smart cities

MDPI

Review

Blue Seaports: The Smart, Sustainable and Electrified Ports of the Future

Daniel Clemente [1,2,*], Tomás Cabral [1,2,*], Paulo Rosa-Santos [1,2] and Francisco Taveira-Pinto [1,2]

[1] Department of Civil Engineering, Faculty of Engineering of the University of Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal; pjrsantos@fe.up.pt (P.R.-S.); fpinto@fe.up.pt (F.T.-P.)
[2] Interdisciplinary Centre of Marine and Environmental Research (CIIMAR), Leixões Cruise Terminal, Av. General Norton de Matos s/n, 4450-208 Matosinhos, Portugal
* Correspondence: up201009043@edu.fe.up.pt (D.C.); up201304327@up.pt (T.C.)

Abstract: Seaports are at the forefront of global trade networks, serving as hubs for maritime logistics and the transportation of goods and people. To meet the requirements of such networks, seaport authorities are investing in advanced technologies to enhance the efficiency and reliability of port infrastructures. This can be achieved through the digitalization and automation of core systems, aimed at optimizing the management and handling of both goods and people. Furthermore, a significant effort is being made towards a green energy transition at seaports, which can be supported through marine renewable sources. This promotes energy-mix diversification and autonomy, whilst reducing the noteworthy environmental footprint of seaport activities. By analyzing these pertinent topics under the scope of a review of container-terminal case studies, and these ports' respective contexts, this paper seeks to identify pioneering smart seaports in the fields of automation, real-time management, connectivity and accessibility control. To foster the sustainable development of seaports, from an energy perspective, the potential integration with marine renewable-energy systems is considered, as well as their capabilities for meeting, even if only partially, the energy demands of seaports. By combining these fields, we attempt to construct a holistic proposal for a "model port" representing the expected evolution towards the seaports of the future.

Keywords: marine renewable energy; green energy transition; blue economy; seaports; smart logistics and management; breakwaters

Citation: Clemente, D.; Cabral, T.; Rosa-Santos, P.; Taveira-Pinto, F. Blue Seaports: The Smart, Sustainable and Electrified Ports of the Future. *Smart Cities* **2023**, *6*, 1560–1588. https://doi.org/10.3390/smartcities6030074

Academic Editors: Jamie W.G. Turner, Giovanni Vorraro, Hui Liu and Toby Rockstroh

Received: 16 April 2023
Revised: 16 May 2023
Accepted: 25 May 2023
Published: 5 June 2023

1. Introduction

The shipping industry is currently responsible for delivering about 80% of global trade, but this comes at a cost, as greenhouse gas emissions rose by 4.7% between 2020 and 2021. Such a trend is partially attributed to an ageing fleet worldwide, since older ships generate more pollution [1,2]. A transition to a new generation of electrified ships integrated with "smart" digital systems is required. Though a full electrification is challenging, mainly on the propulsion front, any partial integration (e.g., lighting and navigation systems) on large vessels would represent an improvement, to which can be added the greater potential for electrification of smaller vessels, such as tugboats, fishing or patrol boats. Moreover, this effort can be extended to the infrastructure responsible for harboring and handling them: the seaports.

Alongside the requirements of handling and expediting cargo, seaports are also responsible for receiving cruise ships, harboring marinas and fishing docks, providing shelter for inner harbor areas, and transferring goods and/or people to the hinterland networks, among other activities. Moreover, seaports must adapt to the abovementioned requirements of the shipping industry, from digital connectivity to ship electrification, and promote measures that mitigate the impacts of pollution and climate change (sea-level rise and extreme events), namely, by transitioning to renewable energy sources (RESs) [3–5]. It is obvious how important maritime transport and seaports are to the stability and growth of modern societies, as well as how necessary their modernization, sustainability and resilience are to meet present and future challenges. To that end, seaport authorities are mobilizing efforts towards making seaports "smarter" and more energy efficient.

On the smart seaport front, several studies address the opportunities and challenges inherent to implementing advanced digital systems. Ilin et al. [6] emphasize the numerous technological options within the framework of Industry 4.0 and "Smart Cities". For instance, the concept of "Smart Port" can integrate technologies such as autonomous vehicles, the Internet of Things (IoT), low-cost sensor technologies, Big Data, augmented/virtual reality, robots/drones and 3D printing. Implementing these technologies will, however, require significant upgrades to information technology (IT) services and connectivity. Managing these systems is also challenging, given their novelty and complexity. To assist in this transition, Min [7] proposes a basic smart-port pyramid architecture, whilst summarizing the necessary software and interconnections (from equipment-level sensors to top-level enterprise resource planning). Durán et al. [8] study the implementation of blockchain and crowdsourcing systems for data transformation for decision-making, namely with the CrowdBC system as a transactional platform for electronic messages. Complementarily, Sangeerth and Lakshmy [9] discuss the role of smart contracts in improving automation, immutability, transparency, decentralization and privacy in the entire shipment process.

Concerning automated terminals and smart-seaport planning, Lakhmas and Sedqui [10] propose a simulator model for congestion management optimization in smart ports, while Yao et al. [11] recommend that seaports invest in a GIS-based Smart Port–Industry–City Spatial Geographic Information Platform, a Port Information Model, a Smart Port Big Data Center and a Smart Port–Industry–City Digital Twin (DT) model. The DT conceptualization is also highlighted in [12], where the authors emphasize not only the opportunities of DT-driven management (e.g., real-time data sharing, predictive optimization and high-fidelity digital representation of seaports) but also the challenges inherent to DT modelling, data connectivity and system security. The latter subject is discussed in [13], where four distinct cyberattack scenarios on container-seaport assets are studied. It is found that all the considered scenarios yield risk levels above the threshold considered acceptable by port authorities, which should be corrected through training, raising awareness, greater control of IT service access and the implementation of backup systems, among other things. Lastly, the role of communication networks is studied in [14,15], which employ an integrated, data-driven DataPorts conceptualization and a crisp/fuzzy-based approach, respectively, for improved data management within smart seaports. All of these systems, alongside others such as cloud computing and radio-frequency identification, comprise the modern definition of smart seaports, distinctive of the fifth and current phase of historical seaport evolution [16]. This phase is also characterized by a strong commitment towards sustainable and energy-efficient seaports, with considerable investment put into smart electrification and RESs, including those found at sea.

On the energy front, a win-win situation presents itself. Marine renewable energy (MRE) can become a significant contributor towards a greener energy mix in seaports, whilst providing highly dense, predictable and directly accessible power sources. Conversely, seaports provide a promising niche market for the demonstration and deployment of MRE technologies, fostering their growth and improvement [17].

Amongst MRE sources, wave energy stands out as a high-density resource that can contribute to Europe's decarbonization goal of becoming the first climate-neutral continent [18]. As seaports are a significant source of air and water pollution [5,19,20], and prominent electricity users [21], they can greatly benefit from including a clean, sustainable and inexhaustible source of electricity in their energy mix. Still, seaports' energy demands are, as of now, fulfilled mainly by means of fossil-fuel energy sources [22]. Transitioning to clean energy sources will not only lead to significant savings in electricity costs, but will also contribute to improving society's perception of ports. According to the European Sea Ports Organization (ESPO), climate change is the top environmental priority of European ports, with air quality and energy efficiency in second and third place, respectively. Ports are increasingly playing important roles as energy hubs and nodes for the blue economy [23]. The ESPO Trends in Port Governance 2022 Report 1 finds that energy is increasingly part of the port business, with ports being prime locations for marine energy production, as well as bolstering the ongoing energy transition. With climate change and air quality as the first and second environmental priorities for ports, it is clear that transitioning to locally harvested energy to provide electricity for port activities and shore-to-ship power (SSP) is the path to follow for seaport authorities to attain their objectives. Furthermore, not only can wave-energy conversion provide electricity to smart-seaport technologies and systems, but it could also add a source of income through the sale of surplus energy to the local grid.

Port authorities are promoting considerable efforts towards the objective of becoming energy self-sufficient by producing electricity using MRE sources, such as offshore wind or wave energy [22]. For the latter, numerous wave-energy converter (WEC) concepts exist at distinct technology readiness levels (TRLs), although widespread commercialization has yet to be reached [24]. To that end, it is of the upmost importance to test WECs under real wave conditions, as other means of research and development, such as physical and numerical modelling, have intrinsic limitations. Moreover, there are some cases of the successful implementation of full-scale wave-energy harvesting technologies in ports, which are important demonstrations that this is a possible path towards sustainability and self-sufficiency. However, these need to be implemented on a large-scale and in multiple locations to de-risk their use and incentivize other port authorities to follow the example. Breakwaters are prime port structures for this goal.

Breakwaters are built to provide protection against wave loads on coastal areas and infrastructures, such as berths, maneuvering areas and port facilities. Integrating WECs into port breakwaters can lead to several advantages, namely: (i) the efficient use of space, since the breakwater, or a section of it, will be replaced by the WEC; (ii) facilitating access to the electricity grid through the port's infrastructure; (iii) general infrastructure for construction and maintenance procedures already being in place, as port breakwaters are accessible from the land; (iv) sharing building costs when the WEC's integration is considered prior to the breakwater's construction; (v) promoting water (re-)circulation within the harbor field, enhancing the water quality; and (vi) an improvement in the performance of protection structures due to the efficient absorption of wave energy.

However, there are considerable challenges to the implementation of wave harvesting devices in ports. On the one hand, the lack of progress in WEC technology means that there is still no design convergence, stalling the low level of maturity of WEC technologies [25]. On the other hand, breakwater-integrated WECs cannot compromise the breakwater's main function of protecting the harbor, nor affect the stability of the structure [26]. What is more, the deployment of these devices inside the ports' protected areas can hinder the safe maneuvering of ships and restrict the traffic inside the seaport. These challenges, alongside others such as the cost of ensuring reliable operation under the harsh marine environment, mean that the current levelized cost of energy (LCoE) for wave energy remains relatively high when compared to other renewable and non-renewable sources. LCoE estimates for wave energy range between EUR 225/MWh [27] to EUR 1220/MWh (for initial, pilot-scale wave-energy projects) [28], with other authors proposing values within this range [29,30]. In comparison, in 2021, onshore wind and solar PV presented LCoE values of EUR 31 and EUR 45/MWh, respectively, and offshore wind an LCoE of EUR 71/MWh [31] (values converted from USD to EUR at the rate of USD 1 = EUR 0.94). Notwithstanding this, the European strategic energy technology plan (SET-Plan) declaration of intent for ocean energy [32] has set ambitious economic targets for wave-energy technologies, as low as EUR 200/MWh in 2025 and EUR 150/MWh in 2030, and this value is expected to reach EUR 100/MWh in 2035 [33].

Complementarily to wave energy, other MRE sources can be harvested in ports, which would benefit from an even more diversified renewable-energy mix, contributing to a reliable and sustainable energy system. MRE also includes wind, tidal, ocean-current, ocean-thermal, osmotic and (floating) solar PV energy, which can all be incorporated into the energy portfolio of seaports. However, each port presents specific characteristics that may enhance or impair the incorporation of these technologies in their jurisdiction areas. Therefore, a thorough assessment of the best site-technology combination is crucial for the successful implementation of MRE in ports. Ramos et al. [34] propose an integrated approach to assessing the wave potential to provide energy to seaports using the Port of Leixões (Portugal) as a case study. Sannasiraj and Sundar [35] suggest selection criteria for WEC technology based on various parameters, such as physical site characteristics, environmental conditions and the regional socio-economic state. Cascajo et al. [22] assess which is the best WEC to integrate into the breakwater of the Port of Valencia, Spain, and estimate its electricity production. Murali and Sundar [36] present a site and technology selection process for tidal energy. Díaz et al. [37] develop and implement a methodology for the comprehensive evaluation of feasible areas for floating offshore wind farms in the Madeira Islands, Portugal. Despite the clear need for a thorough assessment of site and technology characteristics for the deployment of MRE, the extensive alternatives and significant number of variables make this a challenging selection process for port authorities, who usually lack the technical expertise to carry out this work. Therefore, they could greatly benefit from broad and general guidelines and perspectives on marine renewable energy integration in ports.

In this paper, the aforementioned topics are addressed. To that end, the paper's structure is aligned with its main objectives. Namely, this study will explore the cutting-edge technologies implemented in seaports across the globe, discussing their advantages and disadvantages. The analysis will primarily focus on cyber technologies, followed by a discussion of the measures taken towards achieving sustainable and clean electricity generation—a process known as energy transition. By synthesizing this information, the benefits of these technologies will be identified, and how they can be effectively combined will be explored. Ultimately, this study will culminate in a concise model for the efficient functioning of the seaports of the future. For this purpose, the paper will be divided as follows. Section 2 looks into noteworthy examples of seaports around the world that have promoted digitalization, automation and complementary systems to develop "smarter" infrastructures and logistics. These role models have different contexts, and they encompass varying challenges and technological solutions. However, given the references found in the literature, this review focuses mainly on container-terminal case studies. Section 3 studies existing cases of ports that have integrated marine renewable-energy harvesting, with a focus on wave energy. An overview of WEC technologies is presented, detailing those that are better suited for integration in ports. Section 4 integrates the examples of Sections 2 and 3 into a proposal for a smart and energy-efficient seaport, which is expected to serve as a role model for port authorities, stakeholders and researchers to analyze and adapt for their own seaport case studies. Section 5 summarizes the main findings and seaport models identified in this paper, as well as the opportunities and challenges intrinsic to the integration of MRE sources and technologies.

2. Smart Seaports: The Role of Cyber Technologies

This section addresses the subject of smart-seaport role models around the world, detailing the technological innovations and strategies implemented by pioneering port authorities. Although the literature review pointed towards a significant concentration of smart seaports in the Northern Hemisphere—mainly in Asia, Europe and North America—there are noteworthy case studies from the Southern Hemisphere, as well, adding which offers a richer context for analysis. The following sub-sections will address state-of-the-art advances by topics, such as blockchain and DT generation, which are associated with the smart seaports where such developments are taking place.

2.1. Seaport Automation: The Ports of Singapore and Jebel Ali

Seaport automation has the potential to significantly increase harbor activity whilst freeing human resources for other activities and ensuring control and monitoring measures. This can be achieved in numerous tasks and is expected to improve over time, with increasing data being collected. Manual ship (un)loading operations can be controlled via automation systems capable of employing real-time 3D ship models, from hatches to conveyor belts, alongside scans and with GPS support for improved precision. This ensures spatial awareness (e.g., of obstacles, ship and cargo movements, loading checkpoints, start/stop/emergency break orders and fading areas), while (un)loading procedures can be pre-configured and remotely monitored [38]. Furthermore, automated terminals can execute these and other tasks with greater efficiency and precision, especially when supported by smart cranes, automated vehicles and data logistics centers [39], which will reduce costs and shipping time. Port access can be regulated by smart gates, yards and roads [40,41], while data management (e.g., for vessel traffic, terminal operations, gate appointments and traffic, vehicle identification and coordination, and port–hinterland intermodal systems) can be managed by closed-circuit television (CCTV), radio-frequency identification (RFID) and complementary automated cybersecurity, thus promoting greater security and control [42]. The introduction of automated mooring systems, studied in [43], can also lead to a significant reduction in CO_2 emissions (up to 77%, based on the case study). However, setting up these automated networks requires significant modernization investment, interconnectivity between systems, constant monitoring and specialized training to configure and maintain them, as well as reliable energy sources to provide electricity. While the latter is currently being studied with RESs, such as solar, wind and marine energy [44], a practical perspective can be obtained from examples of smart seaports around the globe.

First is the Port of Singapore, and specifically the Tuas Megaport, a project that is expected to be concluded by 2040 and which has already been granted the title of the ”world’s largest automated container terminal” [45]. It is using a four-phase process, starting with the construction of 21 m deep-water berths over 26 km. For phase 2, an area of 387 ha has been reclaimed, enabling a capacity addition of 21 million twenty-foot equivalent units (TEUs)—up to a total of 65 million—by 2040. Currently, caisson fabrication has been completed, and planning is underway for phases 3 and 4 [46]. To ensure full automation, port authorities are developing a “Next Generation Vessel Traffic Management System” capable of providing accurate, real-time situational awareness of the shipping traffic. This will be complemented by the smart data-driven digitalPORT@SG™ tool and a 5G network to enhance port operation efficiency and reduce the turnaround time of ships. Wharf and yard automation will also be implemented, as well as fully autonomous guided vehicles (AGVs). Maneuverable electrified, automated yard cranes will be implemented to further support cargo transport, which will be managed via a control center for improved productivity and human-resource allocation. These investments will also benefit local IT companies working with the port authorities to build these automated systems, as highlighted in [47]. Lastly, electrified equipment and vehicles [39,48] are expected to reduce carbon emissions by 50% when compared to standard diesel options, complemented by energy certification, the construction of low-energy buildings, smart grids and the implementation of solar energy solutions [46].

In Dubai, the Port of Jebel Ali is also investing in the automation of its infrastructure and equipment. It features one of the world’s largest semi-automated terminals, with 67 berths and equipped with 19 automated quay cranes, 50 automated rail-mounted gantry yard cranes and the capability of handling ultra-large container vessels [39]. RFID-based technology was installed in 2017 to monitor/reduce fuel consumption and manage scheduled vehicle maintenance [49]. The port is also receiving a fleet of autonomous intra-terminal vehicles [50]. The automated container-handling system Boxbay is being tested for this seaport, which can hold nearly 800 containers at once [51]. Furthermore, the ZODIAC terminal operating system has been implemented at Container Terminal 3, featuring 18 internal integrated systems, including the cranes’ automation system, berth planning and management of the rail and inland container depot. It also enables real-time container tracking and processing, automated vehicle-fleet management and automatic terminal-gate control [52,53]. To power these and other systems, a recent study has analyzed the potential incorporation of RESs in the Port of Jebel Ali [54]. In detail, a prototype experiment was set up, assisted by the numerical software HOMER™, to assess the local wind and solar potential. Total cost reductions ranged between 10% (only solar photovoltaic) and 20.8% (only wind), with a combined reduction of 28.7%.

Two seaport conceptualizations are depicted in Figure 1.

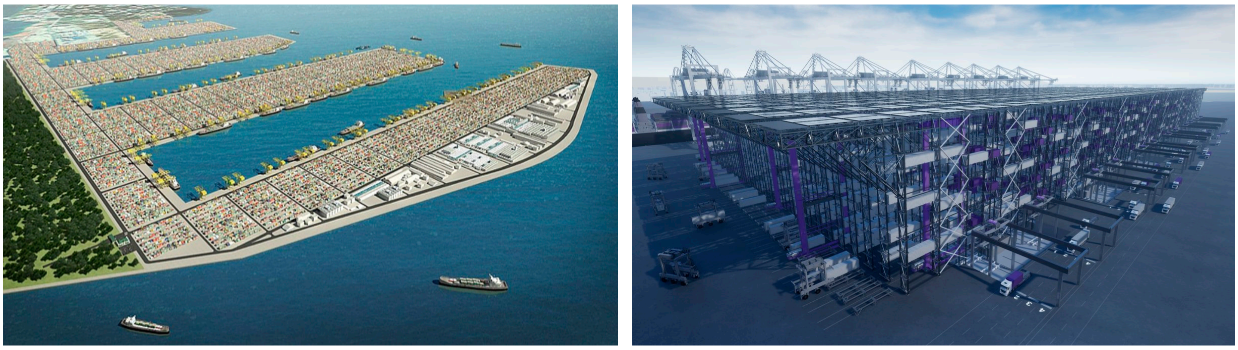

Figure 1. Concept art for the Tuas Megaport (**left**) and the Boxbay container system at the Port of Jebel Ali (**right**). Source: Maritime Port Authority of Singapore [46] and DP World [51].

2.2. Incorporation of 5G at Seaports: The Ports of Shangai and Santos

As highlighted in [55], implementing 5G (and, eventually, 6G) networks in seaports can provide a mobile, yet robust, communication system with low latency, enhanced bandwidth, and capacity that is able to collect and process the vast amounts of data produced by the port's information grid. It is constituted by numerous wireless devices, actuators, data centers and other smart sensors, which establish an encompassing communications network between ships, cargo terminals and other facilities. Therefore, 5G networks promote efficient, interconnected, autonomous and secure seaport operations, whilst boosting port competitiveness and sustainability. Energy use, labor risks and costs are also mitigated when handling/employing automated cranes, autonomous vehicles/drones and condition monitoring systems, as emphasized in [56]. Furthermore, by splitting/slicing the physical network—known as network slicing [57]—into multiple logical networks, based on their attributes and requirements, an improved system flexibility and resource allocation can be achieved since each network is reserved and adapted for specific applications. Even so, there are security, privacy and network function distribution issues yet to be fully addressed. The 5G networks can also be conjugated with immersive virtual reality (VR) [58] through an edge–cloud architecture applied to ship-information visualization (live video), simulation and modelling (e.g., for issuing control commands, assisted driving, remote cargo management, smart security and emergency systems). So long as the virtual scene is sensibly structured to transmit a minimum amount of data, to ensure the required quality-of-service level, the VR–5G combination should be feasible. However, not all applications are fully verified and implemented, as specific quality-of-service and user-experience parameters are required. These topics are discussed for the real cases of the Ports of Shanghai and Santos.

In the Port of Shanghai, which has the world's largest automated container terminal and competes with the Port of Singapore for the prime seaport ranking position, the pier operations plan is supported by on-site computer systems [6]. Equipment such as cranes and self-driving trucks are managed through monitors in the operator cabs, which can also communicate with a control center up to 100 km away. This enables remote adjustment of the containers' movements and control of the trucks through commands via wireless routers, thus allowing for greater cargo transfer between the seaport and the terminals or warehouses [39]. The 5G network also ensures a very low error and/or container-loss probability, and is crucial for establishing AI-based systems alongside a blockchain and a digital twin of the automated Yangshan Deep Water Port terminal [11]. This network information is integrated with the overall strategy for Shanghai, as a part of the "One Belt One Road" initiative (Yangtze River Economic Belt), and it is managed with the support of FusionCloud's Oracle software [59]. Further details on the 5G implementation and other smart-seaport measures for the Port of Shanghai can be consulted in [60], including its energy sustainability activities.

The Port of Santos, a key port terminal operator in South America, is looking to upgrade its Wi-Fi network (currently with 45 access points) through 5G implementation. Through numerous international partnerships and regulator support (Anatel), the improved network is expected to handle large data transfers for a crane remote-control system (Fluid Mesh), the smart sealing of containers, cargo security and truck arrival expediting, among other improvements [61]. According to port authorities, the 5G network is private and operates on a 3.5 GHz band, thus improving contact between workers and enabling remote, real-time equipment monitoring [62]. It is a pioneering development for Latin American ports, and it complements the expected LoRa (long-range) standard for implementing an IoT network [63]. The IoT will, in fact, be addressed in the next sub-section of this paper.

Potential applications of 5G in these two seaports are depicted in Figure 2.

Figure 2. AGV loading a container—using remote 5G-network command—at the Port of Shanghai (**left**), and a container terminal at the Port of Santos (**right**), whose operations may soon be supported by a fully implemented 5G network. Source: [64] (**right**).

2.3. From AI to Blockchain at Seaports: The Ports of Montreal and Hamburg

The aforementioned 5G networks are closely related to the concept of the IoT, as well as to artificial intelligence (AI), cloud computing (CC) and blockchain (BC). These advanced technologies are expected to enhance smart-seaport operations and improve the overall efficiency of the maritime supply chain. These technologies can potentially revolutionize how the current fifth generation of seaports is managed, as well as create new opportunities for increased collaboration and cost savings, as discussed in [65]. BCs, for example, offer a secure and transparent way for tracking the movement of cargo and information within the supply chain. As highlighted in [8], this is due to the fact that BCs are immutable, centralized and verifiable. Additionally, BCs can help seaports better manage their operations by reducing manual processing time, reducing the risk of errors and increasing the level of transparency in their processes. Complementarily, smart contracts, which are self-executing contracts with the terms of the agreement directly written into their code, can also play a key role in the management of smart seaports. These contracts can be used to manage the exchange of goods and services, streamlining processes and reducing the need for manual intervention. By using smart contracts alongside BCs, seaports can automate processes, reduce the risk of errors and fraud, and increase the speed of transactions [9]. As for AI, it can be used to optimize the allocation of resources, reduce waiting times, analyze large amounts of data, make predictions and enhance the overall performance of seaports. By leveraging AI-powered algorithms, seaports can make better decisions and respond more effectively to changing conditions, leading to improved efficiency and lower costs [66]. Nonetheless, data quality should be ensured through

AI-related activity regulation and control, which may be jeopardized by sensor faults or human intervention [67]. Finally, the IoT is a critical component of smart seaports, as it provides a platform for the real-time monitoring of assets and data collection. IoT-enabled devices and sensors can be used to track the location of cargo, monitor the condition of ships and provide real-time information on the status of operations. The IoT, AI and other technologies can be articulated into a reliable automation network, but it is essential to create guidelines and policies for their adoption and management [68]. Two real case studies—the Ports of Hamburg and Montreal—demonstrate the likely path ahead.

The Port of Hamburg, one of Europe's largest seaports, is making significant investments in these new technologies to improve its operations and become a leader in the field of smart ports. As an example, a joint solution for the digitalized release of import containers is being developed by a national consortium of IT companies, as detailed in [69], and being coordinated by the Hamburg City-State Municipal Government to mitigate potential negative effects [70]. One of the goals involves improving the sea-freight-container release by providing a common data platform for sea-freight carriers, terminals, truck companies and freight forwarders. To that end, BC options are being implemented with integrated smart contracts, a project which started in 2018 through Robob (Release Order Based on Blockchain) [71]. While it provides traceable proof of ownership, it can also prompt privacy concerns and/or sensitive information disclosure, given BC's decentralized nature, through data triangulation [72]. Currently, the port is investing in the smartPORT solution, for issues ranging from logistics to energy management, which enables real-time navigation tracking and support, as well as renewable energy supply to cruise liners. Another benefit comes from an intelligent railway system capable of identifying the condition and wear of key intersection points, through sensors, for early-stage smart maintenance/repairs, which reduces downtime. A cloud-based system supports a virtual depot to minimize truck journeys with empty containers, while complementary IoT sensors (Cisco's Wi-Fi Real-Time Location System) are being installed to monitor parameters for pollution, wind speed and direction, and temperature. A central-control-room software, Port Monitor, provides stakeholders in the port with real-time information on harbor activities, and uses AI tools to bolster predictions of maritime and land transport operations. Lastly, port authorities are also investing in e-mobility and parking management (a smartPORT logistics app for trucks) to further promote the sustainable development of the Port of Hamburg [73].

The Port of Montreal, a major gateway for trade in Canada, is also implementing smart-seaport technologies to bolster its efficiency (e.g., reducing congestion in intermodal transportation [74]) and competitiveness. A prime example comes from the "District3 Center" hub initiative, covering a wide range of port logistics projects. These also involved Concordia University and several start-ups specialized in numerous fields, such as AI, automation and robotics [75]. Among them was Canscan, which is responsible for an AI system that links with terminal cameras, processes the images, identifies issues with containers and forwards the necessary information to the client [76]. Furthermore, the incorporation of AI had a positive impact during the COVID pandemic through the establishment of the Cargo2Ai solution. This AI tool facilitated the handling of goods, particularly critical cargo, to promote faster expediting to populations in need [77]. More recently, investment has been made in the AI Galileo tool, which ought to improve the multi-criteria planning for the dispatch of the port workforce and predict ship arrival times up to 21 days in advance [78]. To bolster trade security, port authorities struck a deal with IBM and A.P. Moller–Maersk to join the TradeLens solution, a BC technology that allows the port to augment its resource planning based on inbound traffic with upstream visibility [79].

In Figure 3, some supplementary demonstrations of the smart technologies are provided for these two case-study seaports. It is worth noting that there is a project—TwinSim—to build a digital twin (DT) of the EUROGATE container terminal [80] at the Port of Hamburg, and a VR solution, from PreVu3D, to set up digitalized 3D models for the Port of Montreal [81]. These technologies will be further discussed in the next subsection.

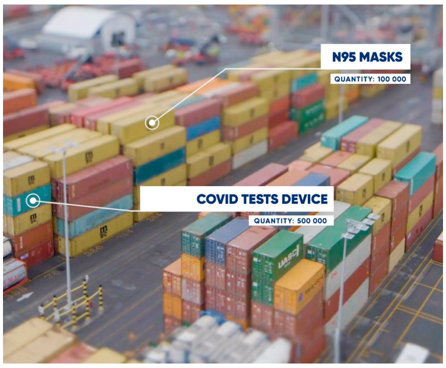

Figure 3. Digital tools of the smartPORT network, in the Port of Hamburg (**left**), and the Cargo2Ai initiative, at the Port of Montreal (**right**). Source: [73] (**left**) and [82] (**right**).

2.4. Digital Twins of Seaports: The Ports of Rotterdam and Antwerp-Bruges

DTs are a relatively new technology that has been gaining popularity in recent years. A DT is a virtual model of a physical object, system or process that is created using real-time data. With the assistance of complementary modelling tools, such as BIM, DTM and GIS, DTs allow port managers to create a virtual replica of the physical seaport environment—a port information model [11]. This technology has been increasingly used in smart ports to monitor and optimize various elements, such as cranes, containers, vehicles, gates, berths, storage areas and ships, and to make better decisions. By collecting data from sensors and other devices installed throughout the port, with IoT and AI support, the DT can create a comprehensive and up-to-date view of the seaport's operations [83]. Though it requires a significant investment in computational resources and connectivity (e.g., a 5G network [84]), this real-time view allows port managers to quickly identify issues and respond to them before they become significant problems. Another benefit of using DTs in smart seaports is the ability to simulate different scenarios. By creating virtual replicas of the port environment, port managers can test different layouts, equipment configurations and traffic patterns to determine the optimal setup for the port. These simulations can also be used to identify potential issues—disruption and recovery scenarios (e.g., power shortages)—as well as to optimize resource allocation and improve operational security, thus bolstering seaport resilience [85]. The use of DTs in smart ports can also help reduce energy consumption and environmental impact. Seaport authorities can reduce the energy required to move goods through the port by monitoring and optimizing the performance of different port elements. This reduction in energy consumption can lead to lower carbon emissions. The increased efficiency and sustainability can also help to make seaports more competitive, as is the case with the Ports of Rotterdam and Antwerp-Bruges.

With an area coverage of over 106 km^2 that handles nearly 30 000 seafaring vessels per year, the Port of Rotterdam is undergoing a significant transformation in order to enhance its vessels' capability to autonomously enter or leave this smart port by 2030, as emphasized in [12,60]. To that end, port authorities are investing, alongside companies such as IBM and Cisco, in BIM-based DT technology through 3D computer-assisted design models. By implementing a sensor-based IoT-cloud and AI dashboard, real-time data on hydrological, meteorological and visibility conditions [76] can be obtained and fed to the DT. It features many services and technologies, from port application programming interfaces (APIs) to the "Boxinsider" cargo tracker [39], among others. This enables port authorities to manage several assets, from smart-quay walls to "digital dolphins", as well as to optimize seaport activities (e.g., berthing) and visibility prediction, reduce vessel waiting time/fuel consumption, and improve cargo handling. Further details on the Port of Rotterdam's DT and other smart-port technologies, from 3D printing to Cisco's Edge Intelligence cybersecurity platform (a topic addressed in the next subsection), can be consulted in [12]. Even so, the Port of Rotterdam is not the only major European seaport developing DTs.

Alongside Rotterdam, the Port of Antwerp-Bruges is one of Europe's largest seaports and is equally resolute on becoming a smart port. Digitalization efforts are mainly aimed at establishing a full cargo authentication process through BC—NxtPort's Bulkchain [86]—and the setup of a digital twin [60]. The DT provides a 3D digital map of the seaport with real-time information on ship positioning, energy supply-chain balancing and the dock situation, thus promoting efficient and safe working conditions. The DT is supported by a network of intelligent wharf walls and a computer vision system. The data originates from digital cameras (over 600) and sensors (iNoses to identify harmful gases), which enable accurate ship berthing, reduced waiting times and optimized preventive maintenance, with the assistance of image recognition [66]. The DT is managed through an application—the Advanced Port Information & Control Assistant (APICA)—configured with a 3D interface. There is also a VR system that estimates water levels and the speed of currents within piers [87]. Lastly, efforts are also being made to implement autonomous boats, drones and a 5G network [39,88].

The application of DT-based models for these two case-study seaports is presented in Figure 4.

Figure 4. DT-based model of cargo handling in the Port of Rotterdam (**left**), and the APICA virtual assistant at the Port of Antwerp-Bruges (**right**). Source: Reprinted with permission from Ref. [12], Copyright 2021, Elsevier (**left**), and [88] (**right**).

2.5. Cybersecurity in Seaports: The Ports of Los Angeles and Tema

As seaports continue to embrace digital technologies and interconnected systems, they become increasingly vulnerable to cyber threats and accessibility security. Cybersecurity in smart seaports is a critical concern, given the significant consequences of a successful cyberattack, unauthorized access or undetected traffic of illegal goods or people. It could potentially cause significant disruptions to port operations, lead to physical damage or loss of cargo, and even threaten human lives, among other potential hazards identified in [13]. Therefore, port operators must implement robust cybersecurity measures to protect their systems and infrastructure from cyber threats. One of the most significant cybersecurity challenges for smart seaports is the complex and interconnected nature of their operations, as they rely on numerous interconnected systems, such as terminal, cargo and vessel-traffic management systems. Any vulnerability in one of these systems could potentially compromise the entire port's operations, as highlighted in [87]. Therefore, port operators must implement robust cybersecurity protocols across all systems and infrastructure to ensure their overall security. Some of the key cybersecurity measures that smart seaports should implement include regular vulnerability assessments and penetration testing, the use of secure communication protocols and network segmentation. Additionally, smart seaports should implement strict access controls and authentication procedures to prevent unauthorized access to their systems. Smart seaports should also invest in cybersecurity training for their staff, as human error remains a significant cybersecurity risk. Port operators should ensure that their employees are aware of cybersecurity threats and best practices, and that they are adequately trained to detect and respond to potential cyber threats [68]. These matters are, hereafter, addressed for the Ports of Los Angeles and Tema.

The Port of Los Angeles, a leading container seaport in North America, has undertaken major efforts to become a smart port, from the development of the Cargomatic Free Flow program to the deployment of "The Signal" cloud-based data tool [39]. However, the incorporation of these advanced cyber technologies presents new risks, which justified the establishment, in 2014, of a Cyber Security Operations Center (CSOC) with a dedicated cybersecurity team. According to port authorities [89], CSOC acts as a centralized hub, enabling proactive monitoring of the port's internal technology environment whilst preventing/detecting potential cyber incidents. This was followed, in 2015, by a pioneering information-security management certification—ISO 27001. Furthermore, in 2021, the Port of Los Angeles established a multi-year partnership with IBM (USD 6.8 million) to set up an upgraded Cyber Resilience Center (CRC). It is operated by IBM but was designed with supply-chain stakeholders, thus instituting an automated port-community cyber-defense solution where cyber-threat indicators can be shared. The CRC includes an IBM Cloud Pak security platform for efficient data analysis and integration, as well as Security X-Force Threat Intelligence experts responsible for cyber-threat management models, the SOAR Security platform for cyber-threat response coding and a security intelligence center to conduct real-time threat analysis and perform defense-coordination activities. These also allow stakeholders and port authorities to help resume operations following a malicious cyberattack, thus bolstering their awareness and readiness to protect key information systems [76]. Lastly, the Port of Los Angeles is involved in numerous cybersecurity initiatives, such as the chainPORT Cyber Resilience Working Group, the American Association of Port Authorities Cybersecurity Committee and a collaboration with the City of Los Angeles' law-enforcement departments on cybersecurity [89].

The implementation of cyber-security and surveillance measures in the Ports of Los Angeles and Tema is depicted in Figure 5.

Figure 5. CSOC at the Port of Los Angeles (**left**), and the Camera Control Room within the Port of Tema (**right**). Source: [89] (**left**) and [90] (**right**).

In Ghana, the Port of Tema is the largest seaport and is responsible for a major share of national trade activities. It covers nearly 4 million square meters of land area and receives, on average, more than 1500 vessel calls per year [90]. Such a pivotal infrastructural asset warrants strict security measures, including against cyber threats and/or unauthorized physical access. To that end, the Ghana Ports & Harbors Authorities (GPHA) invested in 24 h CCTV surveillance supported by trained security personnel who monitor all port zones, including entrance and exit gates [91]. In fact, since 2017, the GPHA has implemented pre-gate security checks via ID cards (biometric authentication through finger scanning) and/or online permit application, which is further bolstered by a smart-turnstile screening system. For vehicles and drivers, there is an online platform that regulates both accessibility and communications. This is complemented by an RFID sticker placed onto the windscreen of verified vehicles. Smart readers and cameras, such as optical character recognition (OCR) readers, within portals and yards, can track the locations, movements, cargo and other pertinent data from both drivers' IDs and their respective vehicles. These tracking systems are also applied in smart cranes and security terminals, in order to monitor the flow of vessels, goods and passengers. All of these data are transmitted to regularly trained IT personnel and the GPHA for improved security and decision making within the Port of Tema. Even so, there are numerous challenges yet to be handled, from the exposure of security systems to weather hazards to potential connectivity shutdowns (e.g., cyberattacks or power shortages). The sizeable amount of generated data requires significant storage capacity, which may be resolved through the implementation of cloud computing [42].

3. Sustainable Seaports: The Role of Marine Renewable Energy

As seaports shift to more sustainable and less polluting solutions, such as electric automated vehicles, cranes and networks, their electricity consumption introduces distinct demand coverage challenges. Moreover, as most of the energy consumption and emissions of ports come from ships, which are still mainly powered by diesel [92], SSP (or cold ironing, shore connection or alternative maritime power—AMP) becomes increasingly common and attractive in ports, which also significantly contributes to increased electricity demand in port facilities. Using SSP instead of energy provided by ships' auxiliary machinery during the hoteling period at ports is an effective method to reduce the amount of emissions from ships in the port area [93]. What is more, Directive 2014/94/EU requires European ports to provide facilities to enable SSP by 2025 [94]. Consequently, producing electricity from MRE, which is directly used in ports' activities, is a promising solution to achieve sustainability targets, lower costs and ensure energy self-sufficiency in ports. In this section, a discussion of WEC technologies is provided, specifically those that can be integrated into ports' breakwaters, along with an analysis of seaports that harvest MRE and a discussion of the future of MRE in ports.

3.1. Wave Energy: Resource, Converters and Port Integration

The wave-energy resource is abundant, clean, predictable, constant and virtually untapped, with an order of magnitude comparable to that of the total world electricity consumption. Gunn and Stock-Williams [95] have estimated that the wave power incident on the ocean-facing coastlines worldwide is about 2.1 TW, i.e., 18,500 TWh available annually, about three-quarters of the world's electricity consumption in 2021 [96]. Reguero et al. [97] consider data from six decades and show that the global theoretical offshore wave power is about 32,000 TWh/yr, or 16,000 TWh/yr if the direction of the energy is considered. Despite this enormous potential, wave-energy-harvesting devices have yet to reach the same level of maturity as other more advanced types of renewable energy, and even other MRE, such as offshore wind and tidal stream. Developers are focusing on utility-scale electricity markets with devices above 100 kW and specialized applications with devices below 50 kW. Hence, only around 25 MW of wave power has been deployed since 2010, with around 3 MW currently operational [98]. This is negligible compared to the available power and should increase considerably in the next few years, especially taking into consideration the ambitious targets set by the European Union for 1 GW of ocean energy by 2030, and 40 GW by 2050 [99].

There are several devices to harvest energy from ocean waves, and more than one thousand patents worldwide [24]. Researchers, inventors and entrepreneurs keep improving old concepts and devising new ones. However, the lack of consensus on what is the best WEC suggests that, until now, no one has been truly successful. Moreover, each device can have different power take-off (PTO) systems, which are the mechanisms that convert mechanical energy to electricity. This brings added complexity to finding the winning concept. The oscillating water column (OWC) is regarded as the first WEC to be conceived and is one of the most studied and developed concepts. It is composed of a chamber of entrapped air, connected to the sea through an underwater opening. The air is pushed through an air turbine by the oscillation of the water's free surface inside the chamber and thus produces electricity. Yoshio Masuda created a navigation buoy powered by wave energy, equipped with an air turbine (Figure 6b), which was in fact a floating OWC. These were commercialized in Japan since 1965, and later in the USA [24]. These can also be bottom-fixed structures (Figure 6a). Some full-sized devices were later constructed in Norway (1985) and on the island of Islay, Scotland (1991) [100], and there was a breakwater-integrated device at the Port of Sakata, Japan [101], and a bottom-standing plant at Trivandrum, India [102]. Since then, other concepts have been proposed, such as the overtopping device (OTD). The Tapchan (Tapered Channel Wave Power Device), seen in Figure 6c, is a device developed in Norway in the 1980s [103] with a prototype built in 1985 at Toftestallen, Norway, and operated for several years. The Tapchan comprises a collector, which concentrates the incoming waves, and a water reservoir where the water is temporarily stored and which serves to provide a stable water supply to the low-head water turbine, which converts the potential energy into electricity.

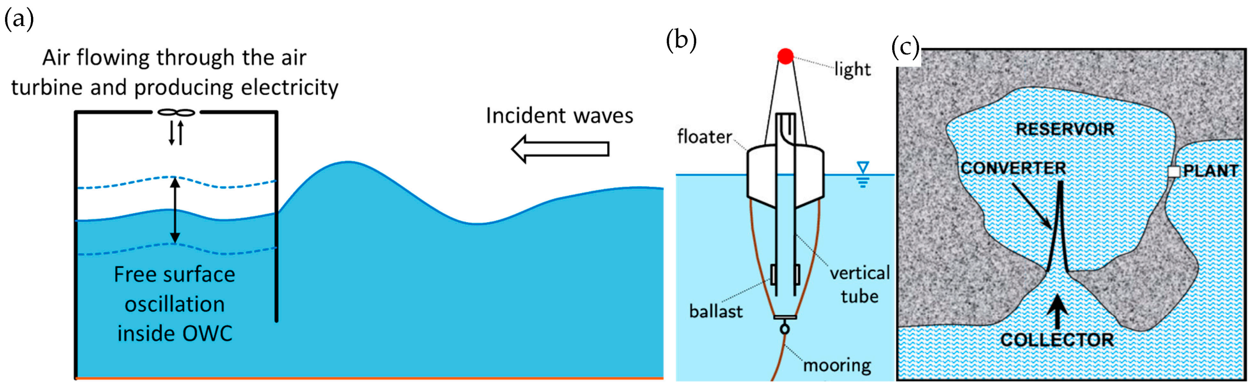

Figure 6. Schematics of (**a**) a fixed OWC, (**b**) Yoshio Masuda's navigation buoy [104] and (**c**) the Tapchan. Reprinted with permission from Ref. [24], Copyright 2010, Elsevier.

Another category of devices, called oscillating bodies, encompasses many diverse solutions formed by oscillating bodies, usually called wave-activated bodies (WABs). These can be classified depending on their mode of operation: single-body heaving buoys; two-body heaving systems; fully submerged heaving systems; pitching devices; bottom-hinged devices; and many body-systems.

Figure 7 shows some examples of oscillating bodies, which are in different development stages, such as CorPower's C4 device, the Waveroller and Eco Wave Power's devices installed in a jetty in Gibraltar.

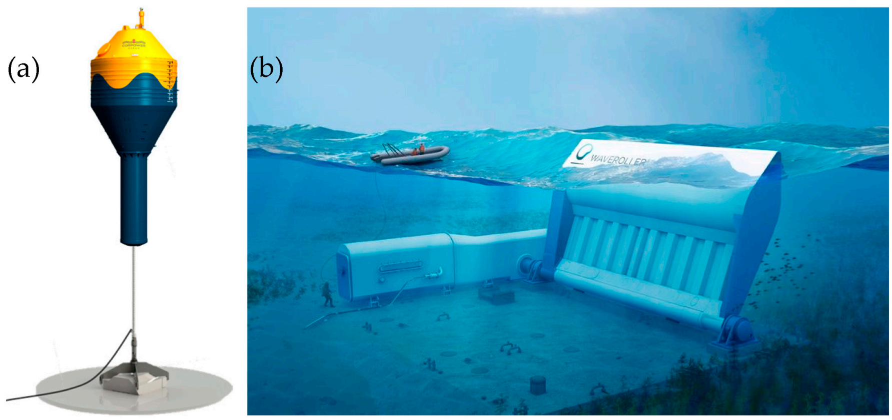

Figure 7. *Cont.*

Figure 7. (**a**) CorPower's C4 converter, (**b**) the WaveRoller and (**c**) Eco Wave Power converters in Gibraltar. Source: (**a**) [105], (**b**) [106] and (**c**) [107].

3.2. Ports Using Locally Generated Electricity from Renewable Sources

Despite the relatively low maturity level of wave energy converters, some full-scale devices are already installed, including in seaports. In what follows, a brief overview of these will be presented. For a more complete review of breakwater-integrated devices, the reader is referred to [108].

1. OWC integrated into the breakwater of the Port of Sakata, Japan

The first breakwater-integrated WEC was the OWC of the Port of Sakata, in Japan, built in 1989 [109], which was equipped with a Wells turbine. This was a pilot breakwater that produced electric power at a wave-to-wire efficiency of only 3.26%. Despite the considerably low efficiency, this prototype proved that electricity can be generated from a breakwater-integrated OWC. Figure 8a shows the schematics of the OWC breakwater and Figure 8b is a photograph of the device.

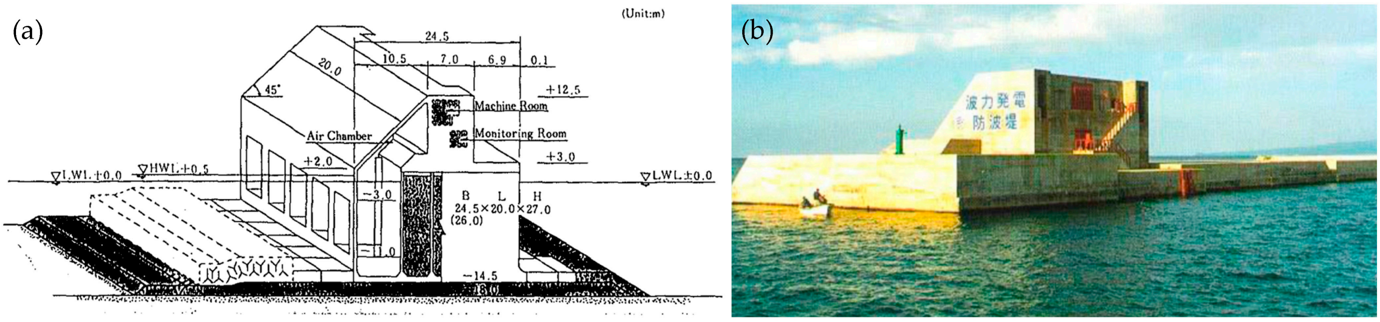

Figure 8. (**a**) Schematics and (**b**) photograph of the OWC integrated into the breakwater of the Port of Sakata, Japan. Source: Reprinted with permission from Ref. [109] (**a**) and [110] (**b**), Copyright 1993 (ASCE) and 2016 (Elsevier).

2. OWC caisson in India

In 1991, an OWC caisson was installed in front of the breakwater of the Vizhinjam Fisheries Harbour in India [111], as seen in Figure 9. The average efficiency of the device was 6.3%, and the amount of power generated was too low to be transferred to the grid most of the time. The device went out of use over the years and was decommissioned in 2011 due to its poor performance.

Figure 9. Bottom-standing OWC installed in 1990 at Trivandrum, southern India. Rated power 125 kW. Source: [110].

3. OWC integrated into the breakwater of the Port of Mutriku, Spain

The Mutriku Wave Power Plant, shown in Figure 10, is located on the Basque coast of northern Spain. It was installed in 2008 and has a capacity of 300 kW. The plant consists of 16 air chambers equipped with Wells turbines. The device has been consistently supplying electricity to the grid, despite the low wave-to-wire efficiency of 2.56% [112].

Figure 10. Mutriku breakwater under construction, Spring 2008. Source: [112].

4. OWC integrated into the breakwater of the Civitavecchia Harbor, Italy

The ReWEC3, Figure 11, is a full-scale U-OWC [113], a slight variation of the OWC, spanning 578 m and including 136 chambers. The ReWEC3 caissons serve the twofold purpose of reducing the reflection coefficient in front of the caisson due to the energy absorption and, simultaneously, converting wave energy into usable electricity. The device showed very high efficiencies, regarding the average absorbed wave power, being on average from 60% to 90% [114]. These efficiencies are, notwithstanding, expected to be lower when the wave-to-wire efficiency is considered.

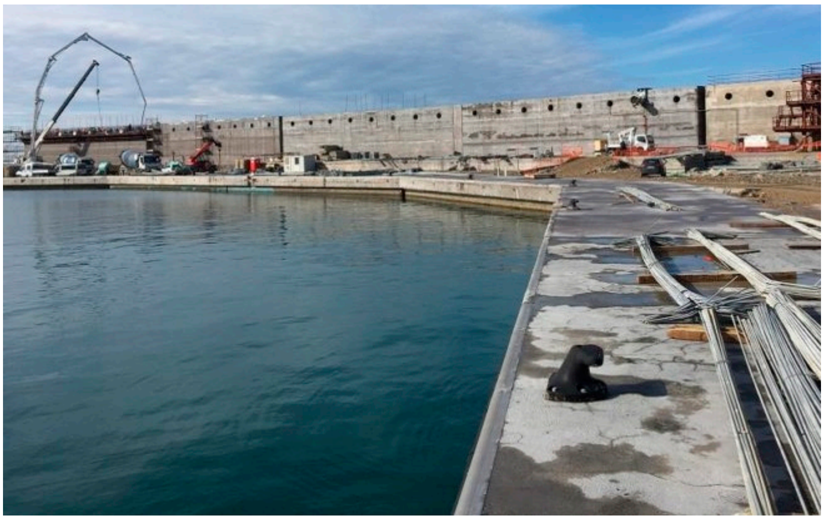

Figure 11. ReWEC3 breakwater at the Port of Civitavecchia, Italy. Source: [115].

5. OBREC

The OBREC is a single reservoir overtopping device (OTD) integrated into a rubble-mound breakwater (Figure 12), built in 2016 at the harbor of Naples, Italy [116]. This pilot is the first OTD device integrated into a breakwater, it is 6 m wide and the depth at the toe berm of the structure is 25 m [117]. It has been providing important research data for WEC developers, but it does not produce electricity.

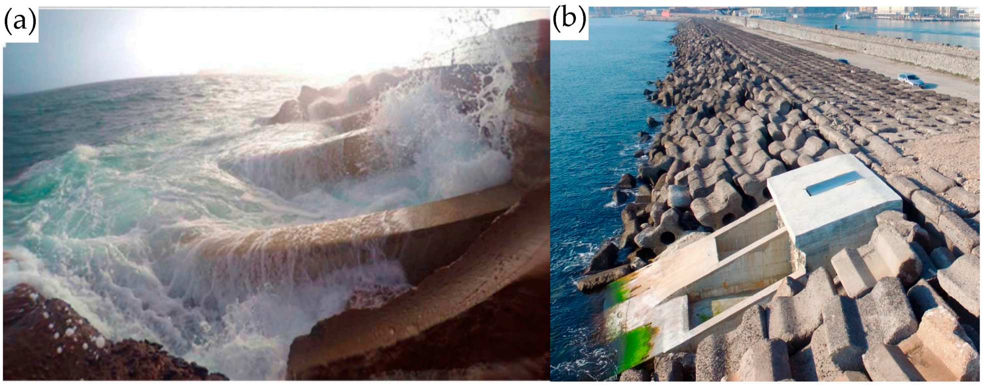

Figure 12. OBREC prototype at Naples harbor in Italy (**a**) under a storm wave (February 2016)—reprinted with permission from Ref. [116], Copyright 2017, Elsevier—and (**b**) in calm weather [117].

6. Seahorse

The Seahorse is a 50 kW WAB device composed of two-point absorbers that was installed at the Port of Pecém, Brazil, in 2012 [118], as shown in Figure 13. The research on this device was carried out between 2013 and 2017 [119], and it was deactivated in 2017 [120]. There is very little information on the performance of this device, but a project exists to deploy an offshore WEC, by the same company, 14 km offshore, with 100 kW capacity [120].

Figure 13. Seahorse point absorbers at the Port of Pecém, Brazil. Source: [121].

7. Eco Wave Power

Eco Wave Power is currently operating the only grid-connected WEC array in the world at the ammunition jetty in Gibraltar, with a 100 kW installed capacity, as seen in Figure 14. The WEC array is an onshore point absorber composed of eight floaters and a conversion unit [122].

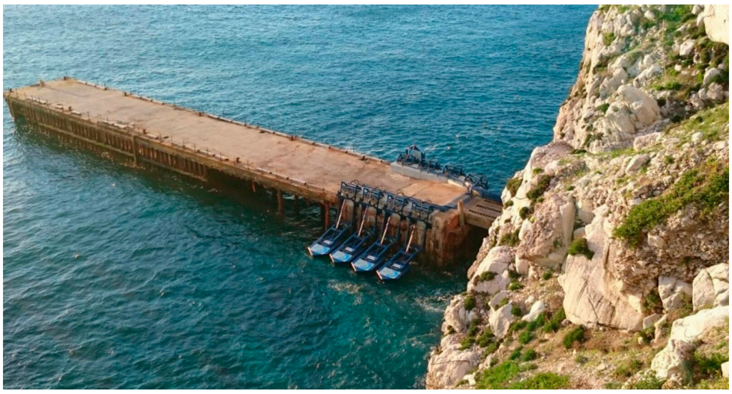

Figure 14. Eco Wave Power's WEC array in Gibraltar. Source: [107].

3.3. Alternative MRE Approaches in Ports

Wave energy is an obvious go-to option to power ports. However, other forms of MRE can be successfully harvested in ports, namely, wind and solar energy (standalone or co-located/hybridized). As the technologies for converting these energy sources into electricity are quite well-established, they will not be detailed here, and only some examples will be presented.

3.3.1. Wind and Solar Energy

Wind and solar energy are growing power sources, generating 6.6% and 3.6% of electricity worldwide in 2021 [122]. Several ports have already started implementing locally produced electricity from these power sources in their energy mix. For instance, the ports of Rotterdam, Kitayjushu, Zeebruges, Hamburg [123], Antwerp [124] and Venice [125] have already introduced locally produced electricity from wind energy. The port of Antwerp also has a solar park that generates "green heat" based on concentrated sunlight [124]. The port of Hamburg has implemented a support scheme which allows port users to establish solar-energy facilities, and solar energy is used to heat water in the port authority's offices [123]. Moreover, the port of Oostende has installed a 10 kWp floating solar-power plant under the DualPorts EU program. Figure 15 shows some of the examples referred to above.

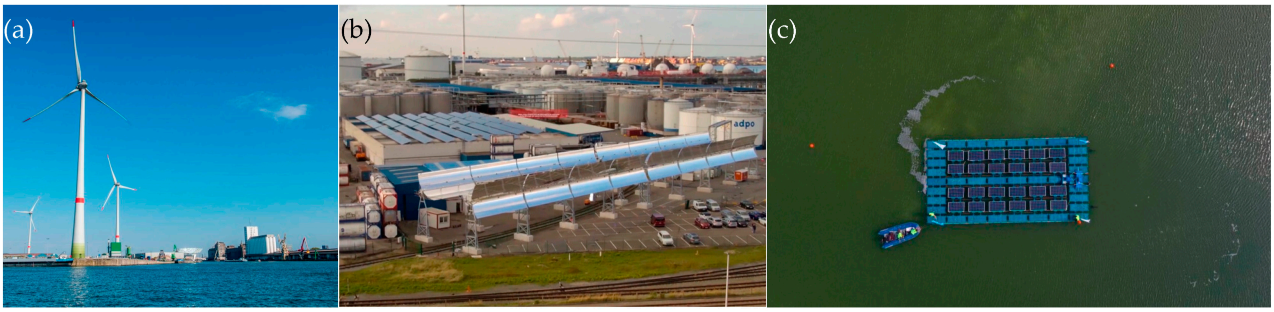

Figure 15. (**a**) Wind turbines and (**b**) solar park at the Port of Antwerp-Bruges—Source: [126]—and (**c**) floating solar power plant at the Port of Oostende—Source: [127].

3.3.2. Hybrid Devices

Despite the obvious benefits of renewable energy, there are still some drawbacks, namely, the fluctuating power availability, with daily and seasonal variability. With that in mind, a possible solution that several authors have proposed is hybridization, i.e., combining multiple concepts in one. Some examples include combining wave and wind energy [128–130], wind and solar [131,132], fuel cells, wave and solar [133], as well as combining wave-energy harvesting concepts [134,135]. Within the existing hybrid WECs, the h-WEC stands out as a promising solution for integration into rubble-mound breakwaters [18] that has higher efficiencies for a broader range of wave conditions when compared to standalone solutions [136], which reduces overtopping rates of the structure by about 50% [26]. This device has been tested using physical [137,138] and numerical [139] modelling at scales of 1:40 and 1:50 (Figure 16).

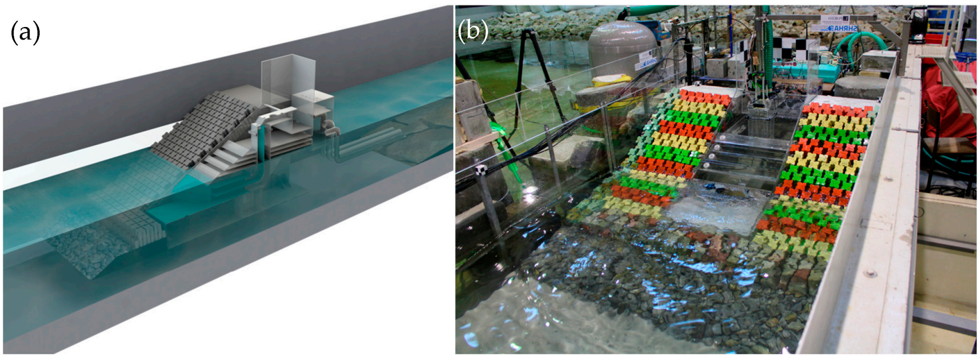

Figure 16. (**a**) Illustrative cross-section of the h-WEC physical modelling tests and (**b**) photograph of the 1:40 model in FEUP experimental facility.

4. Discussion and Model Seaport Proposal

Based on the topics presented in the previous sections, a model seaport will be proposed that represents the path that port authorities should follow to reach sustainability within the seaport environment. Although this holistic proposal is mainly based on the reference container terminals, the premises and technologies ought to be applicable, after adequate adaptation, to other types found within seaports, from RO-RO to cruise-ship terminals.

For instance, within the digital regulatory framework of the EU, Tsoukos et al. [140] propose a cloud-based yard-management platform, CloudYMS, to support operations in RO-RO/RO-Pax ports—including port, supportive, interface and administrative operations—for cargo handling and passenger traffic. The platform has three main layers—presentation or user interface, business logic and data—which incorporate management tools and sub-systems for shipping-lane interface, berthing allocation, gate accessibility, yard parking/storage, vessel (un)loading control and a dashboard for overall status overview. CloudYMS can, therefore, contribute towards greater security, real-time monitoring and greater efficiency in port operations. Another noteworthy case study is the Norvik seaport, in Sweden, for which a simulation model has been proposed to enhance capacity handling [141]. Several modules, from operation to resource, were structured into a multi-level architecture that encompassed multiple agents responsible for transport, customs and planning, among other things. The study incorporated ferries carrying lorries and trailers, with an estimated flow of 200,000 units/year coming and leaving by two ferries/day, considering 4 h as the inter-arrival time. The model was successfully validated and it enabled the identification of potential issues regarding resource capacity, terminal bottlenecks and equipment mobilization. An experimental extension was carried out in [142] to provide a scalable framework to support decision-making processes within RO-RO terminals. It features key performance indicators to assist in discrete event simulations of scenarios regarding intermodal-transport unit flow, planning and operations (e.g., waiting times, berthing utilization, energy consumption and economic analysis). Additional tools to which port authorities may resort include IoT-based platforms, such as Obelisk (e.g., for improved interoperability of wireless systems and data transfer, stability and scalability based on data volume, and data isolation through multi-tenancy) [143]. To these can be added AI-based algorithms, including the hybrid proposition from [144], which incorporates artificial neural networks, empirical mode decomposition and permutation entropy to enable optimal prediction of daily RO-RO freight traffic. In turn, this allows for advanced planning of schedules and traffic management, thus bolstering decision-making and resource-allocation processes by port authorities.

4.1. Conceptual Framework Overview

The implementation of smart technologies in seaports presents a pertinent antinomy. On the one hand, their integration is aimed at improving the efficiency and quality of port activities, infrastructure management, decision making, and quality control. These are expected to reduce overall expenditures, improve competitiveness and enhance the allocation of resources, including in terms of energy efficiency. On the other hand, smart systems do need energy to operate, and even by assuming low individual requirements, there may be a significant cumulative energy demand to meet. This adds to existing energy demands, particularly for electricity, from port activities. While many of these activities should benefit from digitalization, expenditures related to installing and operating smart systems/equipment (including electricity costs) ought to play an increasingly important role in decision making, investments and budgets by port authorities. Therefore, it will be important to ensure competitive costs from MRE sources, as well as to prove that they can bolster the energy independence, reliability, resilience and sustainability of modern seaports. As demonstrated previously, several ports are already on the path towards an idealized smart and sustainable seaport framework, whose potential can be summarized in a conceptual scenario, as described in the following paragraphs. In a more viable situation, the proposed vessel is assumed to operate with a standardized cargo (e.g., a container vessel), or with cassettes and MAFI trailers (e.g., RO-RO vessels).

Vessels arrive at a seaport being monitored and assisted by automated/remotely operated systems (e.g., GPS, autonomous marine vehicles, drones and remote-control stations). The entry into the port has been simulated through 3D DT models and AI-driven algorithms, in order to prevent potential hazards and optimize both the allocation of resources and the entry path/operations. Sensors measuring weather and wave conditions, as a part of the port's IoT setup, bolster these models and the consequent resource allocation and decision making. Access is also regulated with the assistance of a specialized cybersecurity team. Re-fueling is available through nearshore supply stations and supplementary onshore electric connections (lighting, electronic systems and, if viable, propulsion), which obtain electricity from solar panels, wind turbines and wave-energy converters integrated into the seaport area (from land area to breakwaters).

The vessel transmits, in real-time and via a 5G network, data to the control centers managed by port authorities and stakeholders. It includes information on crew, cargo, destination, onshore operations, re-fueling and involved entities, among other things.

These data are matched against those of the original smart contracts established between the contracting entities and the port authorities, in order to verify all requirements and detect potential issues. The smart contract is one of many found within the BC and CC digital archives, which promotes their validity, security, transparency and incorruptibility.

The vessel reaches the assigned berth, a decision-making process also supported by AI and/or a seaport DT model. Automated mooring systems, transport vehicles, cranes and other auxiliary equipment are standing by to support berthing and (un)loading operations. CCTV, RFID and other monitoring equipment (e.g., IoT sensors and AI-driven image/pattern recognition systems) are remotely managed by specialized port workers, who check the cargo, crew and/or passengers from the newly arrived vessel.

Cargo is (un)loaded with optimal precision and efficiency from vessel to transport vehicles (or vice versa) through automated cranes, which are assisted by IoT sensors, cameras and other monitoring equipment. The data are transmitted in real time thanks to the 5G network, and this further bolsters the reliability of the DT and AI-driven models (Big Data portfolio of the seaport). Cybersecurity teams constantly monitor the operations in conjunction with workers and port authorities. Automated electric vehicles, which obtain electricity from MRE devices installed within the seaport area, receive and tag the cargo for transportation. The information on the destination is received and processed, after which the vehicles begin their pre-defined and optimized journey. Crew and cargo are identified and granted access to the seaport infrastructures through remote scanning, profiling and recognition procedures (e.g., biometric IDs).

Cargo and/or crew and passengers arrive safely at their intended destinations after successfully passing access gates and terminals. Port workers carry on with their activities, with the supporting seaport infrastructure being powered by MRE sources. Once the vessel is ready to leave port, the smart-seaport systems and workers now provide assistance in the exit operations. The vessel is resupplied with standard fuels, which are complemented by electricity for electronics and lighting. This is derived from MRE sources, either through direct supply, e.g., SSP, or by storage units (e.g., in batteries from a seaport storage station). Alongside the electricity supplied to port infrastructures, a significant amount of greenhouse-gas release is avoided whilst promoting a sustainable, energy-independent and eco-friendly seaport. Any eventual disruptions to these and other port activities are closely evaluated by the cybersecurity team and algorithms, in order to prevent and/or mitigate negative impacts (e.g., operations shutdown, data theft, cyberattacks or illegal access/goods) and restore regular operations rapidly.

This framework, as conceptualized in Figure 17, demonstrates the high degree of interconnectivity between smart-seaport and MRE technologies, from which gains in operational efficiency, information flow and system control are expected. However, it also shows the inherent risks of system failure/downtime/corruption, as well as the need for safety, security and redundancy measures to contain potential disturbances of regular operations. There are also limitations intrinsic to system compatibility and viability. For instance, not all vessels can be retrofitted to be fully electric, especially in terms of propulsion units (e.g., diesel engines). Even so, a partial incorporation of MRE-based electricity for specific purposes is plausible. Electric vehicles and cranes operating within the seaport should also be adequately isolated and managed during operations with high-risk fuels, such as oil, gas and other inflammable fluids. This requires staff training, systematic maintenance and monitoring to ensure operational safety. The framework is also the basis of the model seaport in Section 4.2.

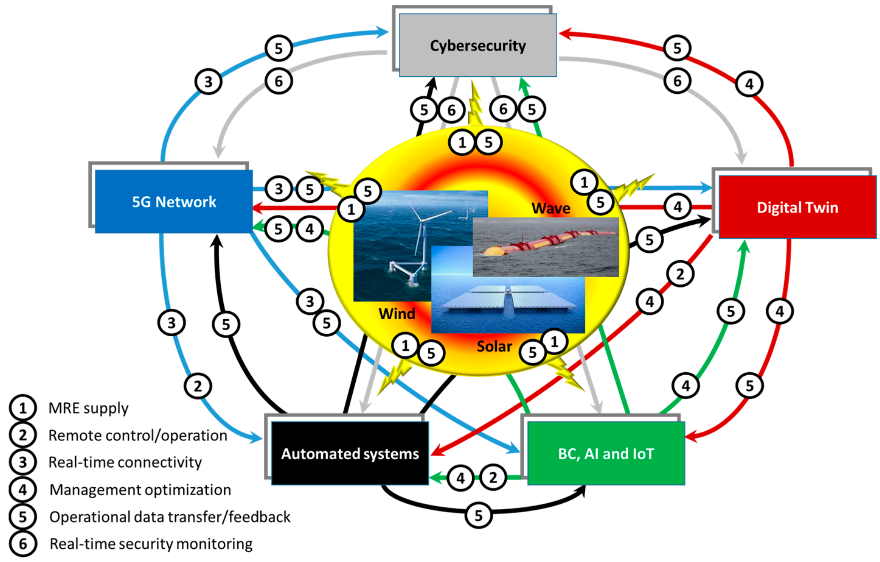

Figure 17. Conceptualization of the smart-seaport framework powered by MRE technologies.

4.2. Smart- and Energy-Sustainable-Seaport Model

Based on the research summarized thus far, a model seaport capable of integrating both smart technologies and renewable energy sources is proposed in this sub-section. As seen in the conceptualization in Figure 18, the proposed model seaport integrates MRE and smart systems in a holistic manner. While MRE devices can provide on-site clean, renewable and abundant electricity to power digital equipment, as well as providing real-time data on their status and on metocean conditions, smart systems can efficiently assist in enhancing MRE operations, as well as those inherent to standard seaport activities (from ship traffic management to automated handling and transport of goods/people).

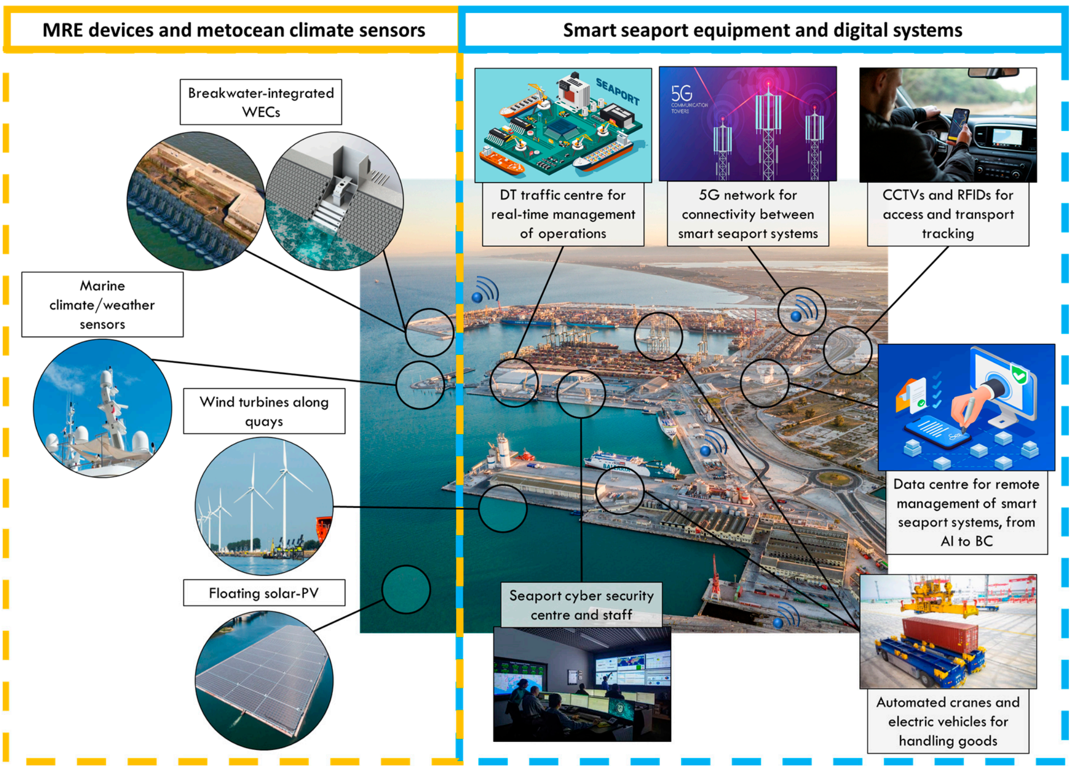

Figure 18. Proposed model seaport: smart, sustainable and energy-efficient.

5. Conclusions

In this paper, an overview of both smart-seaport and MRE technologies has been performed, aiming at an integrated perspective on both topics for a digital and sustainable seaport model. Pioneering harbors and port authorities have seen growing efforts towards building smart infrastructure and systems, from the application of AI to optimal management through fully automated terminals, cranes, gates and electric vehicles. The DTs of seaports enable a fully 3D digital reconstruction of their physical equivalents, with accurate, real-time data crucial for optimal management and decision making. The use of 5G (and future 6G) networks enables real-time data transfer at high speed and low latency between digital systems found within the seaport area. This digitalization enables significant efficiency gains through consistent control and management, as well as scenario simulation. However, it also leaves seaports open to cyberattacks, which justifies the presence of a well-trained cybersecurity team equipped with state-of-the-art protection software. Physical accessibility can also be monitored through RFID and CCTV, whilst BC and smart contracts bolster the transparency and integrity of port activities and trade.

All of these systems require electricity to operate. In the context of the ongoing energy transition, MRE plays a crucial role in the strong commitments that nations worldwide are making to reach fully renewable electricity production. Using MRE to power equipment within seaports' facilities is recommended for this global decarbonization framework. Some seaports, such as the ports of Rotterdam, Kitayjushu, Zeebruges, Hamburg, Antwerp and Venice, already locally produce electricity from wind energy, whilst the ports of Oostende, Hamburg and Antwerp use solar energy for various purposes. Other pioneering port authorities are already implementing electricity production from wave energy within their ports, such as the ports of Mutriku and Civitavecchia.

While MRE can power, even if only partially, the operation of smart-seaport systems and/or vessels and electric boats, it can also contribute through real-time data generation of local weather and metocean conditions, or even by integration with defensive structures, such as breakwaters. The collected data can be transmitted to (and processed by) AI algorithms and DT models that, in turn, issue operational instructions for the optimal operation of MRE technologies and enhanced efficiency, as well as real-time integrity and operational monitoring and management under severe climate conditions. Ensuring data flow is equally essential for the numerous smart-seaport systems, as it enables real-time control, optimal resource allocation and informed decision making, to which can be added improved security against illegal traffic and access.

While most smart seaports and MRE technologies tend to be found in the Northern Hemisphere, the Ports of Santos and Tema serve as leading examples from the Southern Hemisphere. Furthermore, not all advanced seaports have been able to fully implement smart technologies, given the necessary capital investments, logistics and staff training. There is also the matter of terminal compatibility, as existing infrastructure requires the adaptation and integration of the smart-seaport technologies to operate. Hence, port authorities must also evaluate which equipment is suitable for upgrades, and which should be replaced, as well as the necessary investments and the means to implement them effectively. Aside from a specialized cybersecurity team, it is essential to train port authorities, stakeholders, ship crews and workers on-site to adequately use the digital tools made available. Otherwise, there are inherent risks including accessibility security, data corruption and extraction without consent, delays and downtimes from the incorrect use of digital tools, inefficiencies from errors regarding the execution of procedures, and potential damage to goods and/or people from the misuse of remote-control tools, among other things.

MRE devices require further refinement and demonstration to reach commercialization stages. However, their fully integrated use, as proposed in the smart and sustainable seaport model in Section 4.2, offers unique opportunities for port authorities to reach unparalleled competitiveness and efficiency, whilst ensuring environment-friendly solutions for the seaport areas under their jurisdiction. Even so, there are practical matters to consider. Not all vessels are currently suitable for full electrification, although a partial process may be viable. Though trends point towards electric-ship manufacture, this is more of a long-term perspective, as it would be economically unviable and impractical to retrofit or repurpose all currently existing vessels. There are also safety concerns regarding specific operations, such as the handling of inflammable fuels, which require training and monitoring for electric isolation to avoid hazardous situations (e.g., spark-induced combustion or explosion).

Author Contributions: D.C. and T.C.: conceptualization, methodology, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, and visualization. P.R.-S. and F.T.-P.: conceptualization, validation, resources, writing—review and editing, project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: D. Clemente was funded by the project ATLANTIDA—Platform for the monitoring of the North Atlantic ocean and tools for the sustainable exploitation of the marine resources, with grant reference NORTE-01-0145-FEDER-000040, which is co-financed by the European Regional Development Fund (ERDF) through NORTE2020. This research was also partially funded by the Ports Towards Energy Self-Sufficiency (PORTOS) project, co-financed by the Interreg Atlantic Area Programme through the European Regional Development Fund, grant number EAPA-784/2018. This research was also partially funded by the OCEANERA-NET Second Joint Call 2019 project WEC4PORTS—a hybrid Wave Energy Converter for PORTS (proposal ID 5111), with the references HBC.2019.2443, under the framework of the Agentschap Innoveren en Ondernemen (VLAIO), and OCEANERA/0004/2019, under the framework of the FCT—Fundação para a Ciência e a Tecnologia. In addition, T. Calheiros-Cabral has been supported by the PhD scholarship grant 2021.07687.BD from the FCT.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: The authors would like to acknowledge the cited seaport authorities and the Freepik platform (macrovector, macrovector_official and freepik) for access to figures and schematics used in this paper. The authors further acknowledge Microsoft Bing's Image Creator platform, which was used to generate the AGV in Figure 2 of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviation

Summary and expansion of abbreviations in the article.

Abbreviation	**Expansion**
AI	Artificial Intelligence
AGV	Autonomous Guided Vehicle
API	Application Programming Interface
APICA	Advanced Port Information & Control Assistant
BC	Blockchain
CC	Cloud Computing
CCTV	Closed-Circuit Television
CRC	Cyber Resilience Center
CSOC	Cyber Security Operations Center
DT	Digital Twin
ESPO	European Sea Ports Organization
GPHA	Ghana Ports & Harbors Authorities
MRE	Marine Renewable Energy
IoT	Internet of Things
IT	Information Technology
LCoE	Levelized Cost of Energy
OCR	Optical Character Recognition
OD	Overtopping Device
OTD	Overtopping Device
OWC	Oscillating Water Column
PTO	Power Take-Off

PV	Photovoltaic
RES	Renewable Energy Sources
RFID	Radio-Frequency Identification
RO-RO	Roll-On Roll-Off
SSP	Shore-to-Ship Power
Tapchan	Tapered Channel Wave Power Device
TEU	Twenty-foot Equivalent Unit
TRL	Technology Readiness Level
VR	Virtual Reality
WAB	Wave-Activated Body
WEC	Wave Energy Converter

References

1. UN. *Review of Maritime Transport 2018. United Nations Conference on Trade and Development*; United Nations: New York, NY, USA, 2018. [CrossRef]
2. UNCTAD. *Review of Maritime Transport 2021*; UN: New York, NY, USA, 2021.
3. Becker, A.H.; Acciaro, M.; Asariotis, R.; Cabrera, E.; Cretegny, L.; Crist, P.; Esteban, M.; Mather, A.; Messner, S.; Naruse, S.; et al. A note on climate change adaptation for seaports: A challenge for global ports, a challenge for global society. *Clim. Chang.* **2013**, *120*, 683–695. [CrossRef]
4. Becker, A.; Inoue, S.; Fischer, M.; Schwegler, B. Climate change impacts on international seaports: Knowledge, perceptions, and planning efforts among port administrators. *Clim. Chang.* **2012**, *110*, 5–29. [CrossRef]
5. Hiranandani, V. Sustainable development in seaports: A multi-case study. *WMU J. Marit. Aff.* **2014**, *13*, 127–172. [CrossRef]
6. Ilin, I.; Jahn, C.; Weigell, J.; Kalyazina, S. Digital Technology Implementation for Smart City and Smart Port Cooperation. In Proceedings of the International Conference on Digital Technologies in Logistics and Infrastructure (ICDTLI 2019), St. Petersburg, Russia, 4–5 April 2019; Atlantis Press: St. Petersburg, Russia, 2019; p. 4. [CrossRef]
7. Min, H. Developing a smart port architecture and essential elements in the era of Industry 4.0. *Marit. Econ. Logist.* **2022**, *24*, 189–207. [CrossRef]
8. Durán, C.A.; Fernández-Campusano, C.; Carrasco, R.; Vargas, M.; Navarrete, A. Boosting the Decision-Making in Smart Ports by Using Blockchain. *IEEE Access* **2021**, *9*, 128055–128068. [CrossRef]
9. Sangeerth, P.S.; Lakshmy, K.V. Blockchain based Smart Contracts in Automation of Shipping Ports. In Proceedings of the 2021 6th International Conference on Inventive Computation Technologies (ICICT), Coimbatore, India, 20–22 January 2021; pp. 1248–1253. [CrossRef]
10. Lakhmas, K.; Sedqui, P.A. Toward a smart port congestion optimizing model. In Proceedings of the 2020 IEEE 13th International Colloquium of Logistics and Supply Chain Management (LOGISTIQUA), Fez, Morocco, 2–4 December 2020; pp. 1–5. [CrossRef]
11. Yao, H.; Xue, T.; Wang, D.; Qi, Y.; Su, M. Development Direction of Automated Terminal and Systematic Planning of Smart Port. In Proceedings of the 2021 IEEE 2nd International Conference on Big Data, Artificial Intelligence and Internet of Things Engineering (ICBAIE), Nanchang, China, 26–28 March 2021; pp. 708–712. [CrossRef]
12. Wang, K.; Hu, Q.; Zhou, M.; Zun, Z.; Qian, X. Multi-aspect applications and development challenges of digital twin-driven management in global smart ports. *Case Stud. Transp. Policy* **2021**, *9*, 1298–1312. [CrossRef]
13. Gunes, B.; Kayisoglu, G.; Bolat, P. Cyber security risk assessment for seaports: A case study of a container port. *Comput. Secur.* **2021**, *103*, 22. [CrossRef]
14. Gizelis, C.-A.; Mavroeidakos, T.; Marinakis, A.; Litke, A.; Moulos, V. Towards a Smart Port: The Role of the Telecom Industry. In *Artificial Intelligence Applications and Innovations.AIAI 2020 IFIP WG 12.5 International Workshops*; Maglogiannis, I., Iliadis, L., Pimenidis, E., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 128–139. [CrossRef]
15. Castellano, R.; Fiore, U.; Musella, G.; Perla, F.; Punzo, G.; Risitano, M.; Sorrentino, A.; Zanetti, P. Do Digital and Communication Technologies Improve Smart Ports? *A Fuzzy DEA Approach. IEEE Trans. Ind. Inform.* **2019**, *15*, 5674–5681. [CrossRef]
16. Sadiq, M.; Ali, S.W.; Terriche, Y.; Mutarraf, M.U.; Hassan, M.A.; Hamid, K.; Ali, Z.; Sze, J.Y.; Su, C.-L.; Guerrero, J.M. Future Greener Seaports: A Review of New Infrastructure, Challenges, and Energy Efficiency Measures. *IEEE Access* **2021**, *9*, 75568–75587. [CrossRef]
17. Clemente, D.; Rosa-Santos, P.; Taveira-Pinto, F. On the potential synergies and applications of wave energy converters: A review. *Renew. Sustain. Energy Rev.* **2021**, *135*, 17. [CrossRef]
18. Calheiros-Cabral, T.; Majidi, A.G.; Ramos, V.; Giannini, G.; Rosa-Santos, P.; Taveira-Pinto, F. Development and Assessment of a Hybrid Breakwater-Integrated Wave Energy Converter. *Int. Mar. Energy J.* **2022**, *5*, 281–291. [CrossRef]
19. Bachvarova, E.; Spasova, T.; Marinski, J. Air Pollution and Specific Meteorological Conditions at the Adjacent Areas of Sea Ports. *IFAC-PapersOnLine* **2018**, *51*, 378–383. [CrossRef]
20. Winnes, H.; Styhre, L.; Fridell, E. Reducing GHG emissions from ships in port areas. *Res. Transp. Bus. Manag.* **2015**, *17*, 73–82. [CrossRef]
21. Sdoukopoulos, E.; Boile, M.; Tromaras, A.; Anastasiadis, N. Energy Efficiency in European Ports: State-Of-Practice and Insights on the Way Forward. *Sustainability* **2019**, *11*, 4952. [CrossRef]

22. Cascajo, R.; García, E.; Quiles, E.; Correcher, A.; Morant, F. Integration of Marine Wave Energy Converters into Seaports: A Case Study in the Port of Valencia. *Energies* **2019**, *12*, 787. [CrossRef]
23. ESPO. ESPO Environmental Report 2022. Available online: https://www.espo.be/media/ESP-2959%20(Sustainability%20Report%202022)_V8 (accessed on 20 March 2023).
24. Falcão, A.F.d.O. Wave energy utilization: A review of the technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 899–918. [CrossRef]
25. Pecher, A.; Kofoed, J.P. (Eds.) *Handbook of Ocean Wave Energy*; Springer International Publishing: Cham, Switzerland, 2017; Volume 7. [CrossRef]
26. Clemente, D.; Calheiros-Cabral, T.; Rosa-Santos, P.; Taveira-Pinto, F. Hydraulic and Structural Assessment of a Rubble-Mound Breakwater with a Hybrid Wave Energy Converter. *J. Mar. Sci. Eng.* **2021**, *9*, 17. [CrossRef]
27. Astariz, S.; Vazquez, A.; Iglesias, G. Evaluation and comparison of the levelized cost of tidal, wave, and offshore wind energy. *J. Renew. Sustain. Energy* **2015**, *7*, 053112. [CrossRef]
28. Chang, G.; Jones, C.A.; Roberts, J.D.; Neary, V.S. A comprehensive evaluation of factors affecting the levelized cost of wave energy conversion projects. *Renew. Energy* **2018**, *127*, 344–354. [CrossRef]
29. Taveira-Pinto, F.; Rosa-Santos, P.; Fazeres-Ferradosa, T. Marine renewable energy. *Renew. Energy* **2020**, *150*, 1160–1164. [CrossRef]
30. Uihlein, A.; Monfardini, R.; Magagna, D. *JRC Ocean Energy Status Report: 2016 Edition*; Publications Office of the European Union: Luxembourg, 2016. [CrossRef]
31. IRENA. *Renewable Power Generation Costs in 2021*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022; ISBN 978-92-9260-452-3.
32. The Set Plan Temporary Working Group. SET-Plan Ocean Energy Implementation Plan. Available online: https://oceanenergy-sweden.se/wp-content/uploads/2018/03/set_plan_ocean_implementation_plan.pdf (accessed on 20 March 2023).
33. Têtu, A.; Fernandez Chozas, J. A Proposed Guidance for the Economic Assessment of Wave Energy Converters at Early Development Stages. *Energies* **2021**, *14*, 14. [CrossRef]
34. Ramos, V.; Giannini, G.; Calheiros-Cabral, T.; Rosa-Santos, P.; Taveira-Pinto, F. An Integrated Approach to Assessing the Wave Potential for the Energy Supply of Ports: A Case Study. *J. Mar. Sci. Eng.* **2022**, *10*, 24. [CrossRef]
35. Sannasiraj, S.A.; Sundar, V. Assessment of wave energy potential and its harvesting approach along the Indian coast. *Renew. Energy* **2016**, *99*, 398–409. [CrossRef]
36. Murali, K.; Sundar, V. Reassessment of tidal energy potential in India and a decision-making tool for tidal energy technology selection. *Int. J. Ocean Clim. Syst.* **2017**, *8*, 85–97. [CrossRef]
37. Díaz, H.; Fonseca, R.; Guedes Soares, C. Site selection process for floating offshore wind farms in Madeira Islands. In *Advances in Renewable Energies Offshore*; Taylor & Francis Group: London, UK, 2018; pp. 729–737.
38. Philipp, R.; Prause, G.; Olaniyi, E.O.; Lemke, F. Towards Green and Smart Seaports: Renewable Energy and Automation Technologies for Bulk Cargo Loading Operations. *Environ. Clim. Technol.* **2021**, *25*, 650–665. [CrossRef]
39. Pavlić Skender, H.; Ribarić, E.; Jović, M. An Overview of Modern Technologies in Leading Global Seaports. *Pomor. Zb.* **2020**, *59*, 35–49.
40. Jović, M.; Kavran, N.; Aksentijević, S.; Tijan, E. The Transition of Croatian Seaports into Smart Ports. In Proceedings of the 2019 42nd International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, Croatia, 20–24 May 2019; pp. 1386–1390.
41. APDL. A Janela Única Logística—Alargamento da Cobertura Digital às Cadeias Logísticas. 2021. Available online: https://www.apdl.pt/en_US/-/a-janela-unica-logistica-alargamento-da-cobertura-digital-as-cadeias-logisticas?inheritRedirect=true (accessed on 20 March 2023).
42. Effah, J.; Amankwah-Sarfo, F.; Boateng, R. Affordances and constraints processes of smart service systems: Insights from the case of seaport security in Ghana. *Int. J. Inf. Manag.* **2021**, *58*, 102204. [CrossRef]
43. Ortega Piris, A.; Díaz-Ruiz-Navamuel, E.; Pérez-Labajos, C.A.; Oria Chaveli, J. Reduction of CO_2 emissions with automatic mooring systems. *The case of the port of Santander. Atmos. Pollut. Res.* **2018**, *9*, 76–83. [CrossRef]
44. Alzahrani, A.; Petri, I.; Rezgui, Y.; Ghoroghi, A. Decarbonisation of seaports: A review and directions for future research. *Energy Strategy Rev.* **2021**, *38*, 18. [CrossRef]
45. Mandra, J.O. Tuas Port Opens with 3 Berths as It Progresses to Become World's Largest Fully Automated Port. Offshore Energy. 2022. Available online: https://www.offshore-energy.biz/tuas-port-opens-with-3-berths-as-it-progresses-to-become-worlds-largest-fully-automated-port/ (accessed on 1 February 2023).
46. Maritime and Port Authority of Singapore. Port of the Future. Maritime & Port Authority of Singapore (MPA). 2022. Available online: http://www.mpa.gov.sg/maritime-singapore/port-of-the-future (accessed on 1 February 2023).
47. Ng, D.; Pei, W.C. *Future-Ready Learners: Learning, Lifework, Living, and Habits of Practices*, 1st ed.; National Institute of Education (NIE), Nanyang Technological University: Singapore, 2020.
48. Tardo, A.; Pagano, P.; Antonelli, S.; Rao, S. Addressing digitalization though out a prototyping framework for agile smart services development: The case of Livorno Port. *J. Phys. Conf. Ser.* **2022**, *2311*, 14. [CrossRef]
49. Al Bawaba. ENOC Enhances Technology at Jebel Ali Port to Boost Fuelling Efficiency. Al Bawaba 2017. Available online: https://www.albawaba.com/business/pr/enoc-enhances-technology-jebel-ali-port-boost-fuelling-efficiency-945592 (accessed on 1 February 2023).

50. Port Technology Team. DGWorld to Boost Jebel Ali Port with Autonomous Vehicles. Port Technology International. 2020. Available online: https://www.porttechnology.org/news/dgworld-to-boost-jebel-ali-port-with-autonomous-vehicles/ (accessed on 1 February 2023).
51. Arabian Business. How Dubai Is at the Centre of a Global Port Revolution. 2021. Available online: https://www.arabianbusiness.com/industries/technology/467239-how-dubai-is-at-the-centre-of-global-port-revolution (accessed on 1 February 2023).
52. DP World. UAE Region Implements Locally Developed ZODIAC System in Jebel Ali Port's Terminal 3 to Enable 100% Automation of Facilities. 2021. Available online: https://www.dpworld.com/en/uae/news/latest-news/dp-world-uae-region-implements-locally-developed-zodiac-system (accessed on 1 February 2023).
53. Moore, R. DP World Launches TOS for 100% Automation in Jebel Ali Terminal. Riviera. 2021. Available online: https://www.rivieramm.com/news-content-hub/news-content-hub/dp-world-launches-tos-for-100-automation-in-jebel-ali-terminal-63880 (accessed on 1 February 2023).
54. Elnajjar, H.M.; Shehata, A.S.; Elbatran, A.H.A.; Shehadeh, M.F. Experimental and techno-economic feasibility analysis of renewable energy technologies for Jabel Ali Port in UAE. *Energy Rep.* **2021**, *7*, 116–136. [CrossRef]
55. Bányai, T.; Bányai, Á.; Kaczmar, I. (Eds.) *Supply Chain—Recent Advances and New Perspectives in the Industry 4.0 Era*; IntechOpen: London, UK, 2022. [CrossRef]
56. Wen, M.; Li, Q.; Kim, K.J.; López-Pérez, D.; Dobre, O.A.; Poor, H.V.; Popovski, P.; Tsiftsis, T.A. Private 5G Networks: Concepts, Architectures, and Research Landscape. *IEEE J. Sel. Top. Signal Process.* **2022**, *16*, 7–25. [CrossRef]
57. Sohaib, R.M.; Onireti, O.; Sambo, Y.; Imran, M.A. Network Slicing for Beyond 5G Systems: An Overview of the Smart Port Use Case. *Electronics* **2021**, *10*, 17. [CrossRef]
58. Han, Y.; Wang, W.; Chen, N.; Zhong, Y.; Zhou, R.; Yan, H.; Wang, J.; Bai, Y. A 5G-Based VR Application for Efficient Port Management. *World Electr. Veh. J.* **2022**, *13*, 28. [CrossRef]
59. Gurzhiy, A.; Kalyazina, S.; Maydanova, S.; Marchenko, R. Port and City Integration: Transportation Aspect. *Transp. Res. Procedia* **2021**, *54*, 890–899. [CrossRef]
60. Heikkilä, M.; Saarni, J.; Saurama, A. Innovation in Smart Ports: Future Directions of Digitalization in Container Ports. *J. Mar. Sci. Eng.* **2022**, *10*, 24. [CrossRef]
61. BNamericas. How South America's Main Port Operator Advances through Technology. BNamericasCom. 2021. Available online: https://www.bnamericas.com/en/features/how-south-americas-main-port-operator-advances-through-technology (accessed on 2 February 2023).
62. SPA. Santos Port Authority. Santos Port Authority. 2023. Available online: https://www.portodesantos.com.br/en/ (accessed on 2 February 2023).
63. BNamericas. Brazil's Santos Port to Deploy a Private 5G Network. BNamericasCom n.d. Available online: https://www.bnamericas.com/en/news/brazils-santos-port-to-deploy-a-private-5g-network (accessed on 6 February 2023).
64. PTM. BTP, TIM and Nokia Partner for First Ever 5G Latin America Port Network. Port Technology International. 2022. Available online: https://www.porttechnology.org/news/btp-tim-and-nokia-partner-for-first-ever-5g-latin-america-port-network/ (accessed on 6 February 2023).
65. Yau, K.-L.A.; Peng, S.; Qadir, J.; Low, Y.-C.; Ling, M.H. Towards Smart Port Infrastructures: Enhancing Port Activities Using Information and Communications Technology. *IEEE Access* **2020**, *8*, 83387–83404. [CrossRef]
66. Kuo, S.-Y.; Huang, X.-R.; Chen, L.-B. Smart ports: Sustainable smart business port operation schemes based on the Artificial Intelligence of Things and blockchain technologies. *IEEE Potentials* **2022**, *41*, 32–37. [CrossRef]
67. Kovač, M. Autonomous AI, Smart Seaports, and Supply Chain Management: Challenges and Risks. In *Regulating Artificial Intelligence in Industry*, 1st ed.; Routledge: London, UK, 2021.
68. Gao, J.; Sun, Y.; Rameezdeen, R.; Chow, C. Understanding data governance requirements in IoT adoption for smart ports—A gap analysis. *Marit. Policy Manag.* **2022**, *49*, 1–14. [CrossRef]
69. Kapkaeva, N.; Gurzhiy, A.; Maydanova, S.; Levina, A. Digital Platform for Maritime Port Ecosystem: Port of Hamburg Case. *Transp. Res. Procedia* **2021**, *54*, 909–917. [CrossRef]
70. Acciaro, M.; Renken, K.; Dirzka, C. Integrated Port Cities: The Case of Hamburg. In *European Port Cities in Transition: Moving Towards More Sustainable Sea Transport Hubs*; Carpenter, A., Lozano, R., Eds.; Springer International Publishing: Cham, Swizterland, 2020; pp. 287–301. ISBN 978-3-030-36464-9.
71. Hamburg News. Blockchain Technology to Boost Release Processes in Ports. Hamburg News. 2021. Available online: https://www.hamburg-news.hamburg/en/location/blockchain-technology-boost-release-processes-ports (accessed on 6 February 2023).
72. Hackius, N.; Reimers, S.; Kersten, W. The Privacy Barrier for Blockchain in Logistics: First Lessons from the Port of Hamburg. In *Logistics Management*; Bierwirth, C., Kirschstein, T., Sackmann, D., Eds.; Springer International Publishing: Cham, Swizterland, 2019; pp. 45–61. [CrossRef]
73. HPA. SMARTPORT—The Intelligent Port. 2023. Available online: https://www.hamburg-port-authority.de/en/hpa-360/smartport (accessed on 14 February 2023).
74. Abu Aisha, T.; Ouhimmou, M.; Paquet, M. Optimization of Container Terminal Layouts in the Seaport—Case of Port of Montreal. *Sustainability* **2020**, *12*, 20. [CrossRef]

75. D'Amico, G.; Szopik-Depczyńska, K.; Dembińska, I.; Ioppolo, G. Smart and sustainable logistics of Port cities: A framework for comprehending enabling factors, domains and goals. *Sustain. Cities Soc.* **2021**, *69*, 19. [CrossRef]
76. MPA. Canscan: The Technology That Checks All the Boxes for Shippers' Benefit. 2023. Available online: https://www.port-montreal.com/en/the-port-of-montreal/news/news/logbook/canscan-en (accessed on 14 February 2023).
77. MPA. Artificial Intelligence at the Service of Port Operations in This Time of Health Crisis. 2020. Available online: https://www.port-montreal.com/en/the-port-of-montreal/news/news/artificial-intelligence (accessed on 14 February 2023).
78. PTM. Port of Montréal Optimises Workforce Planning with AI-Powered Tool. Port Technology International. 2022. Available online: https://www.porttechnology.org/news/port-of-montreal-optimises-workforce-planning-with-ai-powered-tool/ (accessed on 14 February 2023).
79. MPA. The Port of Montreal Joins Maersk IBM Platform. 2018. Available online: https://www.port-montreal.com/en/the-port-of-montreal/news/news/press-release/tradelens (accessed on 6 February 2023).
80. HPA. Digital Testing Ground. 2023. Available online: https://www.hamburg-port-authority.de/en/themenseiten/digital-testing-ground (accessed on 14 February 2023).
81. MPA. PreVu3D: Rethinking Port Space. 2023. Available online: https://www.port-montreal.com/en/the-port-of-montreal/news/news/logbook/prevu3d-rethinking-port-space (accessed on 14 February 2023).
82. MPA. Agility and Resilience through Tech: A Lifeline for Distribution Logistics. 2023. Available online: https://www.port-montreal.com/en/the-port-of-montreal/news/news/resilience-en (accessed on 14 February 2023).
83. Yao, H.; Wang, D.; Su, M.; Qi, Y. Application of Digital Twins in Port System. *J. Phys. Conf. Ser.* **2021**, *1846*, 7. [CrossRef]
84. Du, R.; Mahmood, A.; Auer, G. Realizing 5G smart-port use cases with a digital twin. *Ericsson Technol. Rev.* **2022**, *2022*, 2–11. [CrossRef]
85. Zhou, C.; Xu, J.; Miller-Hooks, E.; Zhou, W.; Chen, C.-H.; Lee, L.H.; Chew, E.P.; Li, H. Analytics with digital-twinning: A decision support system for maintaining a resilient port. *Decis. Support Syst.* **2021**, *143*, 27. [CrossRef]
86. Port of Antwerp Bulkchain. 2023. Available online: https://www.nxtport.com/market/live/bulkchain (accessed on 20 February 2023).
87. Jović, M.; Tijan, E.; Aksentijević, S.; Čišić, D. An Overview of Security Challenges of Seaport IoT Systems. In Proceedings of the 2019 42nd International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, Croatia, 20–24 May 2019; pp. 1349–1354. [CrossRef]
88. Port of Antwerp Smart Port | Port of Antwerp-Bruges. 2023. Available online: https://www.portofantwerpbruges.com/en/our-port/port-future/smart-port (accessed on 20 February 2023).
89. Port of Los Angeles about Cybersecurity at the Port of Los Angeles. 2023. Available online: https://www.portoflosangeles.org/business/cybersecurity (accessed on 10 March 2023).
90. GPHA. Ghana Ports & Harbours Authority: Welcome to Port of Tema. Company Website. 2023. Available online: https://ghanaports.gov.gh/page/index/4/ZE4GGQFA/Welcome-to-Port-Of-Tema (accessed on 1 March 2023).
91. GPHA GPHA Takes Key Step to Upgrade Security Surveillance at Port of Tema. 2021. Available online: https://www.ghanaports.gov.gh/media/news-details/323/HZR851WMJDE/GPHA-TAKES-KEY-STEP-TO-UPGRADE-SECURITY-SURVEILLANCE-AT-PORT-OF-TEMA (accessed on 10 March 2023).
92. Yun, P.E.N.G.; Xiangda, L.I.; Wenyuan, W.A.N.G.; Ke, L.I.U.; Chuan, L.I. A simulation-based research on carbon emission mitigation strategies for green container terminals. *Ocean Eng.* **2018**, *163*, 288–298. [CrossRef]
93. Kose, S.; Sekban, D.M. Emphasizing the importance of using cold-ironing technology by determining the share of hotelling emission value within the total emission. *Transp. Saf. Environ.* **2022**, 4. [CrossRef]
94. DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094 (accessed on 20 March 2023).
95. Gunn, K.; Stock-Williams, C. Quantifying the global wave power resource. *Renew. Energy* **2012**, *44*, 296–304. [CrossRef]
96. Enerdata Electricity Domestic Consumption. 2021. Available online: https://yearbook.enerdata.net/electricity/electricity-domestic-consumption-data.html (accessed on 21 March 2023).
97. Reguero, B.G.; Losada, I.J.; Méndez, F.J. A global wave power resource and its seasonal, interannual and long-term variability. *Appl. Energy* **2015**, *148*, 366–380. [CrossRef]
98. REN21. *Renewables 2022 Global status report*; REN21 Secretariat: Paris, France, 2022; pp. 1–309.
99. European Commission. An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future. Available online: https://climate-laws.org/documents/an-eu-strategy-to-harness-the-potential-of-offshore-renewable-energy-for-a-climate-neutral-future_0290 (accessed on 22 March 2023).
100. Whittaker, T.; McIlwaine, S.; Raghunathan, S. A review of the Islay shoreline wave power station. In Proceedings of the First European Wave Energy Symposium, Edinburgh, UK, 30 October–1 November 1993; pp. 283–286.
101. Ohneda, H.; Igarashi, S.; Shinbo, O.; Sekihara, S.; Suzuki, K.; Kubota, H.; Morita, H. Construction procedure of a wave power extracting caisson breakwater. In Proceedings of the 3rd Symposium on Ocean Energy Utilization, Tokyo, Japan, 22–23 January 1991; pp. 171–179.
102. Ravindran, M.; Koola, P.M. Energy from sea waves—The Indian wave energy programme. *Curr. Sci.* **1991**, *60*, 676–680.
103. Mehlum, E. *TAPCHAN*; Evans, D.V., de Falcão, A.F.O., Eds.; Springer: Berlin/Heidelberg, Germany, 1986; pp. 51–55.

104. Henriques, J.C.C.; Portillo, J.C.C.; Gato, L.M.C.; Gomes, R.P.F.; Ferreira, D.N.; Falcão, A.F.O. Design of oscillating-water-column wave energy converters with an application to self-powered sensor buoys. *Energy* **2016**, *112*, 852–867. [CrossRef]
105. Energy Capital Media. Energy Capital—The Magazine. Energy Capital Media. 2023. Available online: https://energycapitalmedia.com/ (accessed on 27 March 2023).
106. AW-Energy Oy. WaveRoller—AW-Energy Oy. 2022. Available online: https://aw-energy.com/waveroller/ (accessed on 10 August 2022).
107. EWP. The Future Is Here: Europe's First Grid Connected Wave Energy Array. 2016. Available online: https://www.multivu.com/players/uk/7851451-eco-wave-europe-first-grid-connected-energy/ (accessed on 20 March 2023).
108. Vicinanza, D.; Lauro, E.D.; Contestabile, P.; Gisonni, C.; Lara, J.L.; Losada, I.J. Review of Innovative Harbor Breakwaters for Wave-Energy Conversion. *J. Waterw. Port Coast. Ocean Eng.* **2019**, *145*, 03119001. [CrossRef]
109. Takahashi, S.; Nakada, H.; Ohneda, H.; Shikamori, M. Wave Power Conversion by a Prototype Wave Power Extracting Caisson in Sakata Port. *Coast. Eng.* **1992**, *1993*, 3440–3453. [CrossRef]
110. Falcão, A.F.O.; Henriques, J.C.C. Oscillating-water-column wave energy converters and air turbines: A review. *Renew. Energy* **2016**, *85*, 1391–1424. [CrossRef]
111. Raju, V.; Jayakumar, J.; Neelamani, S. Concrete Caisson For Also Kw Wave Energy Pilot Plant: Design, Construction and Installation Aspects. In Proceedings of the Second International Offshore and Polar Engineering Conference, San Francisco, CA, USA, 14–19 June 1992; OnePetro, 1992.
112. Torre-Enciso, Y.; Ortubia, I.; de Aguileta, L.I.L.; Marqués, J. Mutriku Wave Power Plant: From the Thinking out to the Reality. In Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 7–11 September 2009; p. 11.
113. Boccotti, P. Comparison between a U-OWC and a conventional OWC. *Ocean Eng.* **2007**, *34*, 799–805. [CrossRef]
114. Arena, F.; Romolo, A.; Malara, G.; Fiamma, V.; Laface, V. *The First Full Operative U-OWC Plants in the Port of Civitavecchia. Volume 10: Ocean Renewable Energy*; ASME: Trondheim, Norway, 2017; p. V010T09A022. [CrossRef]
115. WAVENERGY.it. ReWEC3 in the Port of Civitavecchia. WavenergyIt. 2023. Available online: https://www.wavenergy.it/projects/rewec3-in-the-port-of-civitavecchia/ (accessed on 20 March 2023).
116. Contestabile, P.; Iuppa, C.; Di Lauro, E.; Cavallaro, L.; Andersen, T.L.; Vicinanza, D. Wave loadings acting on innovative rubble mound breakwater for overtopping wave energy conversion. *Coast. Eng.* **2017**, *122*, 60–74. [CrossRef]
117. Contestabile, P.; Vincenzo, F.; Di Lauro, E.; Vicinanza, D. Full-scale prototype of an overtopping breakwater for wave energy conversion. *Coast. Eng. Proc.* **2017**, *1*, 12. [CrossRef]
118. Curto, D.; Franzitta, V.; Guercio, A. Sea Wave Energy. A Review of the Current Technologies and Perspectives. *Energies* **2021**, *14*, 31. [CrossRef]
119. Florêncio, M.; Trigoso, F. *Pesquisas e Projetos Desenvolvidos No Brasil Para o Aproveitamento do Potencial de Geração de Energia Elétrica com Ondas e Marés*; Lepidus Tecnologia: Fortaleza, Brasil, 2020.
120. Sánchez, A.; Rodrigues, D.; Kalid, R.; Torres, E. Potencial energético das ondas na costa brasileira. *Rev. Bras. Energ.* **2017**, *23*, 60–71.
121. SEAHORSE. *Seahorse Wave Energy. Seahorse Wave Energy*. 2023. Available online: http://www.seahorseenergy.com.br/en/ (accessed on 20 March 2023).
122. Enerdata. Share of Wind and Solar in Electricity Production. 2021. Available online: https://yearbook.enerdata.net/renewables/wind-solar-share-electricity-production.html (accessed on 21 March 2023).
123. Acciaro, M.; Ghiara, H.; Cusano, M.I. Energy management in seaports: A new role for port authorities. *Energy Policy* **2014**, *71*, 4–12. [CrossRef]
124. Port of Antwerp-Bruges Climate and Energy Transition. 2023. Available online: https://www.portofantwerpbruges.com/en/our-port/climate-and-energy-transition#hernieuwbaar (accessed on 21 March 2023).
125. Li, J.; Liu, X.; Jiang, B. An Exploratory Study on Low-Carbon Ports Development Strategy in China. *Asian J. Shipp. Logist.* **2011**, *27*, 91–111. [CrossRef]
126. Port of Antwerp-Bruges. Our Port in a Single Click | Port of Antwerp-Bruges. *Company Website*. 2023. Available online: https://www.portofantwerpbruges.com/en (accessed on 20 March 2023).
127. Greenpipe. Greenpipe—Experts on Divisible Cable Protection. *Greenpipe*. 2023. Available online: https://greenpipegroup.com/ (accessed on 20 March 2023).
128. Ramos, V.; Giannini, G.; Calheiros-Cabral, T.; López, M.; Rosa-Santos, P.; Taveira-Pinto, F. Assessing the Effectiveness of a Novel WEC Concept as a Co-Located Solution for Offshore Wind Farms. *J. Mar. Sci. Eng.* **2022**, *10*, 267. [CrossRef]
129. Perez-Collazo, C.; Greaves, D.; Iglesias, G. Hydrodynamic response of the WEC sub-system of a novel hybrid wind-wave energy converter. *Energy Convers. Manag.* **2018**, *171*, 307–325. [CrossRef]
130. Perez-Collazo, C.; Pemberton, R.; Greaves, D.; Iglesias, G. Monopile-mounted wave energy converter for a hybrid wind-wave system. *Energy Convers. Manag.* **2019**, *199*, 111971. [CrossRef]
131. Bi, C.; Law, A.W.-K. Co-locating offshore wind and floating solar farms—Effect of high wind and wave conditions on solar power performance. *Energy* **2023**, *266*, 126437. [CrossRef]
132. Adetunla, A.; Rominiyi, O.; Adaramola, B.; Adeoye, A. Development of a wind turbine for a hybrid solar-wind power system. *Heliyon* **2022**, *8*, e11458. [CrossRef]

133. Talaat, M.; Elgarhy, A.; Elkholy, M.H.; Farahat, M.A. Integration of fuel cells into an off-grid hybrid system using wave and solar energy. *Int. J. Electr. Power Energy Syst.* **2021**, *130*, 106939. [CrossRef]
134. Clemente, D.; Rodrigues, C.; Esteves, R.; Correia, J.; Pereira, A.M.; Ventura, J.O.; Rosa-Santos, P.; Taveira-Pinto, F.; Martins, P. Experimental Performance Analysis of a Hybrid Wave Energy Harvesting System Combining E-Motions with Triboelectric Nanogenerators. *J. Mar. Sci. Eng.* **2022**, *10*, 26. [CrossRef]
135. Zheng, S.; Zhang, Y. Theoretical modelling of a new hybrid wave energy converter in regular waves. *Renew. Energy* **2018**, *128*, 125–141. [CrossRef]
136. Cabral, T.; Clemente, D.; Rosa-Santos, P.; Taveira-Pinto, F.; Morais, T.; Belga, F.; Cestaro, H. Performance Assessment of a Hybrid Wave Energy Converter Integrated into a Harbor Breakwater. *Energies* **2020**, *13*, 22. [CrossRef]
137. Calheiros-Cabral, T.; Clemente, D.; Rosa-Santos, P.; Taveira-Pinto, F.; Ramos, V.; Morais, T.; Cestaro, H. Evaluation of the annual electricity production of a hybrid breakwater-integrated wave energy converter. *Energy* **2020**, *213*, 17. [CrossRef]
138. Rosa-Santos, P.; Taveira-Pinto, F.; Clemente, D.; Cabral, T.; Fiorentin, F.; Belga, F.; Morais, T. Experimental Study of a Hybrid Wave Energy Converter Integrated in a Harbor Breakwater. *J. Mar. Sci. Eng.* **2019**, *7*, 33. [CrossRef]
139. Koutrouveli, T.I.; Di Lauro, E.; das Neves, L.; Calheiros-Cabral, T.; Rosa-Santos, P.; Taveira-Pinto, F. Proof of Concept of a Breakwater-Integrated Hybrid Wave Energy Converter Using a Composite Modelling Approach. *J. Mar. Sci. Eng.* **2021**, *9*, 27. [CrossRef]
140. Tsoukos, G.; Giannopoulos, A.; Bizakis, A. Efficient Management of Operations in Ro-Ro/Ro-Pax Terminals Using a Cloud-Based Yard Management Platform. In *Smart Energy for Smart Transport*; Nathanail, E.G., Gavanas, N., Adamos, G., Eds.; Springer: Cham, Switzerland, 2023; pp. 1205–1217. [CrossRef]
141. Abourraja, M.N.; Kringos, N.; Meijer, S. Exploiting simulation model potential in investigating handling capacity of Ro-Ro terminals: The case study of Norvik seaport. *Simul. Model. Pract. Theory* **2022**, *117*, 16. [CrossRef]
142. Abourraja, M.N.; Rouky, N.; Kornevs, M.; Meijer, S.; Kringos, N. A simulation-based decision support framework devoted to Ro–Ro terminals: Design, implementation and evaluation. *Comput. Ind. Eng.* **2023**, *180*, 19. [CrossRef]
143. Bracke, V.; Sebrechts, M.; Moons, B.; Hoebeke, J.; De Turck, F.; Volckaert, B. Design and evaluation of a scalable Internet of Things backend for smart ports. *Softw. Pract. Exp.* **2021**, *51*, 1557–1579. [CrossRef]
144. Moscoso-Lopez, J.A.; Ruiz-Aguilar, J.J.; Gonzalez-Enrique, J.; Urda, D.; Mesa, H.; Turias, I.J. Ro-Ro Freight Prediction Using a Hybrid Approach Based on Empirical Mode Decomposition, Permutation Entropy and Artificial Neural Networks. In *Hybrid Artificial Intelligent Systems*; Pérez García, H., Sánchez González, L., Castejón Limas, M., Quintián Pardo, H., Corchado Rodríguez, E., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 563–574. [CrossRef]