thus, a real-time monitoring and control system including measurement devices, communication lines and control devices must be implemented [75,76]. Smart-meters and sensors can be used to monitor the power demand of harbor loads [77,78]. Also, a shared database can also be considered to gather the different measurements [79].

The changes required to allow the pollution and reliability regulations to be met imply an optimization of microgrid design and sizing, to avoid high investments and operating costs. Thus, the next section proposes a review of the energy management and sizing of harbor microgrids.

4. Sizing and Energy Management of Harbor Microgrids

The design, sizing, and energy management of harbor microgrids have been increasingly considered in recent years, to foster their development and to give answers to new environmental and technical regulations. Several aspects must be considered, related to cost, pollution, and reliability.

The following sub-sections describe the criteria and the methods used in existing publications for the sizing and energy management of harbor microgrids, according to the review proposed in Table 1.

4.1. Sizing Aspects

To determine the relevant sizing of microgrid elements, it is necessary to know the power demand of the loads that must be supplied by the sources, and the storage solutions. For example, the existing publications dealing with sizing aspects have considered many kinds of load profiles for the sizing of a harbor microgrid: vessel cold-ironing [20,30,33], container terminals [27,29,38], harbor cranes [28,48], or even several harbors [34]. Different evaluation criteria are used for the sizing of harbor microgrids:

- **Economical:** Sizing can be done by minimizing the total life cycle cost, including the different kinds of costs met during the exploitation of the project: investment, operation and maintenance and sometimes the replacement of some elements such as storage solutions [30,40]. However, some studies only considered investment costs. For example, the sizing optimization proposed by W. Wang et al. in [38] is based on the minimization of the investment costs related to wind turbines, storage solutions, and cold-ironing facilities. In [29], the investment costs of the dispatchable and non-dispatchable units, as well as of storage, is minimized.
- **Pollution:** Some studies proposed an optimization of sizing, considering a minimization of the pollution emitted by vessels (auxiliary turbines) or by power plants in the main grid [33,37]. This pollution can be reduced by using renewable energy sources on the land, sized according to the energy needs of berthed vessels [33].
- **Reliability:** Sizing of the microgrid must allow critical loads to be supplied, for example reefer containers or quay cranes for which a power supply failure can lead to serious technical and financial consequences. To ensure service continuity, a redundancy can be integrated into the design of the microgrid, for example by adding some interconnections between several parts of the microgrid [27] or between several harbors [34]. This is called a meshed network topology. Moreover, grid line congestion [34] and the operating power limits of the microgrid elements [40] must be taken into account to avoid blackout.
- **Geographical:** The area available for the installation of new electrical facilities in seaports can be limited, as many buildings and facilities are pre-existing. For example, the area available in the harbor for the installation of solar photovoltaic panels is considered in some sizing studies [30,37]. Also, the interconnection with other grids (main grid or other seaports) can be considered to improve reliability. For example, the sizing of battery capacities and their arrangement in an archipelago of islands with multiple harbors is investigated in [34], to improve the power supply reliability and to foster the integration of wind turbines and solar photovoltaic panels in forthcoming years.

The methods used for the sizing of harbor microgrids are listed in Table 2.

Table 2. Methods and tools used in articles dealing with the sizing of harbor microgrids.

| References | Method/Tool | Merits | Demerits |
|------------|----------------------------------|---|--|
| [34,38] | Iterative search | Easy implementation | Possible high computation time depending on the search space |
| [29] | Optimization/integer programming | The best solution can be obtained | High computation time |
| [30,48] | HOMER [80] | Simplicity of use with predefined sources and storage solutions | Difficulty to implement specific harbor components |

4.2. Energy Management Aspects

The diversity of the systems which can be integrated into a harbor microgrid, the stochastic nature of the power generation from renewable energy sources and the difficulty of assessing the demand of some

harbor loads can lead to a complex energy management system. Moreover, the management of these microgrids faces environmental, technical, and economic regulations and constraints. The literature survey shown in Table 1 demonstrates that several aspects are often considered for energy management:

- **Minimization of operating costs:** the operational planning of sources, storage solutions and loads is often done according to the purchase and selling costs [23,29,38,40,53,54]. To limit the amount of electricity purchased, the power generated by the sources in the harbor is used for local loads (self-consumption). If a surplus of energy exists, it is sold to the grid aggregator. The operating cost of certain systems is sometimes considered, as for example in [38] where the operating costs of the batteries and the wind turbines are minimized, while ensuring the load demand is met. Other kinds of costs can be considered: other energy sources (natural gas, fuel), demand-side management integration, and renewable energy source curtailment [40].
- **Minimization of pollution:** the pollutants emitted by a vessel's auxiliary engines or by the main grid's conventional energy sources can be considered [23,53,54,59].
- **Ensuring service continuity:** the reliability of the power supply must be considered so as to avoid blackout situations and to ensure the power supply of the most critical loads (reefer containers, cranes, etc.) [29,38].

These features are often considered simultaneously. For example, a multi-objective optimization is proposed by A. Molavi et al. in [29]. The power generated by the renewable energy sources, the grid power and the load power are optimized by minimizing several criteria: unmet load demand, pollution, curtailment of the power generated by renewable energy sources, and blackout. In [23], the power supply of the reefer containers and the quay cranes is managed according to the price of electricity and the batteries' state of charge, whilst the use of vessels' auxiliary engines is allowed under a maximal pollutant emission rate. The limitation of pollution is integrated as a constraint in [38]. Other constraints must be taken into account for the design of energy management rules: power balance, limits of the microgrid elements (storage state of charge and maximal powers), demand scheduling, dynamic behavior, etc. [29,38,40].

Moreover, some trends related to the management of specific elements of a harbor microgrid can be highlighted according the reviewed publications, as described below.

- **Energy management of the power generated by renewable energy sources:** this power is mainly used for local loads, to reduce the power from the main grid, and thus the cost of electricity purchased [29,34,38,48]. For example, the power generated by solar photovoltaic panels and wind turbines can be used for vessel cold-ironing [33,37], or for seaport onshore loads such as quay cranes or reefer containers [29,38]. The surplus of power generated can be fed into the main grid [33], or stored in storage solutions for later use in the case of a low level of generation from renewable energy sources. This latter reduces the amount of electricity purchased from the main grid [30,34,35,38]. In [40], the exceeding energy from wind turbines is converted into natural gas for cooling or heating purposes.
- **Energy management of quay cranes:** the energy harvested during lifting down of the container can be stored in flywheels [28,49,50], batteries [23,65], or supercapacitors [41]. This stored energy can be used later to supply power to the crane during the containers' hoisting. Thus, the peak load is reduced, as shown in [49] with a power reduction of 50% due to the use of a storage solution during hoisting. The stored energy can also be used to supply power to the crane when electricity is expensive [42,51,52]. The control of power converters of the crane and the flywheel was studied in [50], considering a DC bus. Optimization of the energy management of several cranes was proposed in [28]: the operational planning of quay cranes is optimized to reduce the power taken from the main grid, by using the regenerative power from a crane in lowering mode to supply power to another crane in hoisting mode. It could be noted that a single flywheel can be used for several quay cranes. In [51], F. Alasali et al. proposed predictive control for a gantry crane and a storage solution according to the cost of electricity, to limit the load peak.

- **Energy management of vessels during berthing:** a comparison of the possible solutions for charging a vessel's batteries was proposed by J. Kumar et al. in [35]. The first possibility is based on an onshore power supply connected to the vessel's batteries during berthing. The second solution is to charge several batteries in the harbor before the arrival of the vessel, then exchange these with the vessel's batteries during berthing. The second solution allows the installation of an onshore power supply to be avoided, and the time spent at berth to be reduced, since the batteries were charged in advance. However, it implies an adapted moving system, and a sufficient number of the same batteries in the harbor. The electrical energy used to charge the vessel's batteries and for cold-ironing can be generated by renewable energy sources (wind turbines and solar photovoltaic panels) [33,81] or supplied by the main grid [27]. Due to their embedded power sources (auxiliary engines and storage solutions), the vessels can provide ancillary services to the main grid during berthing, such as frequency and voltage regulation, power quality, load levelling, etc. [32,36,39]. This innovative concept is called boat-to-grid (B2G) [32] or ferry-to-grid [36], similarly to the existing concept for well-known vehicle-to-grid (V2G). The berth allocation of the vessels can also be taken into account in the energy management system, so as to minimize the pollutants emission and meet the load requirements of the vessels, according to the arriving vessels [82]. Moreover, a moving platform can be considered for the power supply of berthed vessels. The project presented in [83] is based on a hydrogen fuel cell placed on a floating platform, allowing the hydrogen to be converted into electricity. As the power supply system can move according to the vessel position in the harbor, the berth allocation of the vessels is simplified in comparison to a stationary power supply.
- **Demand side management (DSM):** although it is difficult to predict the loads of a harbor due to their stochastic nature [84], several publications have described the investigation of the application of DSM in harbor microgrids. The main loads considered were cold-ironing of the vessels [32,35,54], reefer containers [23,54,55,85], cranes [28], and electric vehicles [56,85]. For example, the operation of the reefer containers can be planned according to the cost of electricity. Thus, the electricity bill is minimized, as described in [23]. In [54], the operation of the reefer containers and the cold-ironing of the boats was scheduled, to minimize several criteria. These included operating costs (purchase of electricity and fuel for auxiliary engines of the boats), pollution emitted by auxiliary engines and wind turbine power fluctuations. Several authors also considered the DSM application for tertiary and residential loads in harbor areas [29,32,40]. In [29], the loads were separated into three levels: critical loads for which no DSM action was possible, high priority loads (quay cranes or reefer containers), and low priority loads (buildings). The power profile of some loads can be modulated as proposed by T. Song et al. [40], allowing the use of the energy generated by wind turbines to be maximized and operating costs to be reduced, as less electricity is purchased from the main grid. It can be noted that DSM application has also been studied for coastal areas, such as in [86] with the management of thermal domestic loads for the case of an island microgrid.

Thus, several differences can be highlighted between the energy management of a harbor microgrid and that of classical microgrids in urban areas [87,88]:

- The topology of the microgrid can change frequently if the boat-to-grid concept is considered (the berthed vessels can operate as a load or a source when they are connected to the onshore grid) [9];
- Logistic aspects must be taken into account, such as the berth allocation or the quay crane operation, which depend on the human activities [9];
- Electrical energy can be generated from industrial facilities (harbor cranes, ships at berth) for which the behavior depends on industrial activities;

- The islanded operating mode of harbor microgrids is less often considered than in classical microgrids due to the difficulty to meet the harbor load demand with only local sources. The purchase of electricity from the main grid is often considered.

The main methods used for the energy management of harbor microgrids are given in Table 3, according to the reviewed articles.

Table 3. Methods and tools used in articles dealing with energy management of harbor microgrids

| References | Method/Tool | Merits | Demerits |
|------------|--|---|--|
| [54] | Fuzzy-logic based rules | Computation time and uncertainty management | Low accuracy |
| [28] | Optimization/meta-heuristics tools (particle swarm optimization) | Best solution is found according to the objective function | Convergence and computation time |
| [29,40] | Optimization/ linear programming | Accuracy of the solution | High computation time |
| [35] | Dynamic analysis/PSCAD [89] | Check the stability of the system during transient | High computation time |
| [30,48] | HOMER [80] | Optimal solution is obtained according to cost minimization and load satisfaction | Difficulty to implement specific harbor components |

5. Discussion and Examples of Industrial Projects

From the literature survey presented in the previous sections, a synthesis of the main aspects considered for the design, sizing, and management of the microgrids in harbor areas is proposed in Figure 3. Four categories of criteria can be distinguished: reliability, economy, operation, and environment.

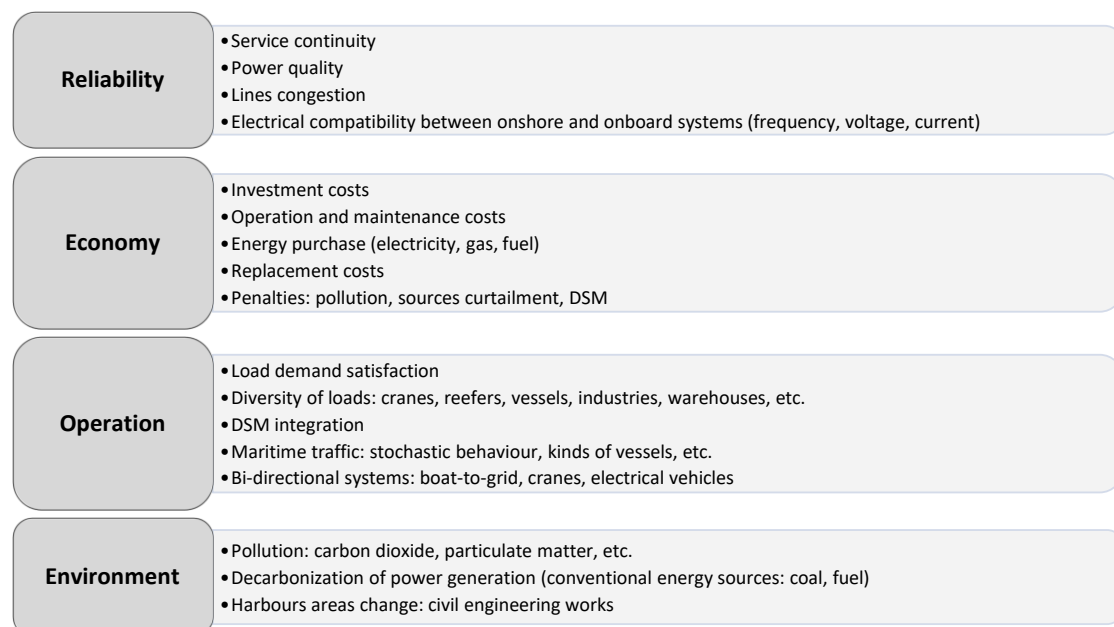


Figure 3. Summary of the aspects needing to be considered for the design, sizing, and energy management of harbor microgrids.

5.1. Innovative Concepts

Several innovative concepts can be highlighted due to the review proposed in the present article. This allows harbor microgrids to be distinguished from classical microgrids according to several points:

- Energy harvesting from harbor facilities: electrical energy can be generated locally due to lowering the container with quay cranes and gantry cranes, which add supplementary energy sources to the renewable and conventional energy sources [21,49];
- Boat-to-grid concept: the connection of the vessels to the onshore grid during berthing can supply ancillary services, by using onboard batteries or auxiliary engines [32,36,39];
- DSM with industrial loads: a few loads in a harbor area can be used in a DSM program to bring a degree of freedom for the energy management of the microgrid, such as reefer containers, quay cranes, cold-ironing of vessels, etc. [23,40,54].

5.2. Examples of Microgrid Implementation in Harbors

Over recent years, an increasing number of seaports have started energy efficiency programs [15]. In some of these harbor areas, a microgrid has been set up or is expected for the near future, with the installation of some facilities described in previous sections. An overview of the microgrid projects in harbor areas is presented in Table 4, demonstrating the main elements, and some key points. It should be noted that most seaports are located in Europe and the USA, and that these correspond to the main seaports for maritime exchanges worldwide. The main renewable energy sources are solar photovoltaic and wind energies, whilst batteries are sometimes used. Cold-ironing is already implemented in several major harbors in Europe and the USA, mostly for cruise and cargo ships with onshore power supplies of several megawatts [13]. Some USA harbors have also instigated a DSM program in their energy policy.

While the energy efficiency and the development of microgrids in harbor areas are a recent topic, several harbors have obtained ISO certifications related to the energy management [14,15,90]:

- ISO 50001: this certification is related to the establishment, the implementation, the maintenance and the improvement of an energy management system, dealing with energy efficiency, energy use and energy consumption [91]. Several harbors get this certification: Hamburg (Germany), Antwerp (Belgium), Felixstowe (UK), Arica (Chile), Baltic container Terminal (Poland), Valencia (Spain), etc. [14,15].
- ISO 14001: this certification is related to the environmental management system, allowing the environmental performances to be improved and the environmental objectives to be met [75,92]. Many European harbors get this certification [93,94].

Moreover, as the energy management in seaports needs sometimes to take into account the air pollution and the security, the certifications ISO OHSAS 18001 and ISO 45001 can be considered. These certifications deal with the health and safety management [95]. Several harbors have obtained them: Rotterdam (Netherlands), San Pedro (Ivory Coast), Calais (France), etc.

Table 4. Examples of microgrid implementation in harbor areas.

| Harbor | Status/Year | Elements Considered | Comments | Ref. |
|----------------------------------|-------------|--|--|-------------|
| Stockholm Royal Seaport (Sweden) | Active | PV (548 kW, rooftop), geothermal, cold-ironing, electrical cars | The microgrid involves the seaport and the nearby residential neighborhood | [96,97] |
| Rotterdam (Netherlands) | Active | PV (3.5 MW, rooftop), WT (200 MW), biomass, lithium-ion batteries (10 MWh), cold-ironing | Onshore renewable energy sources are expected in the future (wind and floating solar panels). | [69,98–101] |
| Amsterdam (Netherlands) | Active | PV (4 MW), WT (100 MW), biomass, biofuel, hydrogen, cold-ironing | To limit the onshore area used, batteries can be placed on floating barges (project under development) | [102–104] |
| Antwerp (Belgium) | Active | PV (56 MW), WT (150 MW), biomass, cold-ironing | Other energy technologies used: hydro-turbine, solar thermal panels, hydrogen. | [105] |

Table 4. Cont.

| Harbor | Status/Year | Elements Considered | Comments | Ref. |
|----------------------------------|--------------------------------|---|--|-----------|
| Gothenburg (Sweden) | Active | PV, cold-ironing | Amongst the first ports to develop onshore power supply for vessels in Europe in the 2000s | [106] |
| Los Angeles (USA) Cargo terminal | Launched in 2016 | PV (1 MW, rooftop), lithium-ion batteries (2.6 MWh), harbor electrical vehicles, cold-ironing | Green Omni Terminal Demonstration Project Investment costs: \$27 million | [107] |
| Auckland (New Zealand) | Launched in 2018 | PV | DC bus microgrid, with integration of buildings and freight hubs | [108] |
| San Diego (USA) Cargo terminal | Launched in 2020 | PV (700 kW), batteries (2.5 MWh), DSM, electrical vehicles | Investment costs: \$9.3 million | [109–111] |
| Long Beach (USA) Cargo terminal | Commissioning expected in 2021 | PV (300 kW, solar carport), Batteries (670 kWh), Diesel generators (500 kW), electrical vehicles charging stations, DSM on harbor loads | Investment costs: \$7.1 million Stationary and mobile battery storage systems | [112,113] |

5.3. Barriers to the Development of Microgrids in Harbor Areas

Although an increasing number of publications dealing with harbor microgrids can be found in the literature, the projects effected in harbor areas are scarce, as several issues and barriers exist, seen from different points of view [15]:

- **Technical:**

- Compatibility between the harbor electrical power facilities and those in vessels, as the frequency and voltage levels can vary from country to country, involving the use of adapted power converters and transformers for cold-ironing facilities [37,114]. Transients during connection and disconnection of vessels to the onshore grid must also be supported by both onshore and onboard power systems [9]. Moreover, all harbors are still not well-equipped for cold-ironing of vessels, and some technical regulations must be followed, depending on the kind of vessels [72] and the voltage and power requirements [115–118].
- Limited area is available in the seaports for the installation of new facilities (solar photovoltaic panels or wind turbines, for example).
- Assessment of the load demand in the harbors expected for forthcoming years is difficult as it depends on maritime exchanges, technological evolution of the vessels, industrial activities, etc.

- **Microgrid management:**

- Management of the berthed vessels: the vessels connected to the onshore grid could provide ancillary services [32,39]. Thus, an adapted and specific energy policy must be defined with the designation of rules between the port authorities, the ship owner and the grid aggregator, for example for electricity invoicing [16]. Moreover, onboard battery charging is a key point, as it defines the duration at berth and the power requirements of the onshore power supply [35].
- Management of flexible loads: several loads can be integrated into a DSM program (reefer containers, cranes, cold-ironing of vessels, administrative buildings, etc.). However, the implementation of a DSM program can be difficult due to the stochastic nature of most of these loads, which depends on maritime traffic, the kind of berthed vessels, the weight of containers, etc. [54]. Thus, the design of DSM strategies must take into account the operational strategies of harbor activities (scheduling of berthed vessels, operation of cranes, etc.).

- **Economical:**

- The investment costs needed for the development of harbor areas can be high, making financial support difficult. High costs can be a barrier to the development of cold-ironing in small ports, due to the investment costs requested for the onshore power supply of many kinds of vessels [119]. Investment sharing between stakeholders must be studied as this can represent a barrier for the development of microgrids [13,14,16]. The public subsidies can also foster the development of harbor microgrids, for example for the shore-side power supply [120].
- A business model must be defined to set regulatory rules between the stakeholders (port authorities, ship owners, terminal operator, etc.) [16].
- Some incentive measures must be defined to foster the application of a DSM program.
- **Environmental:**
 - Pollution emitted during the recycling process of renewable energy sources and storage solutions [121].
 - The installation of renewable energy sources and energy storage systems requires sufficiently large available area, which is often limited in harbor areas.
 - Robustness of the microgrid facilities against weather conditions, as possible severe weathers conditions in harbor areas can occur, for example storms.
 - Management of air quality if the operation of vessels auxiliary engines is totally or partially allowed during the berth [5,33].

Thus, numerous challenges remain to obtain a widespread development of microgrids in harbor areas. An increasing number of projects are expected for forthcoming years.

6. Conclusions

The development of microgrids in harbor areas has been increasingly considered in recent years, in both academic and industrial studies. This is due to the necessary adaptation of harbors to meet recent environmental and technical regulations, such as the reduction of environmental pollution (diminution of the operation of the vessels' engines at berth) and evolution of the load demand (all-electric ships for example). The review presented in this article highlighted a wide diversity of possible elements for harbor microgrid: renewable energy sources (solar photovoltaic panels and wind turbines), storage solutions, energy harvesting from cranes, power supplies for cold-ironing, harbor loads (reefer containers, cranes, warehouses, lighting, etc.). As the electricity generation from some local sources (renewable energy sources and cranes in hoisting mode) is non-dispatchable, storage solutions must be integrated into the microgrid to allow the energy generated to be consumed later by harbor loads. Thus, an adapted energy management system must be implemented to allow the load demand of harbor facilities to be met at all times. In addition to the reliability aspects, the review presented here showed that pollution and operating costs are often taken into account in energy management strategies. Also, some harbor loads can be integrated in a DSM program to bring a degree of freedom to the management of the microgrid. Moreover, the sizing of sources and storage solutions must be optimized to minimize the investment costs and environmental pollution. However, some constraints must be considered for design and sizing, such as the available area, grid topology, power limits, etc.

Thus, the literature survey carried out for this article summarized the main aspects which must be taken into account for the design, sizing, and energy management of microgrids in harbor areas, due to a review of many research articles. Several benefits provided by the development of microgrids in harbor areas can be highlighted:

- The diminution of pollution due to the shutdown of vessels' auxiliary engines, by implementing cold-ironing solutions and using renewable energy sources [14,33];

- The reduction of electricity bills, since the electricity is generated locally by renewable energy sources or harbor systems [29];
- The reduction of investments for a regional grid due to the installation of sources in harbor areas [34].

Some industrial developments are generated in several harbors worldwide, but most only consider a few facilities: implementation of onshore power supplies for cold-ironing, installation of solar photovoltaic panels, use of a storage solution to harvest regenerative energy of cranes, etc. The development of microgrids in harbor areas remains rare due to many factors: high investment costs, complex energy management involving many stakeholders, difficulty to assess and forecast the load demand (load diversity, many kinds of vessels, stochastic nature, etc.), the need of an adapted energy policy, etc. These weaknesses offer several research perspectives in the coming years, so the development of microgrids in harbor areas should be fostered. The research perspectives include: management of the wide diversity of loads in a DSM program, investment and operating costs limitation, operating strategies at the scale of the harbor (for example, demand scheduling according to the availability of sources and storage), the management of multiple vessels cold-ironing, etc.

On the other hand, some solutions can already be implemented in forthcoming years thanks to the maturity of several systems and the projects developed worldwide (Table 4). For example, solar photovoltaic panels can be installed on the roofs of seaport warehouses and buildings. Also, some manufacturers also commercialize cranes with an integrated storage solution, such as flywheels, allowing the harvested energy during the lifting down of the container to be used [66–68]. Thus, the integration of renewable energy sources and electrified quay cranes to the harbor grid seems to be relevant in the forthcoming years due to their current maturity level, before the integration of shore-to-ship power supplies and DSM programmes. A smart energy management system must be implemented, and the ISO 50001 certification could be considered [91]. This certification involves a careful study of the energetic needs of the seaport, so as to correctly size the renewable energy sources and the storage solutions, allowing the objectives to be met. Several performance indicators can be considered: self-consumption rate, energy saving, etc. Moreover, an evaluation of the future needs must be done and the results must be considered in the action plan to determine strategic decisions.

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