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Review

A Review of the Conceptualization and Operational Management of Seaport Microgrids on the Shore and Seaside

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Abstract: Seaports are well known as the medium that has evolved into the central link between sea and land for complex marine activities. The growth in maritime logistics particularly necessitates a large volume of energy supply in order to maintain the operation of sea trade, resulting in an imbalance between generation and demand sides. Future projections for three major concerns show an increase in load demand, cost of operation, and environmental issues. In order to overcome these problems, integrating microgrids as an innovative technology in the seaport power system appears to be a vital strategy. It is believed that microgrids enhance seaport operation by providing sustainable, environmentally friendly, and cost-effective energy. Although microgrids are well established and widely used in a variety of operations on land, their incorporation into the seaport is still limited. The involvement of a variety of heavy loads such as all-electric ships, cranes, cold ironing, and buildings infrastructure renders it a complicated arrangement task in several aspects, which necessitates further research and leaves space for improvement. In this paper, an overview of the seaport microgrids in terms of their concepts and operation management is presented. It provides the perspectives for integrating the microgrid concept into a seaport from both shore side and seaside as a smart initiative for the green port's vision. Future research directions are discussed towards the development of a more efficient marine power system.

Keywords: cold ironing; electrification; operation management; renewable energy source; seaport microgrids; shipboard microgrid; maritime

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1. Introduction

Recent decades have witnessed the rapid expansion of the global economy. This development was motivated by an even faster escalation in international trade. Seaport plays a significant role in this economic liberalization as sea trading is in high demand due to its cheap prices and capability to support goods transportation at a large volume through cargo services. Currently, the marine transport network accounts for more than 90 percent of global trade, and according to the International Maritime Organization (IMO) annual report, it is predicted to be tripled by 2050 [1]. Seaports have become complex hubs due to the multifunctional operations that need to comply with various factors such as marine regulations, technologies, transportation, operational, and policy requirements. Hence, high investment is required to expand ports facilities and infrastructure and to enhance their operation management and maintenance in order to boost all marine operations.

The increasing number of ships, cranes, and trucks for port transportation requires high-energy consumption. Moreover, the size of ships has become much larger nowadays, with ships measuring hundreds of meters long and kilotons in terms of weight. All of these factors consequently result in a huge volume of fossil fuel burning in order to fulfill the entire load at the port. Overuse of energy always results in unbalance energy issues, which makes the energy system inefficient and prone to frequent power outages and thereby huge economic losses.

Research in developing more efficient power systems for port operations has attracted special interest in recent years. Incorporating renewable energy sources (RESs) and energy storage system (ESS) technologies through microgrid systems has been viewed as an essential route. By utilizing microgrids, power generation is not limited to the conventional fossil-based resources anymore, and the flexibility to integrate multiple RESs such as wind turbines (WTs), photovoltaic (PV) systems, biomass, ocean energy, hydrogen, and geothermal sources all contribute to sustainable energy when introduced efficiently. Deploying ESS at seaport will enhance better energy distribution by providing backup energy during emergencies and providing the capability of storing excess energy generation.

The promising benefits of microgrids to the marine sector can be categorized into four groups, namely energy efficiency, economic, environmental, and security benefits. However, the variation of heavy loads energy demand at the port both at the shore and seaside results in complex control for seaport microgrids. Although microgrids coordination is an undeniably established technology in land-based applications that currently provides tremendous economic and environmental benefits, there are still several issues that need to be addressed before incorporating them in maritime applications. Moreover, the literature in this field is far from conclusive. Many aspects need further exploration in order to ensure the optimal benefits of integrating the microgrid concept into seaports.

In this perspective, this paper presents an overview of the seaport microgrids concept and its operational measures for seaport applications on both shore and seaside (shipboard microgrid). Moreover, from a macro perspective to most co-occurrence research studies, VOSviewer visualization analysis is provided to illustrate the trending and probable future research directions of microgrid applications in the maritime sector.

The rest of this paper is organized as follows. Section 2 is dedicated to introducing the variation of load demand and current major issues at ports as well as energy evolution in seaports over time. In Section 3, the conceptualization of microgrids on shore and seaside is presented, while topology and operation management of the seaport microgrids are also discussed. In addition, a few constraints and potential aspects for further research investigation are highlighted in Section 4. Finally, the significant findings of the paper are summarized in Section 5.

2. Seaport

Seaports are well known as significant interfaces for both sea and land transportations, which is supported by their strategic geographical locations between the sea and land, as shown in Figure 1. Ports are among the largest parts of the industrial sector for economic and social development across the world. However, the growing demand for logistics globally increases the volume of sea traffic.

Port functions have aggressively changed along with global development compared with the conventional ports as shown in Figure 2, where the first generation of ports in the early 1960s only focused on the modes of transportation without any trading and commercial activities. It then experienced more advances in terms of technology, networking, international trading, and logistics. In the fifth generation, ports moved toward smart ports by employing automation, advanced technologies, hybrid and intelligent infrastructure, and efficient energy management systems.

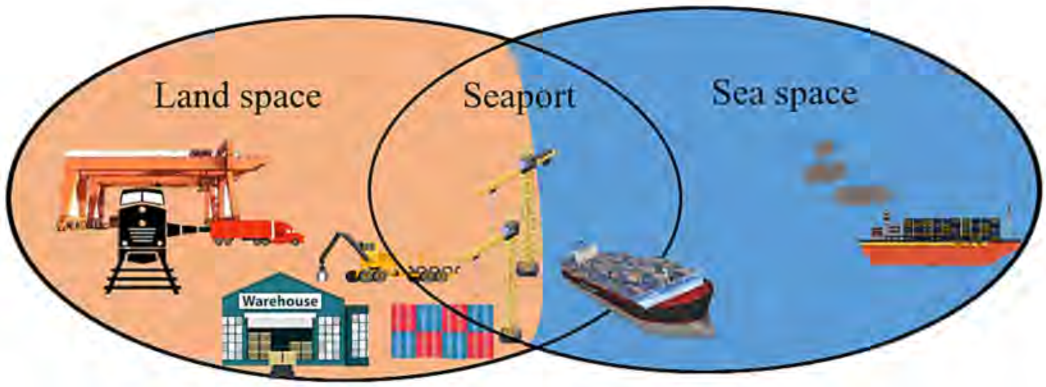


Figure 1. Seaport intersection between land and sea space [2].

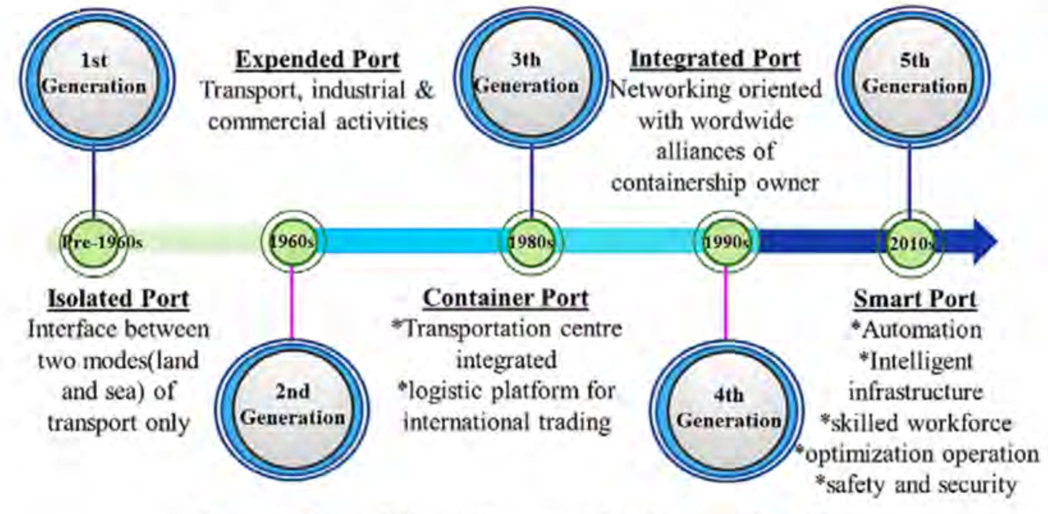


Figure 2. The evolution of the seaport functions over time [2–5].

2.1. Port Activities and Power Consumers

Port engagement with respect to energy can be classified into energy generation and power consumption mainly in the form of electricity and fuel. It is crucial to comprehend the load components and monitor energy-related activities taking place within the port before initiating any energy planning. The purpose is to analyze the amount of energy demand and ensure that there is enough power supply to prevent power shortages. However, load profile measures at seaports vary according to several factors such as the type of port and activities conducted at that particular port.

Seaports by definition can be viewed as centers of economic activities associated with any kind of arrival (tourist or goods), service of ships, and cargo [6]. The most common ports can be categorized into commercial/industrial ports [2], container terminal ports [7], and intermodal ports [8,9]. In another classification provided in [10], ports are classified into three types, such as local ports, national ports, and international ports. These classifications are based on the ports' characteristics, region of the port, the volume of loads it serves, vessel type, port's operation and services, the annual number of passengers, and the annual number of ships berthing in and out from the port. Different types of ports and their characteristics are summarized in Table 1.

Table 1. Classification of ports [10].

Port Type	Characteristics
Local port	Serves for local needs Limited space and capacity Small size No logistic activity handling Do not support cruise ships Boats, vessels, yachts, and small-sized ships < 500 passengers
National port	Serves country needs Medium-sized (larger than local port) Cover all ships type with small logistic and cruise activities Medium-sized ships < 2500 passengers, cargo (packages), and logistics (only trucks)
International port	Serves international needs Largest sized Provide huge logistic infrastructure Cruise ships > 2500 passengers, cargo, containerships, and RTG cranes

Geographically, a seaport is the point of interaction between land and sea, which involves two modes of transportation (water and road traffic) with different characteristics. From this perspective, the seaport area can be sorted into the seaside, shore side, and intermediate space. Each space is utilized for a different type of activity, transportation, and application, all of which have an impact on the amount of energy demand. Figure 3 illustrates the most common activities running in the seaport area and its load components.

Figure 3. Seaport activities and load components (abbreviations: rail mounted gantry (RMG), rubber tyred gantry (RTG), and ship to shore (STS)).

Loads on the shore-side: On the shore side, administrative buildings and a custom facility, as well as a warehouse for goods, are built. In this infrastructure, electricity is consumed mostly for lighting; Heating, Ventilation, and Air Conditioning (HVAC) system; and equipment [11]. Many factors influence the building's energy consumption, including weather conditions, building materials, occupant behavior, work durations, equipment, and electrical load used [12].

In terms of transportation, different land vehicles such as trucks, cranes, yard tractors, and trains are powered by diesel fuel, and electricity is needed for electric vehicle (EV) charging stations. Typically, diesel is used as the primary source for motor movement in the cranes. However, recent research studies on electrical cranes show a lot of interest in energy storage systems for storing potential energy regenerated from lowering and lifting cranes operations [13].

Loads on the seaside: The seaside is includes a marine vessel or any watercraft transportation voyages across the ocean that serves the purpose of carrying passengers or delivering cargo. Ships will make more voyages, consume more fuel, and increase the volume of water traffic as global trade expands. Normally heavy fuel oil (HFO) is consumed for big vessels and bulk carriers. General cargo vessels consume the most HFO, followed by oil tankers and cruise ships accounting for 66,000 t, 43,000 t, and 25,000 t of HFO annual consumption, respectively [14]. The spill of fossil-based marine fuel into the water and its combustion into the air can become a major threat to the environment [15]. Despite its undesired environmental impacts, HFO continues to be the preferred fuel of the maritime transport industry due to its relatively low cost, widely available resources, and the ability to suit engines that were originally designed for HFO [14].

In order to prevent heavy utilization of HFO and to be in line with port development, ship technology is embracing the electrification concept by implementing an Integrated Power System (IPS) and storage system known as All Electric Ship (AES) [16]. Energy usage for a vessel is hard to measure as it depends on numerous aspects such as the size of the vessel, onboard loads, vessel speed, sea waves, and weather conditions.

During berthing for transit or transferring goods, the auxiliary engines of the ships are kept operating in order to supply the energy for onboard loads [17]. To overcome continuous fossil fuel burning, cold-ironing facilities are provided at the intermediate area between the sea and shore side. Power requirement varies from 300 kW to 7 MW depending on the type of ships and berthing duration [18]. In addition to the onshore power supply, the port must accommodate shore charging facilities. Some of the vessels with storage components such as hybrid vessels and AES will need a charging station in the port area for recharging their batteries and supplying onboard loads.

Loads in the intermediate area: In this region, there are cold ironing, charging stations, and container terminal facilities. The container terminal is an important part of international logistics and requires a large amount of energy, both fuel and electricity [19], for loading and unloading cargo as well as the transshipping goods to the next mode of transportation [20]. Container terminals serve three primary functions: yard side, quayside, and landside [21]. Each side has its operation and transportation needs. Cold storage facilities among the terminal operation consume a lot of energy, as it is a temperature-controlled storage solution for perishable goods. The Port of Wilmington built a 101,000 square foot refrigerated warehouse to refrigerate food, pharmaceutical, floral, and other items that require maintaining specific temperatures for storage [22]. It allows distribution companies to deliver their goods locally, nationally, and globally in good conditions.

In the container terminal, there are various types of cranes in use, from ship to shore (STS)/quay cranes (QC) to automated guided vehicles (AGVs)/automated straddle carriers (ASCs), and, finally, rail-mounted gantry (RMG) cranes, before they are transferred into truck/trains [23]. Considering peak power demand, cranes need about 72% of total energy (STS cranes about 37%, ASC cranes 32%, and RMG around 3%) [24]. The breakdown of the cranes' power demand is shown in the pie chart of Figure 4.

From the appliances that are used and activities conducted within the marine port, it can be observed that the seaport sector has a large energy demand that makes the energy-handling problem a complex task. Hence, a reliable power system is required that can provide sufficient energy supply to all distribution loads. Any shortcoming in energy delivery will cause a big disruption to the seaport's operations.

Therefore, it is very important to distinguish between critical and non-priority loads so that the critical loads will receive priority during emergencies in order to obtain energy supplies [25]. Table 2 summarizes the findings regarding seaport-related services and their load.

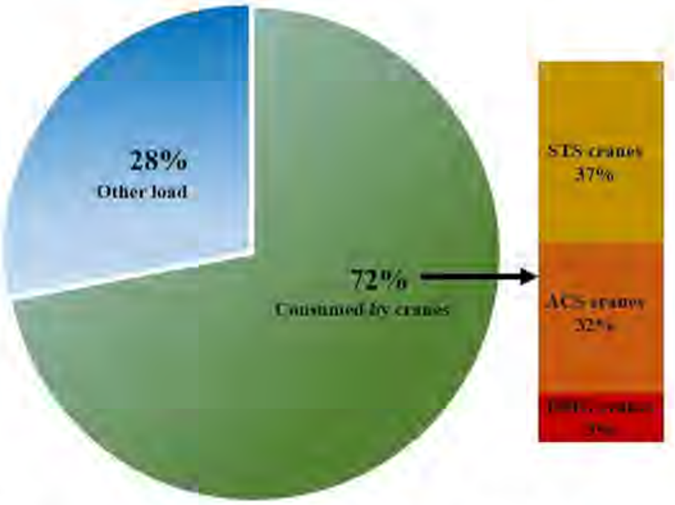


Figure 4. Breakdown of cranes power demand during demand peak intervals.

Table 2. Seaport activities and loads variation [2,26].

Seaport's Services	Load	Factor Influence Energy Consumption	Load Classifications	Form of Energy
Vessel	Passenger ships (cruise, ferry), container ships, electric ships, tugs, gliders, bunkers, boats, tankers, hovercraft, sailboats, submarines, yachts	Size of the ship, activity conduct on the ship, time of operation, weather, wave, speed	(1) Peak load (2) Critical load (3) Non-critical load (4) Variable load (5) Constant load	(1) Electricity (2) Fossil fuel
Goods handling	Cargo, container, quay, logistic, freight forwarder, customs warehouse, storage, security, loading-unloading	Number of cranes, amount of cargo, hours of operation		
Administration	Management and administrative building, planning, service solution, IT, monitoring	Type of electrical equipment, weather, building material, hours of operation, occupant behavior		
Transportation	Electric vehicles, cranes, trucks, yard tractors, trains	Number of transportation, hours of consumption		
Electric Facility	Cold ironing, charging station for electric vehicles	Time of berthing, number of ships per berthing, size, and ship's load		
Maintenance	Repair and maintenance	Type of the maintenance		

2.2. Port Critical Concerns and Green Maritime Policy

The urgent need for a more efficient maritime system demands a great effort to increase the performance of every subsystem linked to it by implementing an energy efficiency program. It is critical to identify the root of the problem and core issues in the port in order to achieve a good outcome from planning.

The European Sea Ports Organisation (ESPO) in their latest report (October 2020) highlighted the top ten priorities of the port sector from 1996 to 2020 [27]. Figure 5 shows the top three port issues from 2009 until 2020. As observed in this figure, most of the issues listed have remained the same while their relative positions have changed over time. However, air quality and energy consumption remained mostly the highest priorities. These data are important as it identifies the vital concerns that port managing sectors are working on.

According to the top three priority issues highlighted in Figure 5, air quality has persisted as number one from 2013 to 2020 followed by energy consumption. The problem arises from the fact that air quality, noise, port waste, and climate change are strongly related to environmental concerns. This indicates that environmental issues are big problems in the port sector and require immediate action. Without fast action, the emissions from maritime transportations are predicted to rise by 250% in 2050 from the amount released in 2012 [1]. Heavy utilization of fossil fuel in marine transportation and other areas contributes to serious air pollution from Carbon Dioxide (CO_2) and greenhouse gas (GHG) emissions. This is because the fossil sources encompass hazardous contents, which in burning it will emit chemical and dangerous gases such as particulate matter (PM); (CO_2); sulphur dioxide (SO^2); nitrogen oxides (NOx); and black carbon (BC) to the air [28]. Consequently, this emission results in acid rain and serious climate changes. It is also capable to reaching 400 km [29] of land and produces a negative effect on human health such as asthma, tuberculosis, impact on children's lung growth, cardiovascular disease, and lung cancer.

	2009	2013	2016	2017	2018	2019	2020
1	Noise	Air quality	Air quality	Air quality	Air quality	Air quality	Air quality
2	Air quality	Garbage/ Port waste	Energy consumption	Energy consumption	Energy consumption	Energy consumption	Climate change
3	Garbage/ Port waste	Energy consumption	Noise	Noise	Noise	Climate change	Energy efficiency

Figure 5. Top three issues in the port from 1996 to 2020 [27].

Meanwhile, ports' energy consumption has increased due to various reasons. Development and expanded port functionalities over time raise the energy demand from many facilities and loads with low and heavy consumption. Continuous heavy use of energy will cause fast energy resources depletion. The inequality between energy production and demand results in frequent unplanned power outages. Poor power quality, lack of energy monitoring, and old instruments are also among the factors that cause the high energy consumption problem resulting in additional energy ***costs*** in ports' daily operation. The need for improvement both in infrastructure and port power system will acquire a huge amount of investment. Lacking proper planning and a solid development framework will cause great losses. Based on these scenarios, three major issues related to seaports include energy, environment, and cost, as shown in Figure 6.

Figure 6. The three vital issues in the maritime sector.

Due to the serious environmental impacts caused by pollution from marine logistics, ports are moving toward a greener industry by implementing various alternatives. Particularly, in recent years, the arising awareness on environmental issues has made this target one of the compulsory goals in achieving high-energy efficiency levels. Authorities have formulated port policies consistently with tight regulation in order to ensure minimum GHG emissions. In this regard, the International Maritime Organization (IMO) in the latest regulation limits the sulfur content in fuel to 0.5% m/m, known as 'IMO 2020' [30]. The change in sulfur limitation from 2000 to 2020 is shown in Table 3. The five most important outcomes from IMO 2020 are as follows: (1) cleaner air, (2) higher quality fuel, (3) positive impact on human health, (4) ship operator role, and (5) changes for enforcement authorities.

Table 3. Change in fuel sulfur limit. Source: Marpol 2018, Marpol Annex VI.

Date	**Sulfur Limit in Fuel (% m/m)**	
	SO_x ECA	**Global**
2000	1.5	4.5
2010	1.0	
2012		3.5
2015	0.1	
2020		0.5

In line with the green port objective, the Port Authority of Genoa (GPA) is developing a plan integrating renewable energy in their marine sector known as the Port Energy Environmental Plan (PEEP). The ultimate goal of the PEEP is to reduce 20,000 t of CO_2 annually by utilizing 12 plug cold ironing facilities, wind turbines, and photovoltaic power stations with an overall investment of 60 million Euros [31].

In order to move towards a healthier environmental space, ports must plan and manage their operations and future potential expansion in a sustainable manner. Saeyeon Roh et al. [32] in their research stated that the majority of the existing literature's emphasis is on the environmental aspects for sustainable development, but they fail to clarify what factors influence this process. Several authors studied the causes that contribute towards air pollution and environmental damage from the operation of the harbors. Bunkering from the vessels generates the risk of oil spill with potentially disastrous impacts on the food chains of beaches [33]. Matishov and Selifonova [34] pointed out that the source of water resources damage comes from a high density of ship transportation via waterborne traffic. Meanwhile, Brigitte Behrends and Gerd Liebezeit [35] addressed that the two leading destructive factors generated by shipping movement are atmospheric and seawater contaminations. In an attempt to safeguard nature and waterways, new legislation for future growth of ports and their construction at both international and domestic levels are released from time to time, aiming to handle environmental issues based on strict standards for core ports' strategies. For instance, legislations in a few countries are listed in Table 4 below [33];

Table 4. List of legislations in a few countries.

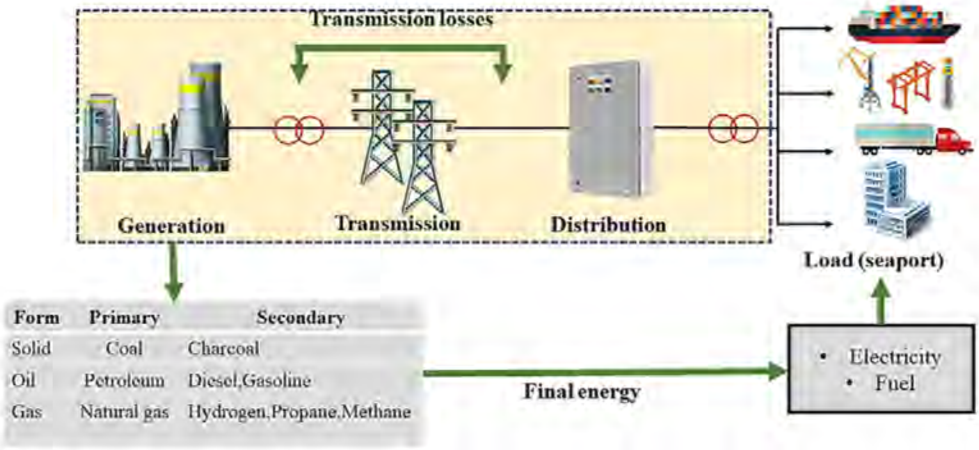
Country	**Legislation**
EU	Classification Societies—Regulation (EC) No 391/2009; Ship-Source Pollution—Directive 2000/59/EC; Marine Equipment—Directive 96/98/EC and Directive 2014/90/EU
Australia	Environmental Protection Act 1986 (WA)
New Zealand	Resource Management (Marine Pollution) Regulations
USA	Diesel Emission Reduction Act (DERA)
Singapore	Environmental Protection and Management Act (Cap.94A)

Without a doubt, all of these environmental legislations offer vast advantages in terms of health, clean air, economy, energy, and potential for new technology if they are properly considered in port planning. Nevertheless, the great challenge is that all the planning steps must be compatible with the rules, from the initial step of research and development, collecting real-time data, collaboration among the parties, implementing, monitoring, and analysis. All of these stages are time consuming and involve high capital investment where payback period analysis is necessary. Cost is one of the main drivers to run all strategic planning. Due to this risk, the relevant parties, especially the ports themselves, are reluctant to implement any environmental program.

2.3. Seaport Energy Revolution

2.3.1. Conventional System

In the beginning phases of the maritime system, there has been no concern for energy because it was solely utilized for shipping transportation. When the industrial revolution arrived, energy demand began to raise. Electricity and fuel are the two main forms of energy used in this sector. Depending on the availability and variation of the primary sources in a particular country, both electricity and fuel are produced from fossil-based sources (coal, oil, and natural gas). Electricity is not freely available in nature, so it must be produced by transforming primary energy to electricity through a process. Figure 7 displays the entire power station network, from generation to the seaport.



Form	Primary	Secondary
Solid	Coal	Charcoal
Oil	Petroleum	Diesel,Gasoline
Gas	Natural gas	Hydrogen,Propane,Methane

Figure 7. The overall framework of the conventional structure.

In the 1880s, coal was first used to generate energy and became a fundamental driver of steamships [36]. Coal is a combustible black rock that is formed over millions of years by the decay of land vegetation and generates energy under high pressure. Coal is convenient to use because it is easily combustible and cheap. Apart from electricity, another fundamental source of energy, particularly for maritime transportation, is fossil fuel, which contains hydrogen and carbon in its particles.

Previously, many vessels, particularly those with bunker fuel, used HFO to allow the ship's propeller or alternator to rotate. This can be accomplished by either burning fuel in the engine combustion chamber or producing steam in the boiler. Due to its relatively higher density and lower cost, HFO is a preferable marine fuel source. HFO is characterized by its heavy molecules containing long-chain hydrocarbons, density greater than 900 $\mathrm{kg/m^3}$ at 15 °C, and kinematic viscosity greater than 180 $\mathrm{mm^2/s}$ at 50 °C [37]. The HFO comes in three varieties, which are listed in Table 5.

Table 5. Three variants of HFO and their sulfur content [30].

No	Variant	Sulfur Content
1	High Sulfur Fuel Oil (HSFO)	3.5%
2	Low Sulfur Fuel Oil (LSFO)	1.0%
3	Ultra-Low Sulfur Fuel Oil (ULSO)	0.1%

Sulfur content is a key differentiator between these three types of HFO. However, from 1 January 2020, HFO can only be used by vessels equipped with exhaust gas cleaning systems (EGCS), and IMO has set new regulations banning vessels from using fuels that have sulfur substances above 0.5% [30]. Due to the tight prohibitions, HSFO and LSFO are no longer practical options for marine transport. The only choice to comply with this limit is ULSO, which has a sulfur content of 0.1%. Unfortunately, the desulfurization process of HFO requires very high costs and is not economical anymore.

Even though electricity and fuel are greatly used in the seaport sector since their early stages of development, due to the arising issues, there is a great interest in alternative solutions. This alternative includes considering electrification of vehicles, cold ironing systems, alternative fuels (i.e., LNG, biofuels, methanol, hydrogen, and low-sulfur fuels), and implementation of both renewable energy and energy storage by implementing microgrid power systems.

2.3.2. Ports and Ships Electrification

From the seaport perspective, electrification can be viewed as the replacement of fossil fuel-based energy with new advanced technologies through the use of electricity. Marine transportation contributes significantly to air pollution and climate change mainly for two reasons: (1) The port is the area where emission sources are least regulated and (2) high reliance on fossil fuels. With the increasing number of ships, the ports' energy management is required to provide sufficient power to supply the ship during berthing. Large ships have a power range between 1 MW and 6 MW [38]. While the main engines are normally switched off during berthing, the vessel's auxiliary engines are switched on to supply power to all loads inside the vessel such as lighting, ventilation, cooling, and other onboard equipment. A study on different types of vessels in Reference [18] shows that the average berthing time per vessel is between 21 and 52 h. Burning diesel oil during berthing for such a long time injects severe GHG emission.

In order to resolve this problem, shore-side electricity practice known as cold ironing is introduced to mitigate undesirable environmental impacts at seaports. Employment of this technique allows a ship to shut off its auxiliary engines when docking, and it receives electricity supplies from the shore to maintain the entire load in the ship. It provides substantial advantages by reducing the dependency on fossil fuels and lessening GHG emissions. The energy required for cold ironing can be supplied directly from the utility grid, RESs, and ESS. Alexander Innes and Jason Manios [39] in their article highlighted a few ports around the world that already utilized cold ironing. Despite the promising benefits of a cold ironing system, many ports, particularly small ports, do not install it due to a few constraints. In order to overcome this, alternative power sources are formed by using shipboard microgrid (SMG), where this method acts as mobile cold ironing facilities by sharing power from multiple ships in the port [16,40]. Another innovative solution with the same concept is known as vehicle-to-grid (V2G) and boat-to-grid (B2G) paradigms [41–43].

However, with the high energy requirement for the entire port operation, reliance on power from the grid alone is not enough. Thus, the port industry has started to explore clean energy resources including renewable energy. A few ports even built their renewable energy power plant. Currently, Jurong Port is the world's largest port that has installed a solar power generation facility, which is estimated to generate more than 12 mil kWh of solar energy per year and covers 60% of the port power demand [44]. In addition, it also does help to reduce 5200 tones carbon emissions in a year. Meanwhile, Aalborg Port, Denmark, not only constructed solar cell systems with an annual production of 80,000 kWh but also included a 2 MW wind turbine in the plan [45].

By utilizing multiple RESs and paying attention to the need for a storage solution, smart technologies such as a microgrid system, are being introduced. Microgrid's alternative is great at solving power supply problems, and it has been gaining more attention lately. The interest in microgrids is increasing due to their promising advantages in providing sustainable, reliable, efficient, and environmentally friendly power supply [46]. Market acceptability of microgrid technologies due to their reliability and cost-efficient power supply makes them a practical and effective solution in power delivery. Although microgrids have been widely developed around the world, their application in harbor areas remained limited. Due to this situation, the development of a microgrid in a port presents significant challenges. Diversity of loads in the seaports (cranes, ship, container, cold ironing, building, etc.) induces difficulties in load forecasting and accurate measurements of power requirement. In order to avoid prohibitive costs and inefficient systems, a comprehensive study on ports microgrids planning, energy management, regulation, and other aspects is required.

Along with the industrial developments and innovations in power systems, ship transportation is also emerging toward the All-Electric Ship (AES) concept [47,48]. Conventionally, ships used a steam turbine as a prime mover, but it switched to steam piston engines in 1850 [49]. The ship's electrification began with an IPS that uses electric propulsion. It gradually evolved into a hybrid power system (HPS) by incorporating energy storage elements. S. fang et al. [50] in their research study modeled the next version of AES by using photovoltaic sources. The goal is to provide better energy production through a hybrid concept that combines diesel generation with renewable sources.

3. Seaport Microgrids

Implementing a microgrid system is advantageous to the seaport because the port's geographical location can provide a strong base for RES production. A port is an area with a large flat surface that is suitable for solar panel installation, such as on the rooftop of a warehouse, a storage area, or a flat roof from a building. However, such infrastructure may not always be appropriate for large-scale solar energy utilization. In addition to wind and PV, some ports utilized other forms of energy such as waves (e.g., Port Kembla in Australia), tide differentials (Port of Digby, Nova Scotia), and geothermal energy (Hamburg) [31]. Thus, seaport microgrids appear to be a feasible option for future power systems in the harbor area.

Thereby, it is important to understand the significant aspects of this research field. VOSviewer is a visualization tool that is useful for mapping large co-occurrence keywords from research sources, especially from Web of Science and Scopus databases [51]. With the assistance of such visualization tools, evolutionary patterns of seaport power systems can be easily interpreted to identify trends and potential future research directions from a macro perspective to the most current research. It will enhance the understanding of the research field in the seaport microgrids and provide an intuitive overview. Figure 8 shows the co-occurrence analysis of the maritime field with the search keywords of (microgrid* AND (seaport* OR "Maritime" OR marine OR ("Ship Harbor"))) from the Scopus database. The larger nodes indicate that more articles have been published in that area, showing that the research field is trending. Small nodes in the network show low co-occurrence of keywords, which might be because of the fact that the topic is still new, providing the opportunities for further research. In this case, larger nodes in Figure 8 represent 'microgrid/microgrids/ship' keywords. It indicates that microgrid power systems are increasingly popular in the maritime sector. Meanwhile, the keywords from the small nodes reflect that researchers from all over the world are engaged in marine power systems, including energy management, optimization, energy efficiency, and other power-related subject areas. Since small nodes are caused by low co-occurrence, this allows more research opportunities for the improvement of marine power systems.

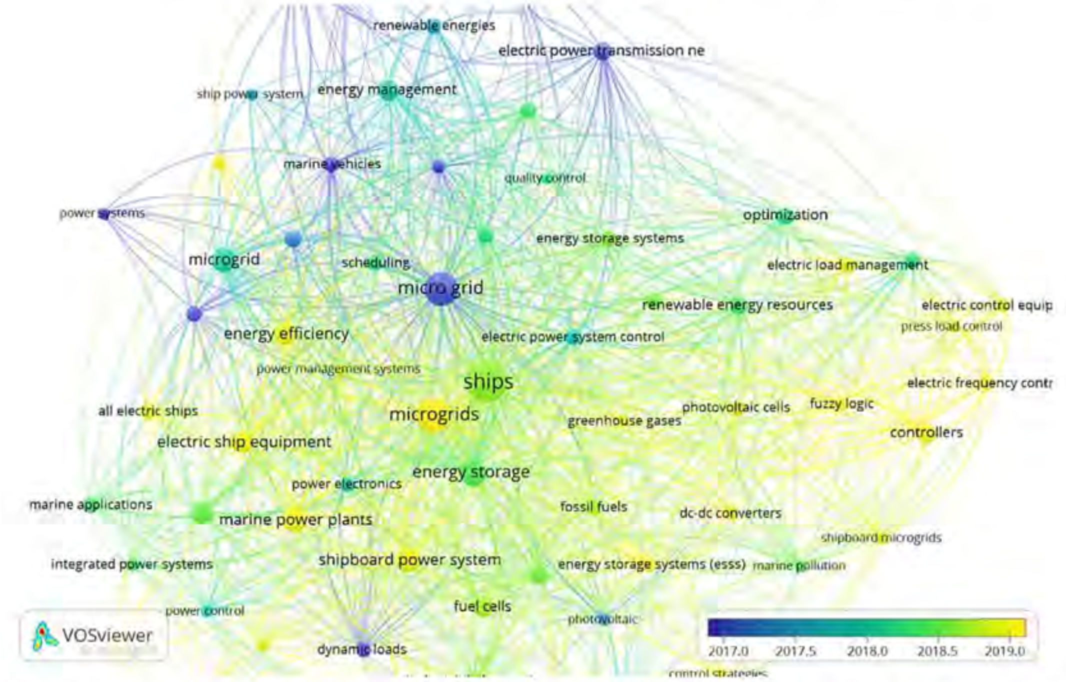


Figure 8. VOSviewer visualization for co-occurrence keywords from recent Scopus research publications on harbor power systems (Accessed on 20 July 2021).

3.1. Seaport Microgrid Topology

A microgrid is a local aggregation of distributed energy resources (DERs) including generators or RES, ESS, power converters, and loads [52]. It links the low voltage (LV) or medium voltage (MV) network to the utility grid at a single point known as point of common coupling (PCC) [53]. Microgrids mainly work in two modes of operation, namely (1) grid-connected and (2) island mode [54,55]. In the grid-connected mode with the main grid fully functional, the microgrid acts as an extension part of the generator by supplying power to the utility grid. However, it can also absorb power from the grid. The inconsistency of power generation from RESs can sometimes produce an abundance of power that exceeds the microgrid's energy demand, thereby providing an opportunity to sell energy back to the main grid and to make a profit [56]. Huang et al. [57] considered 'market-based time-of-use (TOU) pricing' strategies for a microgrid in order to reduce the cost of electricity. A microgrid can also operate independently as an autonomous power system in the island mode [58]. Microgrids help in power restoration after the occurrence of a failure on the utility side, ensuring that end consumers have continuous access to energy, particularly for critical loads. Utility failures can occur as a result of an unplanned shutdown due to the fault or when power demand surpasses power generation [59,60].

Basically, microgrids frameworks can be classified into three topologies including (1) AC microgrids, (2) DC microgrids, and (3) hybrid AC/DC microgrids [53,59,61]. In AC microgrids, the common bus is the AC bus where DC-to-AC inverters are needed for ESSs and DC generating units such as PV and fuel cells. Meanwhile, AC-to-DC rectifiers are normally used for supplying DC loads. However, for DC microgrids, the common bus is in DC and requires AC-to-DC rectifiers for AC generating components, and AC loads are supplied via DC-to-AC inverters. In the case of hybrid microgrids, both types of buses exist in the same network. It allows the flexible connection of DC and AC components to their bus accordingly and reduces unnecessary converters. Figure 9 shows all three topologies and their basic network connections.

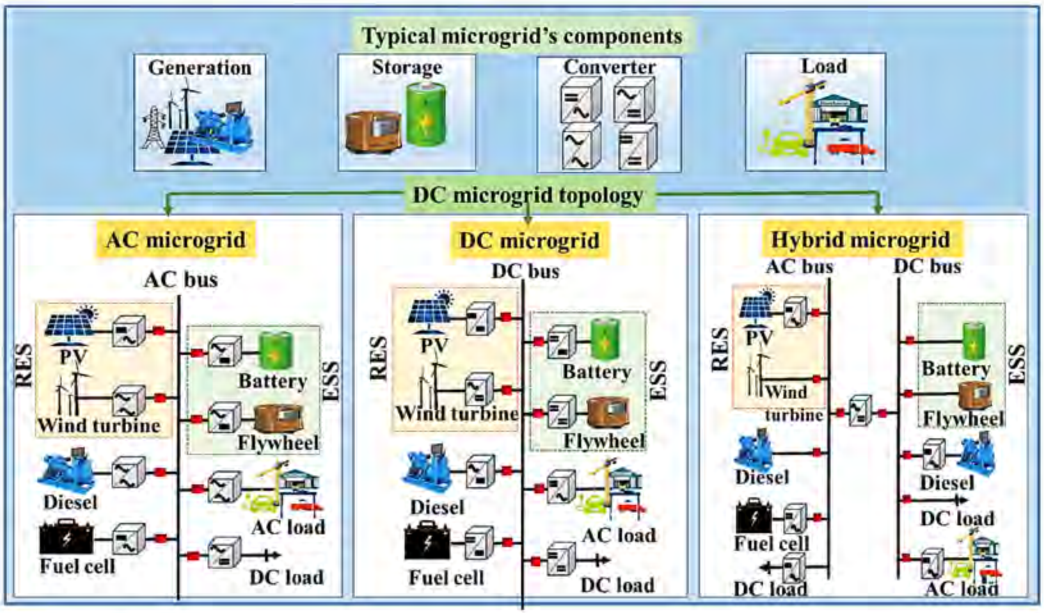


Figure 9. Microgrid topology options for a seaport.

The AC topology is the most commonly used topology that has become the standard choice from the early phase of microgrid invention due to its ability to be synchronized with the AC distribution network, its simple structure, and its economic viability [54]. Normally, when a microgrid has a connection with the main utility, AC microgrids become an ideal choice. It has the capability to transmit power over a long distance, adjust the AC voltage is easy to adjust into different levels for various applications, and it is applicable for induction motors. Despite all of these benefits, long-distance transmission lines are one of the barriers that make it cost-ineffective and impractical in some cases.

However, if the microgrid system is completely isolated without connection to the grid, DC microgrids happen to be the preferred option. The advancements of power electronics technology have resulted in arising the number of DC loads, indicating that modernization of the existing energy system is inevitable [62]. Continuously using AC configuration will require a lot of converters for DC applications and reduces the microgrids' efficiency [63]. In addition, encouragement toward storage systems and clean energy resources such as PVs in power systems, which are in DC, oblige better coordination for the distribution network. As a result, DC microgrids have drawn a lot of interest in the research community in examining possible direct connections with DERs, ESSs, and DC loads through the DC bus and decreasing the impact on the AC networks. DC distribution systems are now gradually used for various applications such as aircraft, automotive, marine, and manufacturing industries [64,65]. Z. Jin et al. [66] investigated the concept of DC microgrids for the onboard power systems of AES. In the maritime sector, the adoption of DC topology brings an enormous range of advantages to the onboard power system by eliminating frequency constraints, allowing the utilization of high-speed generators and providing systematic management [66]. R. Prenc et al. [67] stated that DC ship power systems in the maritime sector prevailed over the AC systems due to the following reasons: (1) improvements in prime mover performance and fuel cost savings; (2) reduction in weight and space; (3) unity power factor for generators; (4) low transmission losses; (5) faster and easier parallel connection of generators; (6) flexible and simple implementation of ESSs.

Both AC and DC microgrids, however, rely on the converter when they interact with the opposite network source that attaches to the buses, resulting in unavoidable power losses during the conversion process [61]. Accordingly, a hybrid AC/DC microgrid appears as a flexible solution for integrating AC or DC-based components while reducing reliance on converters. The reduction in conversion equipment improves overall system efficiency and reliability whilst also lowering costs [68]. X. Liu et al. [69] looked into different operating modes of hybrid microgrids and applied coordinated control schemes to produce maximum power from RES, to reduce power transfer between AC and DC networks, and to enhance stabilization in operation with various networks of DER, ESS, and load components.

By the presence of two types of buses in a hybrid microgrid, control, operation, and management become more complex compared to individual AC or DC microgrids. Furthermore, the exploration of hybrid microgrids is still in its formative development stages and requires extensive research. Table 6 presents the reference of research publications that apply three kinds of microgrid topology into seaport applications.

Table 6. Seaport application with different topologies.

Topology	Seaport Application	References
AC	Shipboard microgrid	[70–72]
	Cold ironing	[73]
DC	Ship-based seaport microgrid	[16,40]
	Shipboard microgrid	[70,74–77]
	Cold ironing	[78]
	Electric ship	[79]
	Offshore application	[80]
Hybrid AC/DC	Electric ferry shipboard	[81]
	Shipboard microgrid	[82]
	Cranes	[22]
	Cold ironing	[83]

3.2. *Conceptual Seaport Microgrids in Shore Side and Seaside*

3.2.1. Shore Side

Conventionally, the relationship between a seaport and ship mainly corresponds to logistic activities. The electrification innovation in the maritime sector is represented by the following: (1) seaport microgrid and (2) all-electric ship (AES), which is the promising solution toward achieving zero carbon footprint in future seaports [51]. Apart from the logistic side, the rising electrification trends in this sector extended the connection of seaport-ships on the electric side. With the broadened infrastructure and multiple functions conducted in the port area, their energy demand continuously grows. Hence, the maritime sector is experiencing considerable power shortage as well as environmental pollution from the burning of fossil fuels. These constraints encourage the incorporation of RES and ESS into the seaport power system, further complicating its control and management. Therefore, the concept of seaport microgrid is introduced in order to provide better coordination for multiple energy resources, storages, and variation in seaport loads [84]. Figure 10 illustrates the concept of microgrid integration on the shore side and seaside.

German maritime sector is an example for manifesting the integration of seaport microgrid, where Hamburg port draws a power of 24.5 MW from renewable energy by installing more than 20 units wind turbines [85]. Moreover, their warehouse rooftops are filled with solar panels with projections to generate 500 MWh of electricity per year [85]. German ports emphasize the importance of renewable energy as they are also considering other sources of energy such as tidal power generation, wave energy, and geothermal energy [86]. Another positive step taken by the Hamburg Port is towards electrification through the installation of cold ironing [39]. These measures are being developed to increase power supply while simultaneously assisting the port in achieving its green maritime goals.

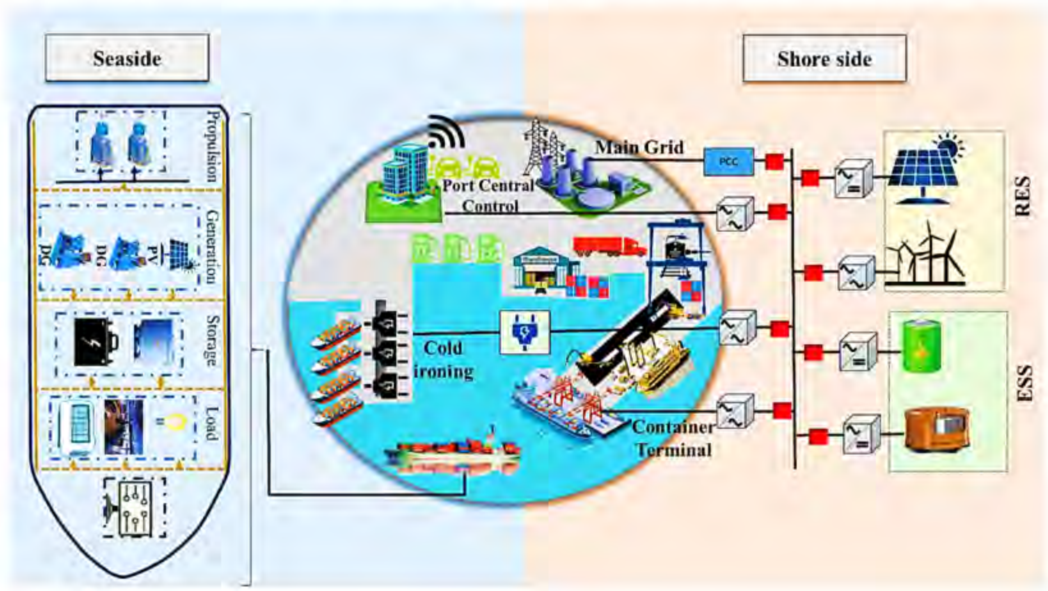


Figure 10. The concept of seaport microgrid on the shore and seaside.

On the shore side, microgrid integration will enhance more electrification and automation for port applications such as heavy lifting devices and transport machinery and enables the transition from diesel to cold ironing during berthing [56]. On the other hand, all of these practices are currently limited as the conventional grid cannot bear the heavy load.

By definition, a seaport microgrid refers to a port that employs microgrid technologies to support its power system and distributed loads. The goal is to improve the port's operation efficiency, maximize renewable energy penetration, provide flexibility for storage installation and allow for more energy sales to the market through the main grid [50]. Basically, seaport microgrids share similarities with land-based microgrids, but they have slight differences in some aspects.

Commonalities: The framework of seaport microgrid has the same components as land-based microgrids, for instance, RES, ESS, converter, and load components. Both microgrids can operate in grid-connected and island modes. In this regard, their basic control and operation frameworks may be similar [50].

Differences: The significant difference between these two types of microgrids stems from their application. Land-based microgrids normally support the power necessary for building electrical appliances, and the most common electricity demand is for lighting and thermal and HVAC systems [11]. Meanwhile, seaport microgrids must consider both the logistic and the electric sides [50]. On the logistic side, a lot of factors need to be considered such as berth allocation [87], port crane scheduling [88], route and voyage scheduling [89], and various cargo transportation. On the electrical side, each application needs a different level of energy, and the energy is volatile depending on many factors.

In addition, cold ironing applications on seaport microgrids will cause frequent berth in and berth out, which will influence the microgrid's performance. Even more difficult, the port is also restricted by the strict policies that are changing over time [89]. Many involved parties such as port entities, port stakeholders, policymakers, port authorities, and the government add difficulty in any decision in the planning of ports. All of these circumstances render seaport microgrids more complex compared to land-based microgrids. Further exploration of the system requirements and modifications for better seaport microgrids is necessary to have compatible and efficient solutions for port electrification.

3.2.2. Seaside (Shipboard Microgrid)

The invention of electric propulsion has resulted in the total electrification of shipboard power systems, referred to as AES. The innovation brings numerous advantages to t maritime ships by reducing manpower, minimizing maintenance workload, improving fuel consumption, fast start-up of ships, and reducing emissions from diesel combustion [48]. AES is considered as the maritime microgrid because of the integration of microgrid technology on shipboard power systems. AES operates in both grid-connected and automation modes. It has similar components as a typical microgrid, whereas generators and ESS deliver power via an energy network in order to supply propulsion and the ship's load. In future shipboards, renewable energy implementations such as photovoltaic systems become trendy. However, the limited space in the ship makes it one big constraint. Ships work in two modes of operation.

Berthed in mode: During berthing, AES is connected to the cold ironing system, receiving electricity so that its auxiliary engine can be switched off. The cold ironing system normally obtains supply from the main grid. Hence, the same concept as the grid-connected mode of operation for land-based microgrids is applied.

Berthed out mode: In the situation where the ship becomes physically independent from the seaport, the electric connection between these two entities (port and ship) no longer exists. The AES voyage at sea is viewed as a mobile microgrid and in island mode of operation. It moves and supplies its entire onboard load with its onboard power system.

3.2.3. Operation Management and Energy Planning of Seaport Microgrid

The complexity of the coordination of various power resources in a microgrid, load management, synchronization with the main grid, meeting policy obligations, and environmental criteria recognizes the importance of the power/energy management system (PMS/EMS) in the seaport microgrids. Energy management systems (EMS) in ships send the signal to the particular component through the communication network after determining the optimal outputs for generators and batteries [50]. P. Xie et al. [90] categorized the PMS and EMS of shipboard power systems into rule-based and optimization-based techniques, where rule-based techniques are highly dependent on human expertise, preconfigured strategies, and priorities. Meanwhile, optimization-based techniques are becoming more trendy as they are capable in providing a better solution by using analytical strategies or numerical optimization algorithms [91]. The diverse assortment of the PMS/EMS strategies in a microgrid system entails managing each component and sub-component by hierarchical control schemes, including primary, secondary, tertiary, and upper-level control systems with different functionalities and time scales [71].

In this section, the importance of the operation management system for better energy planning within the seaport microgrid is highlighted. The demand for energy in the maritime sector keeps increasing over time because of the expanding infrastructure, increasing size and number of seaport transportations, need for handling multi functions, and increase in global demand for logistics. The load will continue to rise due to the above-mentioned factors, but there are several operational practices for controlling energy demands, including load scheduling, load forecasting analysis, improving load factor, peak shaving, and enhancement of ESS utilization. Moreover, price and tax incentives also play a vital role in the operation management of seaport microgrids.

Shipboard/Seaport Microgrid Power Management and Load Scheduling

In the maritime sector, seaport controls on the shore side and seaside (shipboard power system) normally have different administrators that seek different goals [50]. The coordination between these two administrative bodies is necessary. For instance, the vessel could choose a berth-in time when the electricity price is low, and the seaport can make more electricity price savings by adjusting the berth allocation during off-peak hours. Load scheduling at the time of the minimum electricity price is beneficial to energy consumers with respect to minimizing total electricity cost while at the same time meeting environmental requirements.

Pricing policy is one of the vital considerations in load scheduling as the price of electricity fluctuates over time. Different pricing policies apply to different applications in industries. Similarly, in the marine sector, in order to achieve energy-saving and to optimize the cost of energy, pricing policy plays a significant role. Sun and Li [92] described two pricing policies, namely Time-Of-Use (TOU) pricing and Critical Peak Pricing (CPP). TOU pricing is a dynamic pricing strategy where electricity is charged at several price levels for off-peak, mid-peak, and on-peak intervals during the day [93]. This pricing strategy allows energy consumers to shift their loads from peak load intervals to off-peak periods and to avoid high electricity prices [94]. In the peak event situation where production is skyrocketing due to very high demand, CPP is the most effective scheme, which selects one price for critical periods [95]. Kyaw Hein et al. [1] proposed robust coordinated operational scheduling for grid-connected seaport microgrids. In that framework, ship-to-shore (STS) power demand is scheduled by using day-ahead and hour-ahead scheduling with different time horizons. The aim is to reduce emissions and minimize the cost of port operation.

In addition, this scheduling technique is widely used in shipboard microgrids. Unlike land-based microgrids, AES at the sea operation can be regarded as mobile microgrids. Hence, power consumption varies with cruise speed and voyage distance. With the help of electric propulsion motors, AESs are capable of adjusting cruising speeds in order to achieve more economical operations. AESs operate at different speeds during different operating modes including docking mode (when ship approaching or leaving the port), cruising mode, and berthed mode. Yuqing Huang et al. [96] could reduce the operation cost and GHG emissions by 17.4% and 23.6%, respectively, by implementing voyage generation scheduling methods in the AES. In [97], the optimal scheduling for a ferry is achieved by employing a rule-based algorithm considering three scheduling models of different DG units and ESS. Simulation results show that by optimally scheduling the onboard power sources, poor low-efficiency situations can be prevented. Appropriate DG selection and load scheduling for the ship can maximize fuel-saving. Srinivasa Rao K et al. [98] minimized fuel consumption in an offshore support vessel with a dynamic positioning system by scheduling generation resources. The Genetic algorithm is applied for the optimal load sharing due to the nonlinear specific fuel consumption curves of diesel engines.

Load Factor Improvement

The load factor is expressed as the fraction of average load during a specified period to peak load in that timeframe [99]. This technique is useful for determining the efficiency of microgrid operations. A low load factor signifies that an electricity system is being operated inefficiently and is economically poor [100]. Thus, a high load factor is desirable in order to ensure that the seaport microgrid is economically viable by utilizing the total plant capacity for the longest possible period [101]. As a result, the overall cost of providing electric energy will be reduced. F.Robert et al. [102] analyzed the impact of different load factors of 0.2, 0.3, and 0.4 on the energy cost at the design stage of a microgrid. The analysis shows that the highest value of load factor can reduce energy costs up to 48% approximately for a solar-based microgrid [102].

In the harbor, instead of running all big operations such as heavy loading/unloading cargo and multiple ship berthing at the same time, which causes peak demand in the specific time, scheduling the time of ship and cargo arrivals is a wise action. When all the high-demand operations are not running simultaneously, peak demand can be distributed over off-peak hours and can increase the average load as well as the load factor.

At the same time, it will result in reducing the total energy purchase costs. Thus, improving the load factor by reducing or shifting the peak load is necessary in order to ensure the profitability of microgrid power systems [103]. In [97], power scheduling techniques are applied to a hybrid ferry microgrid. The results show that the right arrangement of DG and ESS is capable for improving the load factor.

Peak Shaving

Electrification technologies in ports, such as AES, the transition from diesel-based cranes to electric cranes, cold ironing, electric vehicles, electric trains, and electric trucks for cargo transportation, change the port's dynamic behavior. Peak shaving is a favorable method to control the operational load at ports. Figure 11 illustrates three peak shaving techniques to scale down peak load profiles and to distribute the load over low-demand time intervals.

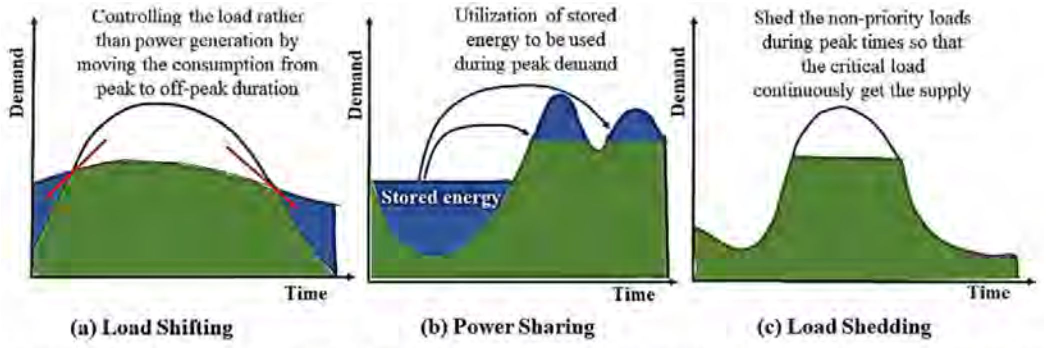


Figure 11. Three type of peak shaving methods where (**a**) is load shifting approach, (**b**) is power sharing approach, and (**c**) is load shedding approach [20,22,52,104,105].

Peak shaving is based on the incorporation of energy storage systems. K. Mostafa et al. [23] coordinated the duty cycles for the STS cranes through full automation of the crane terminal and integrating peak shaving methods through the deployment of ultra-capacitor (UC). The outcome shows that the higher amount of the peak load absorbed by the UC results in more operational earning. Harry Geerlings et al. [106] investigated the effectiveness of peak shaving at the container terminal (CT) by applying 'new rules of operation' with the aim of cost saving while analyzing its effect on the handling time of containerships. They highlighted that the peak shaving method not only reduces the handling costs at CT but also enhances power stability. However, because the number of terminal equipment and processes operating at the same time may be limited, this may result in additional handling time for containerships [107]. This load-leveling technique also applies to shipboard microgrids. In [76], in order to organize the operation in shipboard, a specialized hierarchical control scheme is proposed. Load sharing levels in primary control aim to distribute the load from peak to off-peak hours. Peak shaving in the shipboard helps to absorb the load variation in the system so that engines can continue to operate at their most efficient operating point. Kiyoune Kwon et al. [77] proposed a load frequency-based approach to manage shipboard power and load sharing in DC hybrid electric ships. Simulation results indicate that load frequency-based power management offers effective load distribution and is capable of protecting the generator from sudden load variations, which results in poor power quality and causes damage in mechanical systems.

Load Forecasting

On the shore side, dynamic load from multiple operations of logistics (container terminal, cargo transportation, vessel, and charging station) and administration infrastructure (communication center, warehouse building, and maintenance) might result in unexpected power consumption peaks. In this situation, a substantial amount of power supply is required to prevent disruption in port operation due to power shortages. Thus, load forecasting in ports is vital for optimizing resource utilization, scheduling the load, and managing alternative energy from RES and ESS. Furthermore, understanding load behavior brings advantages for complex decision making in energy management. However, several uncertainty parameters influence the dynamic load of port operation in seaport microgrids, demanding the use of innovative load forecasting techniques. Various techniques can be used to implement load forecasting ranging from parametric-based methods to the evolutional artificial intelligent techniques listed in Table 7.

Table 7. Load forecasting methods [108–112].

Load Forecasting Approach	Technique	Parameter Requirement	Load Forecasting Time Horizon
Traditional parametric techniques	(1) Gray dynamic methods (2) Regression methods (3) Time-series prediction methods (autoregressive (AR), moving average (MA), autoregressive moving average (ARMA), autoregressive integrated moving average (ARIMA), seasonal autoregressive integrated moving average (SARIMA), autoregressive moving average exogenous (ARMAX))	– Historical data of load profile – Influential factors: weather, air temperature, humidity, wind speed, calendar seasonal information, economical events, and geographical information	– Short-term load forecast (STLF)-typically from one hour to one week for economic dispatch – Medium-term load forecast (MTLF)—typically from one week to one year – Long-term load forecast (LTLF)-typically longer than one year suitable for capacity expansion
Artificial intelligence-based techniques	(1) Artificial neural network (ANN) (2) Fuzzy logic (3) Genetic algorithm (GA) (4) Support Vector Machine (SVM)		

One of the electrification innovations in ports is related to the transition from a diesel-powered rubber-tyred gantry (RTG) to an electric RTG [113]. To understand the energy behavior of electric RTG, Feras Alasali et al. [114] implemented three different methods of load forecasting, namely autoregressive integrated moving average with exogenous (ARIMAX), artificial neural network (ANN), and autoregressive moving average exogenous-support vector machine (ARMAX-SVM). The purpose is to find the most accurate forecasting method so that peak demand can be reduced effectively. Several simulation analyses are conducted by implementing STLF techniques (24 h) on the load profile of an electric RTG crane from the Port of Felixstowe [114]. The results show that ANN outperforms ARIMAX and ARIMAX-SVN forecasting techniques with minimum errors during a prediction interval.

Another vital seaport application, onshore power system (OPS) or cold ironing, involves the interaction between ship and shore-side power facilities. Accordingly, the dynamic load of OPS fluctuates with various parameters from both sides. The power of the ships varies depending on the load they carry and the size of the ship. Moreover, the arrival and departure times of ships affect the power consumption of OPS. In addition, ship traffic at the port is also inconsistent. Thus, these factors have an impact on OPS load behavior. However, in a few forecasting techniques conducted for OPS load forecasting, the mentioned factors are either neglected or only one of them is considered. Hence, research studies on how these parameters affect the OPS load profile are still lacking. The authors in [115] conducted OPS load forecasting by considering the traffic volume of ship berthing at two different seasons, winter and summer. The goal is to observe how the number of ship berthing varies in different seasons. Still, it is better to conduct a forecasting method for all seasons including spring and autumn in order to obtain the overall pattern of ship berthing during all year. D'Agostino et al. [116] performed OPS load forecasting by using two methods, namely the Environmental and Protection Agency (EPA)-based method and Monitoring, Reporting, and Verification (MRV)-based method. These techniques measure the ship's load demand based on four operating modes: sailing at sea, maneuvering, cargo handling in port, and idle mode. The results show that peak demand varies depending on the ships' categories and operating mode.

The amount of shore power demanded by ships changes randomly depending on the number of berthed ships and their auxiliary power requirement. In order to determine OPS power capacity, Yun Peng et al. [117] used the stochastic nature of arriving ships. The goal is to observe the manner in which ships' arriving patterns affect OPS power consumption. In another research study [118], OPS power requirement is determined by utilizing the predicted energy consumption of auxiliary engines and by obtaining hourly energy consumption for different kinds of ships by using the Monte Carlo procedure. The power consumption prediction data are necessary for energy management. In [119], forecasting data are utilized for the day ahead optimization of a hybrid ferry with OPS. Two conflicting objectives of minimizing the operation cost and degradation of energy storage are considered.

Regarding the seaside microgrid (isolated shipboard), the dynamic positioning (DP) system, which is used in marine vessels to keep the ship position from displacement, is important for determining how thrusters should act to stabilize the position and heading of vessels. However, the uncertainty during the voyage that stems from sea waves and weather conditions affects DP, vessel's speed, and ship power. Hence, DP load forecasting by considering the uncertainty is essential for better shipboard power consumption management. M. Mehrzadi et al. [120] utilized the deep learning method for DP load forecasting by using the Levenberg–Marquardt algorithm based on a nonlinear recurrent neural network to predict thrusters' power consumption in different sea states. The case study is divided into several clusters of sea conditions including calm, moderate, rough, and high states. As DP power consumption considerably changes based on the sea states, wave height and wind speed are significant factors to be taken into account. The sea state parameters change the vessel's motion and affect the thrusting power demand, thereby resulting in a dynamic load pattern. Meanwhile, Kyaw Hein et al. [121], with the same consideration of sea states parameters, provide the simulation results in which sea states have a big influence on voyage path and ship's velocity. The volatility of the sea wave and wind speed uncertainties influence propulsion power requirements. This DP forecasting practice greatly aids the ship's operation management and power system planning in maintaining the stability of the ships' DP handling. However, there is no analysis based on real-time data, which is very important for observing the effectiveness of the proposed load forecasting technique.

Storage Management

The incorporation of a RES component in a seaport microgrid necessitates the use of an ESS to store excess energy and absorb RES power fluctuations. Due to the weather-dependency of the RES power generation and uncontrolled weather conditions, the generated energy will fluctuate, which highlights the importance of ESS integration. Chun Sing Lai et al. [122] reviewed two types of energy storage systems for storing low carbon energy, namely generation-integrated energy storage (GIES) and non-GIES. GIES stores a substantial amount of energy along with the transformation from primary energy to electricity. GIESs typically consists of power generating technologies and are more efficient for RES generation sources such as wind and solar thermal energy. Non-GIES is a common type of ESS that converts primary energy directly into electricity for storage. Meanwhile, Amirante et al. [123] made an overview of the three types of ESS:

(1) Mechanical-compressed air energy storage (CAES), pumped storage hydropower (PSH), and flywheel;
(2) Electrical-supercapacitors and superconducting magnetic energy storage (SMES);
(3) Electrochemical-lead-acid batteries, lithium-ion batteries, and flow batteries;
(4) Hydrogen.

In maritime transportations, ESS is beneficial for strengthening the system in order to avoid instability, which is caused by the engines' delay in responding to load demand [124]. It will also serve as an additional power reserve in the event of a generator failure, reducing the risk of a blackout. In [96], a virtual ESS between shipboard thermal storage and thermal load is used in an AES for mutual support between voyage scheduling and economic dispatch. The optimization model is formulated in order to effectively coordinate voyage scheduling and power generation considering different load conditions. The results show that operational cost and emission can be reduced by 17.4% and 23.6%, respectively.

However, in some operating conditions, a low load factor of the parallel generator in a ship might cause a detrimental effect on the fuel consumption rate. In order to solve this issue, M. Othman et al. [97] utilized a battery for optimally arranging power generation in a hybrid shipboard microgrid. Three case studies with different numbers of diesel generators with and without batteries are performed. Optimization results illustrate that fuel consumption can be reduced significantly, and the load factor is improved with battery application compared to solely using a diesel generator. However, coordination between several generators and battery needs to be carefully planned in order to achieve better results.

M. Mutarraf et al. [17] signified the importance of battery banks in the DC bus seaport microgrid in providing a mobile cold ironing facility at the harbor. Due to the highly dynamic behavior of the port's load, wise distribution of RES and ESS during peak and off-peak duration help greatly in balancing demand and supply. For instance, during a sharp rising in energy demand from cold ironing due to high traffic of ships berthing, where generation is insufficient, ESS can come to the scene.

In another case, the storage component provides a solution to store energy generated from ports' applications that generates energy. In [13], a flywheel storage system is used to harvest energy from the harbor's electrical cranes. This idea comes from the problem of conventional cranes operation that ignores the regenerated energy from cranes when the container is lowered. As a result, most of this energy is dissipated as heat in resistor banks. Thus, developing this flywheel storage system will avoid energy loss when the cranes are lowered. In this manner, a significant amount of energy can be stored and reused during peak hours.

From the emissions point of view, ESS is a promising solution relative to the port for reducing pollution. Kyunghwa Kim et al. [125] proposed a hybrid storage system by integrating supercapacitors (SC) and lithium-ion batteries (LIB) by targeting a bulk carrier with four deck cranes. The capacity of SC and LIB is selected based on the load consumption from the cranes in loading and unloading modes. Simulation results show that emissions were reduced by roughly 77%, 93%, and 99% for CO2, SOX, and NOX, respectively, for this specific case study. Emission reductions might vary in different marine applications.

Several different methods for reducing peak demand have been proposed in the literature. Some countries offer rewarding incentives so that energy consumers willingly shift their electricity consumption to off-peak periods. Storage technology has merit over this rewarding program in allowing customers to have their normal daily lives while lowering their peak demand charge. The cost-benefit analysis is based on the battery's lifespan, state of health, and discharge time [100]. With the increase in storage capacity, more loads can be scheduled at the minimum cost duration, thereby reducing the potential for higher electricity charges [126]. The trade-off between financial gain and operational efficiencies is quantified. In order to ensure the high efficiency of ESS integration, suitable type storage systems must be carefully adapted by considering the type and scale of applications. Nowadays, in some complex maritime applications, storage technology is growing toward hybrid energy storage in order to satisfy demand from the ports' dynamic loads.

Price and Tax Incentives

Demand response is an efficient strategy to moderate electricity consumption in response to the market incentives relative to either price or tax reduction. There are two types of demand response programs: time-based rate (TBR) programs and incentive-based programs (IBPs) [127]. TBR programs provide consumers with time-varying rates based on the price of electricity in different periods (real-time pricing (RTP), TOU, and CPP), motivating users to adjust their consumption patterns by changing price signals [128]. On the other hand, IBP is the form of incentive that provides advantages in the time of stress. Considering environmental issues at ports, port authorities from U.S and EU offer shipping rebates to reward ship operators that satisfy environmental requirements [129]. In practice, the Port of Long Beach implemented the Green Ship incentive program to reduce NOx emissions from shipping [28]. Another alternative is the introduction of various environmental indexes such as the Environmental Ship Index (ESI), Green Award (GA), the Clean Shipping Index (CSI), and Blue Angel (BA) [28]. These programs give special discounts on port dues if the port score satisfies the baseline index. For instance, in Bremen, ships with an ESI score of 30 to 40 receive a 5% discount on port dues, while ships with an ESI score of more than 40 receive a 10% discount. These incentives will encourage port entities to take the necessary actions to improve their port so that they can achieve more discounts on port dues. J. Sanz et al. [130] reviewed four types of incentives for microgrids, including (1) feed in tariffs, (2) market premium, (3) green certificates, and (4) tenders. Each incentive is initiated for different conditions and rewards but with the same goal toward energy saving and zero footprint ports.

4. Seaport Microgrid Challenges and Future Trends

4.1. Challenges in Developing Microgrid Systems at Seaports

The increasing number of publications from researchers around the world indicates a growing trend towards maritime microgrids. However, real implementation of seaport microgrids in the harbor is scarce due to several issues and barriers that exist from various perspectives. Anthony Roy et al. [43] discussed a few aspects of seaport microgrids, namely technical and managerial. Security and regulatory aspects are also among the important perspectives. Some of these challenges are addressed below.

4.1.1. Technical Challenge

Relying solely on the utility grid is inefficient when considering heavy appliances at the harbor. The grid must be close to the port or the cables will be very expensive. Thus, harnessing energy from RES is more economical due to local generation advantages. However, ports have limited space for RES installation [81]. Undeniably, solar panels can be installed on the flat rooftop of the buildings or warehouse but with restricted capacity, and it is not applicable for large-scale exploitation. Shipboard microgrids suffer from the same problem. Many of the commercial AES use diesel generators and batteries for propulsion and supplying onboard loads [131].

For the next AES evolution, the implementation of RES such as photovoltaic systems is discussed in [50] to support the power required by the shipboard microgrid. However, there is no discussion on a compatible unit of solar panels that can be placed on the ship. It is well known that ships have very limited space due to existing bulky equipment on board, especially in cargo ships, which usually use the space to place the cargo. Furthermore, coordination of the RES will be complicated because ships are always on the move and isolated when they are at sea [81].

For the wind turbines, installation can take up a significant portion of land and deforestation to set up a wind farm that treats wildlife such as birds and bats. Moreover, it does not only require a high upfront investment but is also prone to noise disturbance and undesirable visual impacts.

Another challenge for RES installation is uncertainty in weather conditions. RESs are unable to produce consistent power, and their power production depends on several factors such as ambient temperature, wind speed, irradiation, and time of the season, among others. Hence, storage elements are always integrated with the RES.

4.1.2. Managerial

According to the literature, a few ports, such as the Port of Hamburg and Port of Genoa, have already taken the initiative for microgrid deployment [31]. In comparison to the massive use of land-based microgrids, port-based microgrid implementation is considered scarce. This situation creates an opportunity to bring microgrids technology into seaports, but it is also difficult to access references in terms of their needs, design, operation, and maintenance requirements. Particularly during the design phase, it is a complicated task to find the optimal design of the seaport microgrid with the compatible configuration and the right size of its components. The research conducted on testing and analysis of seaport microgrids lacks real-life data. This can be explained by many of the studies that are conducted based on the simulated data sets. Thus, it is hard to know if the simulation result is compatible with real implementation or not.

In addition, considering that the seaport microgrid is a relatively new topic, the required manpower that has the expertise and enough experience is limited. Due to this, port entities find that new power system technology is difficult to handle, leading them to decide not to take any risks by denying microgrid implementations. Not only that, the planning for the implementation takes a long time before it can be executed. Revolutionizing the ports to microgrid technology may appear great on paper; however, one of the biggest hurdles that have to be overcome is the human factor with different mentalities. Moreover, the requirement to make an agreement and synchronization between all parties involved such as port entities, stakeholders, port authorities, policymakers, and government makes it more difficult. This explains the reason why the majority of the ports are more comfortable with traditional power systems.

4.1.3. Security and Regulation

Operation management and control of seaport microgrids are very different from conventional power systems due to the characteristics of power electronic converters and highly dynamic load behavior. A port is the site that has highly volatile loads due to the frequent arrival and departure of ships. Microgrids must achieve a balance between supply and demand in order to maintain voltage/frequency stability. Particularly during isolated operations, system instability is a major concern. In order to effectively manage these issues, hierarchical control techniques have been proposed [21]. On top of this, shore-side and shipboard microgrids (seaside) have different administration and rules of conduct.

In terms of security, the lack of an efficient monitoring system makes microgrids extremely vulnerable to cyber threats [132]. Malicious cyber assaults are a threat to power network operations, causing massive damages from different technical, economic, social, and control points of view. According to statistics from the energy sector, more than 150 cyber-attacks occurred in 2013 and 79 in 2014 [133]. Accordingly, the cost of power outages in the United States is estimated to be around $ 80 billion per year [133].

Above all of the aforementioned concerns, one of the biggest challenges of the maritime sector is the implementation of strict policies for marine operations both on the shore and seaside. Policy regulations are in place either to restrict emissions or to stimulate the use of improved technologies at ports. These guidelines must be followed in any future port planning. It is becoming more difficult for existing appliances that require immediate replacement. In accordance with a current IMO rule limiting sulfur content in fuel to 0.5% m/m, ships must either find alternative clean fuels or integrate a fully electric ship.

On the positive side, certain legislation exists that provides incentives and subsidies to stimulate the use of new technologies. Taxes, for example, are proposed as a strategy by increasing taxes on older systems while lowering taxes on newer systems. It is important to formulate a legislative scheme that favors microgrids as a power system at ports, as this legislative framework will result in switching to microgrids that are more cost-effective than staying with conventional fossil-fuel-based systems. Adam Hirsch et al. [94] attracted the attention to two key questions about the rules that require clarification, where the answer eventually has a significant influence on microgrids. The first question is whether a microgrid is considered as electrical distribution utilities and, thus, whether it should be subject to state regulatory control or not. The second clarification is, in the case that microgrids are excluded from state regulation as utilities, do microgrids fit into existing legal frameworks governing energy sale and purchase, as well as rights to generate and distribute electricity. Microgrids require a rightful legal identity and regulatory certainty in order to ensure that their implementation is profitable; otherwise, the upfront cost is too high, and the profit is too uncertain with respect to rationalizing the investment of time and money.

4.2. Potential Future Research Directions

The ongoing challenges of seaport microgrids including the barriers mentioned in the previous subsection and other technical aspects require more investigation to find effective solutions to improve the ports' performance. The know-how to manage all of these will benefit the ports in a variety of ways, including energy efficiency, cost-saving, and environmental issues. Below are some of the identified potential issues on the seaport microgrids that can be considered for future studies.

4.2.1. Mobile Cold Ironing

Currently, cold ironing in the harbors mostly uses direct energy from the main grid. There is a chance that a few large vessels with high power requirements will arrive at the same time. Thereby, the reliance on grid supply alone is insufficient to keep all parts of ports operational and might result in power shortages. Furthermore, most of the smaller seaports are not equipped with cold ironing stations, resulting in continuous pollution from auxiliary engines during berthing [17]. In order to address these issues, mobile cold ironing by forming a power-sharing network between nearby ships called a 'moveable shipboard microgrid' appears to be a potential solution for providing temporary power. Further research on this technique can be pursued with respect to putting it into practice.

4.2.2. Optimal Port Planning

Considering that seaport microgrids involve different kinds of load, various objectives, and constraints, it is critical to plan efficient coordination among the components in the microgrid. There is limited literature that addresses compatible configurations and appropriate size/capacity for each component in a seaport microgrid. Outstanding coordination is needed in addition to determining the right type of RES/storage component/converter installation and suitable topology. This is to ensure that there is no lacking or oversizing in microgrid implementation, allowing power to be distributed efficiently and avoiding unnecessary investments.

4.2.3. Cluster Seaport Microgrids

From the available literature, most of the publications on seaport microgrids contribute to the overall performance of the microgrid. However, the port itself deals with many kinds of large energy applications such as container terminals, cold ironing, cargo transportation, vessel, and administrative buildings for port handling. Thus, it is a good opportunity to implement a cluster seaport microgrid by grouping the loads into different load clusters.

4.2.4. Optimization

Due to the current firm policy for the port operation to control prolonged toxic pollution, an optimization algorithm that will benefit both the legislative body and the port entity is required. The analysis will help port entities in future planning so that it is compatible with the port policy.

4.2.5. Economical Analysis

All the alternatives carried out in the marine sector from renewable energy harnessing to electrification innovation undeniably bring a plentiful amount of energy-saving and emission reduction benefits. Most previous research has focused on the technical aspects, and a comprehensive economic analysis is still lacking. For a stakeholder, financial management and revenue generation from investment is vital before executing any planning process. Further economic analysis on the seaport considering the market price, the tax charged, energy price, and return on investment would be necessary. The authors in [134] provide net present value for the OPS system at ports. However, this OPS installation involves retrofitting on both sides of ships and shore facilities. It would be insightful if economic analysis can be provided in terms of investment needed and potential savings made from the point of view of ships' owners and port entities. In addition, in order to observe the effectiveness of the return on investment from OPS implementation, a comprehensive comparison between energy production cost from diesel auxiliary engines and electricity purchase cost from OPS is necessary. If it is proven that this strategy can bring economic advantages, it will encourage more OPS implementation in seaports worldwide.

Another alternative for future study is to develop an economic model that benefits all parties in the port. This can be explained by the fact that national electricity rates vary per country. Some countries offer electricity at a high cost, while others obtain lower costs. In a country where electricity is expensive, the maritime industry has a big potential to maintain using diesel energy regardless of whether it would harm the environment. A good economic model that is capable of attracting all port stakeholders not only because of environmental concerns but also because of economic benefits can be implemented. For instance, by reducing energy tax for those shifting to electrification applications, more savings are obtained compared to the traditional paradigm of port operation. The port policymaker, port entities, and ship owner should all be taken into account.

5. Conclusions

Ports are sites with major contributions to pollution as large vessels keep their engines running even when berthed, and heavy lifting work is operated by diesel-powered cranes. Dynamic behavior and the diversity of the port applications emphasize the promising role of microgrid technology in supporting the utility grid. This paper addressed the concept of the seaport microgrid and its integration into seaport from both shore and seaside (shipboard microgrid) points of view as well as its operational management. After the thorough literature review, the following points are some of the significant conclusions drawn in this paper:

- Three major concerns at the ports include energy, environment, and cost. Future port planning should be geared toward addressing these issues.
- A microgrid is a promising power system for the marine sector that is capable of supporting the industry's heavy loads. It enables the diversification of alternative energy resources, such as harnessing power from RES, rather than being limited to only fossil-based energy. A port will manage to achieve a substantial amount of cost-saving since electricity is generated locally by RES in the harbor area. It will reduce the investment costs in both utility grid expansion and long distribution cables.
- Furthermore, ESS components in the microgrids help in improving port performance and serve as a useful tool for demand-side management. The good practice from the operation management in seaport microgrids enhances better operation at a lower price.
- With a seaport microgrid, it is possible to bring more electrification and automation into the ports than compared to the conventional grid, which cannot support factors such as large-scale cold ironing, full electrification of cranes, improved charging stations, and electrification of other modes of transportation.

Electrification movement in the ports implies that the connections between seaport and ships are no longer on the logistic side only but are also on the electric side. It requires an efficient transportation system and power system, rendering the seaport microgrid more complicated than the traditional land-based microgrids. Thus, further actions for improvement in ports are needed in order to synchronize both the logistic and energy side in a more coordinated manner.

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