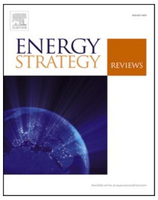
Energy Strategy Reviews 38 (2021) 100727

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr



Decarbonisation of seaports: A review and directions for future research

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ARTICLE INFO

Keywords:
Decarbonisation
Green seaports
Seaports
Smart energy
Smart seaports
Zero carbon

ABSTRACT

Marine activities in seaports account for circa 3% of total carbon emissions worldwide, prompting several initiatives to decarbonise their energy systems and make seaports smarter and greener. This paper provides a thorough and authoritative review of the vast array of research in this field, including past and ongoing initiatives. The study reveals that existing research leverages recent ad-vances in digital technologies while focusing on one or several of the following themes: carbon reduction, use of renewable energy resources, cost-performance optimisation, deployment of smart control technologies, the regulatory land-scape for greening seaports, and implementing green port practices guidelines. As such, the paper provides a critical review of existing technologies and con-cepts that promote and contribute to the decarbonisation of seaports, including Smart Grids and Virtual Power Plants. Several avenues for future research are then discussed, including (a) total life cycle approach to seaport energy manage-ment, (b) Semantic-based modelling, forecasting and optimisation of seaports energy systems, (c) Secure and reliable seaports energy services, and (d) Transi-tion towards prosumer-driven seaport energy communities. The paper concludes by emphasising the importance of an adapted energy regulatory landscape at a national and EU-wide level to meet EU phased energy reduction targets.

1. Introduction

Seaports are important contributors to economic growth worldwide [1]. Since before the Industrial Revolution, seaports have played an essential role in fa-cilitating import and export movements between countries. This has directly contributed to the formation of international trade and global supply chains [2]. However, because of the congestion of commercial activities from ships, and the operations of lifting and unloading containers, as well as the local presence of fish industries, seaports and their surrounding cities, have become carbon-intensive and have experienced substantial pollution levels [3].

The most polluted cities in the world are all coastal cities, which is exac-erbated by the fact that 70% of emissions from ships worldwide occur within 400 km from coastal areas [4]. Based on a recent health board study, emis-sions from seaports and ships lead to about 19,000 annual cases of lung cancer, while approximately 60,000 die every year from conditions caused by pollu-tants [5]. Carbon emissions from ships have increased gradually over time and are currently estimated at circa 2.7% of total CO_2 emissions [6,7]. Based on the United Nations annual review of maritime transport that the annual CO_2 emissions from maritime transport are estimated to be about 1000 (961) million tonnes of CO_2eq [8]. The intensive use of energy from primary sources has led to an increase in carbon emissions. Consequently, there is a pressing need to transition towards clean, affordable and resilient energy systems to help mitigate carbon emissions and limit the effects of global warming [9].

Key milestones in this climate mitigation journey include the 2005 Kyoto protocol [10,11] and the 2015 COP21 Paris agreement [12], where 184 coun-tries agreed to implement practical steps to limit and lower the global average temperature by reducing emissions, as well as increasing reliance on renewable energy [13]. As a result of this international agreement, several countries have begun to establish regulations, legislation and policies to promote the uptake of Renewable Energy Sources (RES) [14]. In order to alleviate some of the burden of decarbonisation from the power sector and to reduce potential decar-bonisation in end-use sectors, some mitigation methods can be implemented. Mitigation methods include (a) integration of energy efficiency and renewable energy, (b) investments in energy savings, and (c) moving towards zero-energy buildings. These aim to increase renewable energy use in buildings and industry, encourage shifts to low carbon technologies and fuels and reduce emissions by optimising building volume, use, and processes [15,16].

The European Union (EU) has approved and launched its European

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https://doi.org/10.1016/j.esr.2021.100727
Received 12 March 2021; Received in revised form 21 September 2021; Accepted 1 October 2021
Available online 14 October 2021

Nomenclature

CO_2	Carbon Dioxide
COP_{21}	Conference of the Parties
RES	Renewable Energy Sources
EU	European Union
RTG	Rubber Tired Gantries
OPS	Onshore Power Supply
AMS	Automatic Mooring System
EMS	Energy Management System
PV	Photovoltaic
PCD	Seaport Container Distribution
MAS	Multi-Agent System
IPCC	Intergovernmental Panel on Climate Change
WPCI	World Seaport Climate Initiative
GHG	Greenhouse Gas emissions
PEEP	seaport Energy Environmental Plan
Rewec3	Resonant Wave Energy Converter
ISWEC	Inertial Sea Wave Energy Converter
IoT	Internet of Things
UNFCCC	United Nations Framework Convention on Climate Change
RO	Renewable Obligation
NFFO	Non-Fossil Fuel Obligation
FIT	Feed-In Tariff
DER	Distributed Energy Resources
DES	Decentralised Energy System
DG	Distributed Generation
ICT	Information and Communication Technology
VPP	Virtual Power Plant
DSO	Distribution System Operator
AI	Artificial Intelligence
ANN	Artificial Neural Networks
GA	Genetic Algorithm
FL	Fuzzy Logic
ES	Expert Systems
LCA	Life Cycle Assessment

green deal [17] which aims to pave the way towards a greener, fairer and thriving European community with a competitive economy that is contemporary and resource-efficient. The Green Deal has the ambition to achieve net-zero carbon by 2050 while promoting economic prosperity. The objective is also to conserve, maintain and improve the natural capital of the EU and to protect individuals health and well-being from environmental impacts.

Many seaports are facing increased pressure to reduce their carbon foot-print while improving their energy efficiency and global competitiveness [18,19]. Moreover, energy consumption in seaports must be continuously monitored to manage increasing energy costs, as reflected by the increase in fuel demand [20]. This review aims to investigate the global efforts to decarbonise seaports, and it aims to answer the following research questions:

- What are the main drivers for the green transition of seaport?
- What is state of the art in delivering the vision of green seaports?
- What are the directions for future research in this seaport decarbonisation journey?

The following section 2 summarizes the methodology that underpins the re-search. Section 3 discusses related works and answers the first research question by discussing the main drivers for greening seaports. Section 4 analyses cur-rent laws, regulations and policies that promote the decarbonisation of seaports. Section 5 discusses interesting, related research initiatives and lists the state of the art technologies that deliver green seaports to answer the second research question. Section 6 concludes the findings of this research and is followed by section 7, which suggests future works.

2. Research approach

This review relied on leading search engines like Science Direct, Web of Sci-ence, Scopus, IEEE and google scholar to identify related research using a set of keywords while covering several decades to factor in key evolutions in the decar-bonisation journey seaports. An initial list of keywords was selected and refined to provide a broad perspective to address the posited research questions. The following keywords were eventually retained as providing comprehensive cover-age of the related academic literature: green seaport, marine energy sources, fish industries, smart energy system, and smart seaport. In the context of this review paper, by Smart we refer to the capability of a system to learn and adapt to changing boundary conditions using digital technologies to address multi-objective scenarios, i.e., the capacity of a seaport to factor in environ-mental, occupancy, and process conditions to reduce energy demand and its carbon footprint.

As shown in Fig. 1, this exercise showed an interesting exponential growth of research papers starting in the late 1990s.

Six main themes have emerged from the analysis of the selected papers, as listed below:

- Carbon reduction
- Renewable energy adoption
- Cost Optimisation
- Adoption of smart control technologies
- Regulatory landscape for greening seaports
- Best practice guidelines for smart green seaports

The research methodology involved five steps, as illustrated in Fig. 2. The first step started with identifying related keywords and then selecting au-thoritative research databases to search for related research. This led to the identification of 428 research papers. Next, the authors have filtered the results by excluding dissertations, duplicate articles, patents, and non-English articles. Fifty-four articles were retained as a result of this process. These themes are discussed in the next section.

3. Related works

This section elaborates on the themes reported in the previous section in-formed by a selected list of related publications listed in Table 3.

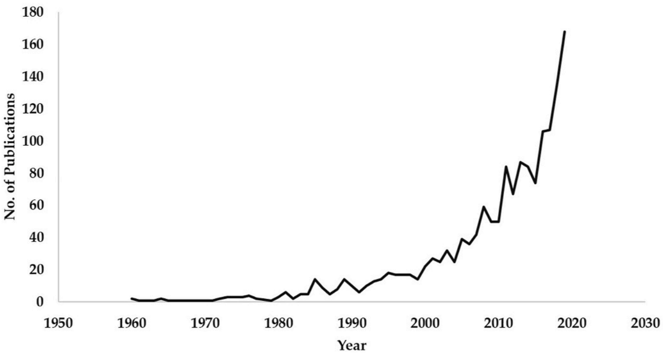

Fig. 1. Profile of relevant publications on green seaports using Scopus.

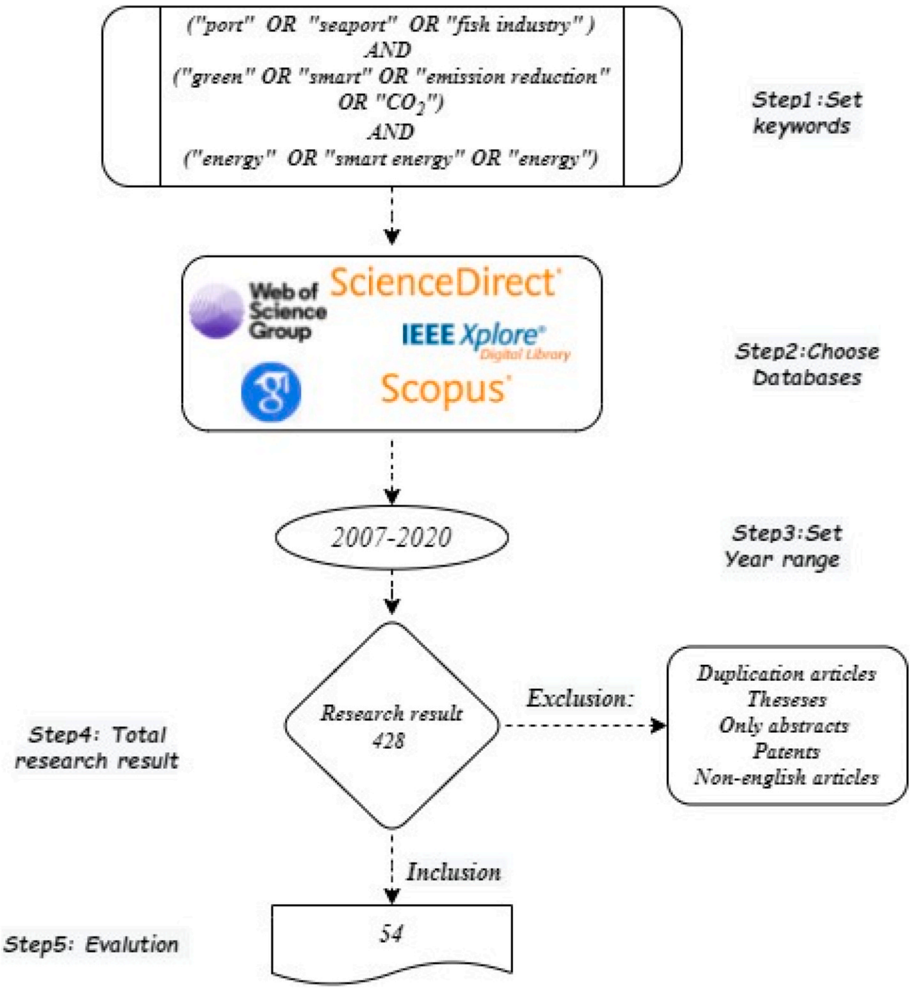

Fig. 2. The phases of the review process.

3.1. *Carbon reduction*

This literature search identified 35 studies that focused on carbon reduction in seaports. These studies are structured into three categories; the first category focuses on the application and implementation of systems that directly assist in reducing carbon emissions in seaports. The second category focuses on in-vestigating and analysing the extent to which systems can be applied to reduce carbon emissions in seaports. The third category proposes practices that may help reduce carbon emissions in seaports. Table 1 present selected studies in each category. Also, these studies are further organised based on whether they relate to a case study, modelling and simulation, or a Framework.

In terms of the first category, Stoll et al. [21] developed an architecture for an active house for residential customers at the Stockholm Royal Seaport. This house can interact with the smart grid at the seaport, reduce carbon emissions and manage the energy consumption in buildings. The study by Aarsaether and Karl [22] presented an initiative used in Norway to reduce carbon emissions by developing battery-based propulsion systems with electric power distribution for the shore-based power supplies of ships in seaports. Yun et al. [23] devel-oped a carbon emission quantification simulation model to eliminate the impact of action strategies on carbon emissions from seaport operations and shipping inside container terminals. The experimental results showed that reducing ship speed in waterway channels from 24 to 8 knots can reduce the carbon emissions of these ships by up to 48.4% and by about 32.9% for the whole container.

Table 1
Carbon reduction studies in Seaports.

Category	Methodology		
	Case study	modelling and simulation	Framework
Category 1	Stoll et al. [21]	Aarsaether and Karl [22]	Wang et al. [24]
	Wang et al. [26]	Yun et al. [23]	Molavi et al. [25]
	Case study	Analysis Approach	Proposed Method
Category 2	Manolis et al. [19]	Fahdi et al. [27]	
	Alzahrani et al. [31, 32]	Gutierrez-Romer et al. [28]	Haibo et al. [34]
	Lam et al. [30]	Piris et al. [29]	Lazaroiu et al. [38]
	Heng et al. [33]	Tovar and Wall [36]	Erdas et al. [39]
	Zhu et al. [35]	Ramos et al. [37]	
	Green Practices		
Category 3	Tsai et al. [40] Twrdy et al. [41] Villalba and Gemechu [42]		

Another important study by Wang et al. [24] proposed a two-stage framework for an optimal design of a hybrid renewable energy system for seaports. This framework can achieve significant reductions in carbon emissions and be used as a reference for green seaport container construction. The study by Molavi et al. [25] explored the impact of applying a smart grid to a seaport using a two-stage stochastic mixed-integer programming model. The results showed that applying a smart grid at a seaport can significantly reduce energy consumption and carbon emissions. Meanwhile, the study by Wang et al. [26] applied a green seaport scheduling model for seaport construction to optimise economic and environmental efficiency. The results showed that such a seaport can reduce the use of coal by about 6527 tonnes, which will consequently reduce CO_2 emissions by approximately 40,875 tonnes.

The second category of research on carbon reduction focuses on the analysis and investigation of systems that will help reduce carbon emissions at seaports. Fahdi et al. [27] compared the performance of Rubber Tired Gantries (RTGs) and Electric Rubber Tired Gantries (E-RTGs). The results showed that using E-RTGs when applying green seaport policies can significantly reduce carbon emissions by about 67.79% and save about 86.6% of energy usage. Gutierrez- Romero et al. [28] investigated the impact of applying an Onshore Power Supply (OPS) for ships at berths. The results showed that applying these technologies can save up to 10,000 tonnes of CO_2. The study by Piris et al. [29] investigated the use of an Automatic Mooring System (AMS), which can result in a reduction of carbon emissions at seaport by about 76.78%.

The study by Lam et al. [30] investigated the feasibility of implementing an Energy Management System (EnMS) for seaports. This study used discrete event simulations for its investigations. The results show that an EnMS can reduce carbon emissions and provide greater benefits for seaport authorities. Meanwhile, Alzahrani et al. [31,32] proposed a smart microgrid for fishery seaports that was validated using a case study of a local seaport. The result shows that the seaport authority and surrounding communities can meet the local power demands using local Photovoltaic (PV) power generation, which will reduce CO_2 emissions considerably. Heng et al. [33] proposed a twin sea-port coordination optimisation model within the framework of vessel terminal coordination. The results showed that both time and fuel consumption could be minimised, which will impact the total amount of carbon emissions. Haibo et al. [34] investigated energy consumption and carbon emissions at seaports using consumption and emission inventories. This study proposed control measures for reducing both energy consumption and carbon emissions.

Lazaroiu et al. [38] highlighted the concept of a zero-emission seaport. This study proposed two scenarios for renewable energy resources at a seaport in Naples to reduce fossil fuel dependency and carbon emissions. Meanwhile, Zhu et al. [35] discussed the use of renewable energy resources to meet power demands in a seaport of Ningbo, Belgium. This study proved that using clean energy in seaports can achieve energy savings and carbon reductions at seaports. Wang et al. [43] analysed the carbon emissions in 30 seaports in China. The authors proposed methods for calculating the carbon emissions from Seaport Container Distribution (PCD). The study by Erdas et al. [39] introduced a strategy for the environmental management of seaports to reduce environmental impacts. Furthermore, Tovar and Wall [36] estimated the environmental efficiency of 28 Spanish seaport authorities using an output directional distance frontier with poor output and high carbon emissions. This study proved that if the seaport authorities provided sufficient environmental efficiency, carbon emissions could be reduced by 63%. Arena et al. [44] studied the feasibility of applying energy systems in seaports that can produce electricity from sea waves and use electric vehicles for mobility. The study by Johnson and Styhre [45] investigated the possibility of increasing energy efficiency in shipping at seaports by reducing the time spent in the seaport. The results showed that an estimated 2–8% reduc-tion in energy consumption could occur in seaports when the time is reduced. Meanwhile, Yang [46] investigated CO_2 emissions from two seaports using car-bon footprint analysis and grey relational analysis. The results showed that a green container should be designed to harmonise container terminal operations with environmental impacts. Ramos et al. [37] investigated the capability of implementing a tidal energy farm to meet the power demands of the seaport of Ribadeo. The results showed that about 25 turbines could meet local power demands and reduce carbon emissions.

The study by Hua and Wu [6] used historical data on the energy consumption of Taiwanese fishing vessels to analyse energy efficiency to find ways to reduce daily emissions. The authors suggested that fisheries should be encouraged via subsidies to use clean energy for their vessels and use informed energy practices for their appliances. Meanwhile, Acciaro et al. [18] urged seaport authorities to apply a smart Energy Management System (EMS) to limit environmental impacts by enhancing the energy efficiency of their systems. The authors in Ref. [18] argued that increasing the energy efficiency of seaport authorities would reduce both carbon emissions and energy costs. This argument was supported through a comparison between two seaport authorities that applied smart energy management strategies. The study by Parise et al. [47] used statistical techno-economic analysis to investigate the impact of applying renewable energy and energy storage for boats to improve the energy network that can exchange power with the grid. The authors argued that applying a smart microgrid can signifi-cantly impact the energy used by the seaport authority. Furthermore, Manolis et al. [19] discussed the importance of a distributed demand response strategy using a Multi-Agent System (MAS) to improve voltage in the energy distribu-tion networks at seaports. Misra et al. [7] estimated the carbon emissions from the seaport of Chennai using guidelines from the Intergovernmental Panel on Climate Change (IPCC) and the World Seaport Climate Initiative (WPCI). The total was found to be about 280,558 tonnes of CO_2/year. The author suggested applying an AMS system and OPS to ate carbon emissions at the seaport site. In addition, Misra et al. [48] proposed that the seaport authority should apply renewable energy technology to help mitigate carbon emissions.

The third category proposes practices that might help reduce carbon emis-sions in seaports. Tsai et al. [40] developed self-management approaches that have the potential to help manage and control the total carbon emissions from seaport activities. Meanwhile, Twrdy et al. [41] investigated the sustainability of seaport logistics and the current status of the seaport in Koper. The authors suggested developing the planning of the seaport site and applying green activ-ities to help reduce carbon emissions at the seaport. A study by Villalba and Gemechu [42] proposed indicator measures of Greenhouse Gas emissions (GHG) for seaport activities that will help monitor and control the carbon emissions in seaports. The author also argued that indicators could help decision-makers prevent and control carbon emissions from seaport authorities over time.

An important finding in relevant studies was the increased role of renew-able energy resources at seaports; therefore, we consider these in a separate subsection.

3.2. Renewable energy adoption

The adaptation of renewable energy is one of the most frequent topics in the review analysis in this study, as shown in Table 3. A large proportion of scientific papers focused on adopting renewable energy for seaports and its effective role in reducing carbon emissions by replacing fossil fuels engines. This section reviews the most important types of renewable energy mentioned in previous studies for use in seaports.

3.2.1. Solar energy

Within the industrial sector, solar power has become an attractive source of energy because it is free, clean and abundant with no pollution [49]. In 2016, the proportion of the renewable share in the form of final energy consumption was about 10% [50]. Also, the installed solar energy capacity globally increased dramatically between 2001 and 2018, as shown in Fig. 3. Two types of solar energy applications are used: solar thermal and PV. Solar thermal industrial applications account for 10% of the total amount of global high-temperature in-dustrial processes [51]. The most common thermal applications are hot water, steam,

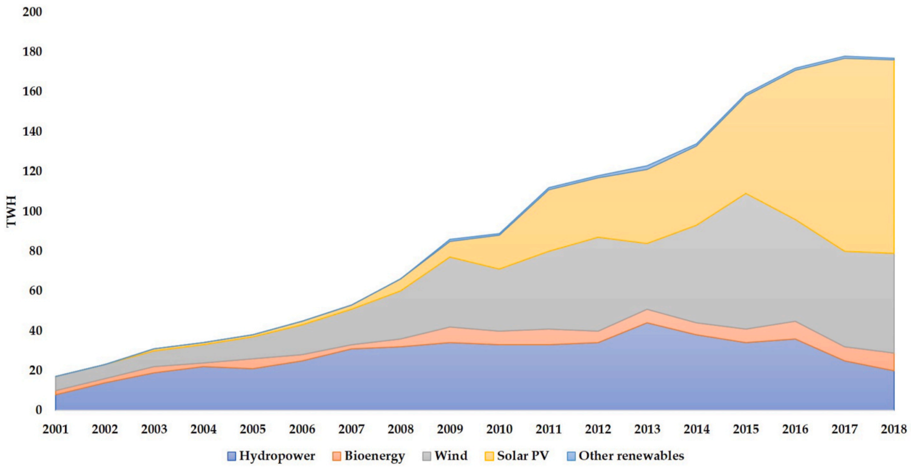

Fig. 3. Global renewable energy capacity from 2001 to 2018 [53].

drying and dehydration processes, preheating, concentration, pasteurisa-tion, sterilisation. Also washing, cleaning, chemical reactions, industrial space heating, food, plastics, buildings, the textile industry, and even business con-cerns [52].

PV refers to the process of converting directly radiated light (solar or other) into electricity [54]. In 2015, approximately 25% of PV solar cells were made of pure monocrystalline silicon. Monocrystalline solar cells are the most effi-cient of all PV panels, boasting efficiency rates of upwards of 15–20% [55]. Many manufacturers offer 25-year warranties on these types of PV systems. In general, solar PV cells involve a simple design component with very competi-tive maintenance costs [56]. PV panels can work effectively in different weather situations. It has also been suggested that the installation costs will gradually decrease due to the increased demand and production of PV panels [57]. PV systems are incredibly versatile, and they can be installed at different sized sites.

For various projects. There are two main groups of PV systems: standalone and grid-connected systems. A stand-alone system is not connected to the grid, and the power production will be used locally to meet power demands. Such a system needs a storage system to meet power demand at night. Solar energy in the industrial sector is used for heating, cooling, air conditioning, and producing energy using PV systems. A PV system can be used directly by storing energy in rechargeable battery systems, which can then be used for different applica-tions [58]. Meanwhile, grid-connected systems are connected to the national grid [59] to feed the surplus power production to the grid and meet demand when the power from the PV system is not adequate. Fig. 3 below shows the installation of renewable energy resources at the global level from 2001 to 2018. Only a few studies [32,48] highlight the application of solar farms, specifi-cally at seaports. The study by Stoll et al. [21] discussed the application of an active house for the sustainability of the Stockholm Royal seaport. This study discussed integrating solar PV systems with smart appliances and local energy storage to enable demand response integration to build automation systems. Furthermore, Brenna et al. [60] investigated the integration of a local PV sys-tem to charge electric vehicles for cities, airports and seaports. A study by Lam et al. [30] analysed the application of an EnMS for a seaport site to reduce costs and carbon emissions. This study suggested that solar energy systems could be used to integrate and meet the power demands of the seaport authority. The study by Alzahrani et al. [31] investigated the implementation of a smart mi-crogrid for a fishery seaport site using a rooftop PV system to meet the power demands of the seaport authority. The same authors in Ref. [32] investigated the integration of a local solar farm to meet the local power demands and those of the surrounding community using modelling and simulation analysis programs. In addition, a case study by Verma et al. [61] discussed the implementation of a 3.3 MWp PV system to help reduce instability in power distribution at the seaport of Jurong. Zhu et al. [35] investigated the application of multiple re-newable energy resources, such as solar, wind and geothermal energy for Ningbo seaport Co. Ltd. Furthermore, Acciaro et al. [18] compared the application of energy management systems for seaports between two seaports: the Hamburg seaport and the seaport of Genoa. The seaport of Genoa applied the seaport Energy Environmental Plan (PEEP), which aims to develop energy production and consumption activities at the seaport.

One of the main goals of the PEEP plan is to install three stations of solar energy, which will help reduce overall carbon emissions in the seaport by more than 20,000 tonnes/CO_2 emission. The study by Misra et al. [7] proposed a microgrid system to meet the power demands of the port authority and applied different kinds of renewable energy resources. The study found that using a five MWp solar PV system with varying energy resources can help meet the power demands of the local port authority. Another case study by Balbaa et al. [62] developed smart electrical intercon-nection management between multiple ports in Egypt. This study proposed that applying a PV system can meet local power demands for the port site and feed surplus power to other ports, which will help green seaports and develop eco-friendly port sites. The case study [63] proposed installing a smart EnMS for a touristic harbour by applying renewable energy resources. This study used a PV system to meet the power demands of the harbours at ports.

3.2.2. *Wind energy*

Since it is clean, accessible, and plentiful, wind energy is considered the most promising renewable Wind energy is considered to be the best renewable energy source because it is clean, accessible and abundant. The concept of wind energy is based on the large scale movement of air mass due to differences in atmo-spheric pressure along with the rotation of the Earth Dincer et al. [64]. There has been significant growth in installed wind energy at a global level. In 2018, the total installed wind capacity was 599 GW. It was projected that the installed wind energy would rise to 664.5 GW [65]. Wind turbines consist of a tower, a wind turbine, a yaw mechanism, a speed control unit, a drive train system, and an electrical generator [66]. There are many benefits to using wind as an energy source as it is simple, produces zero emissions and offers high efficiency. While wind is a popular energy source, wind turbines require further development to minimise their noise generation. Wind turbines are not considered to be aes-thetically pleasing, and they are also considered to be very expensive to install compared to other renewable energy sources [67]. While wind turbines can be installed both on and offshore, Cavvazi and Dutton [68] suggested that using offshore wind energy could be more effective and stable compared to onshore wind energy. With the UK looking to increase its RES power generation by 35% by 2020, the UK sees offshore power as a solution to achieve this target, and it aims to generate 22 GW from offshore power supplies [69]. The litera-ture on using wind energy for seaports remains very limited because not all the seaport locations are suitable for installing onshore or offshore wind turbines. Wind farms are significant, and there is often not enough space close to port sites to install them. The study by Acciaro et al. [18] noted that the Hamburg port authority has invested in renewable energy since 1990 and has installed 58 turbines with a capacity of 52.75 MW. Furthermore, Wang et al. [26] proposed a framework to help find the optimum design capacity of a hybrid renewable energy system for seaports. This model proposed installing wind energy as a sub-system to meet the power demands of the port site. Meanwhile, Gutierrez- Romero et al. [28] investigated the capability of renewable energy resources to meet power demands for a port site. This study found that wind energy can be efficiently applied to the site to meet the power demands of the port authority.

3.2.3. Marine energy

Three-quarters of the Earths surface is occupied by oceans and seas, which offers the potential for energy generation. Marine renewable energy power gen-eration occurs from tidal movement and ocean circulation. There are many types of marine renewable energy sources that can be utilised to generate elec-tricity, including wind, tides and waves [70]. According to the World Offshore Renewable Energy Report 20, 022,007, the worlds potential tidal energy is esti-mated to be 3000 GW, with less than 3% being located in areas suitable for power generation [71].

The biggest challenge associated with marine renewable energy is its instal-lation, which can be time consuming and expensive. 16.2 GW of offshore wind capacity is expected to be installed in Europe, with the majority located in the North Sea. The United Kingdom alone is expected to install 18 GW of offshore wind by 2020. Tidal currents are very predictable, as high and low tides develop with well-known cycles, making marine renewable energy much more accessible to predict than renewable resources that rely on wind and sun exposure. Compared to other renewable energy sources, marine renewable en-ergy is less complicated to connect to the national grid. Furthermore, Rourke et al. [72] argued that the installation costs of marine energy are much higher than those of any other renewable energy source and marine renewable energy sources require regular maintenance by highly skilled labourers.

This review did not yield many studies to highlight marine energy as a re-newable energy resource for port applications. Based on our search, only three studies mention the application of marine energy to meet the power demands of the port authority. First, the study by Ramos et al. [37] investigated the imple-mentation of tidal energy to meet the power demands of the port authority and showed that about 25 turbines of tidal energy could fulfil the total power de-mands. Second, Alvarez et al. [73] designed a tidal energy turbine to investigate the capabilities of the proposed tidal turbine to meet the local power demands of the port site. Finally, Lazaroiu et al. [38] investigated the application of a sea wave energy converter to utilise power for port applications. This study investigated the application of Resonant Wave Energy Converter (Rewec3) and Inertial Sea Wave Energy Converter (ISWEC) devices to convert waves to en-ergy and showed that Rewec3 is the best system to apply from a theoretical and experimental point of view.

3.3. Cost Optimisation

This review has identified that most studies focused on minimising the cost of the energy used for seaport activities. In contrast, few researchers have discussed maximising profit by installing green energy resources to help meet local power demands. Based on the analysis of the studies in Table 3, cost optimisation is divided into two main categories: profit maximisation and cost minimisation. The studies that optimise costs via profit maximisation focus on increasing the income from investing in energy systems and their applications in seaports. In contrast, studies that optimise costs via cost minimisation focus on reducing the costs of energy usage, lowering the investments needed to apply smart systems, and reducing the impact of carbon emission taxation on seaport authorities and critical workers.

Our review shows that most existing literature discusses cost minimisation at seaports, while only three studies highlighted cost optimisation through profit maximisation [30,38,61]. Studies that discuss the minimisation of costs are divided into direct effect and indirect effect minimisation. Direct effect studies aim to reduce costs directly at the seaport via different techniques and opti-misation strategies [22,24,31,32,62,74,75]. Indirect effect studies focus on reducing the costs of operations at seaports, such as energy costs and emission and operational costs, indirectly by applying a smart system, increasing energy efficiency [26,27,45,46,73,76].

3.4. Adoption of smart control technologies

The search results show that studies on seaport energy applications are mov-ing toward deploying smart technologies to increase the operating system's ef-ficiency at port facilities. These studies discuss three main areas: introducing smart grid approaches, proposing energy management systems for seaports and using Internet of Things (IoT) approaches for port activities. Table 2 shows the comparison of selected studies that apply smart technologies for seaports.

For smart grid approaches for seaports, the Royal Port of Stockholm [77] started a project in 2009 by the Stockholm City Council, which aims to achieve a fossil-free port by 2030. Stoll et al. [21], discussed the applicability of sustain-ability at the Royal Port of Stockholm via developing smart house architecture that will provide interactions between consumers and their utilities to improve the energy usage in each house. The study by Alzahrani et al. [31] developed a smart microgrid for a fishery port site that aims to increase the use of renewable energy resources and reduce both energy consumption and carbon emissions.

Furthermore, Niglia et al. [78] discussed the role of securing critical infras-tructure with smart grids for seaport applications. This study argued that, due to the importance of applying smart grid technologies at seaports, security is crucial for the smart grid system to protect the port from disruptive cyber-attacks. Meanwhile, Verma et al. [61] developed a smart grid approach for the port site using renewable energy sources and an energy storage system to meet local power demand for the port site and to sell the surplus power to the grid. In addition, Molavi et al. [25] explored the benefits of applying a microgrid at a port site. This study developed a multi-stage stochastic mixed-integer pro-gramming model to investigate the effectiveness of applying a microgrid to a port site based on different parameters. These authors argued that applying a microgrid can impact the overall activities of the port site. Finally, Arena et al. [44] investigated the feasibility of producing energy from sea waves and using it to charge electric vehicles for seaports.

In their study, Gutierrez-Romero et al. [28] investigated the application of an onshore power supply at the port to meet the power demands of ships at their berths. This study argued that the proposed system would reduce carbon emissions and increase energy efficiency at the port site. Meanwhile, Ramos et al. [37] investigated the implementation of a tidal farm to meet the power demands of a port site. The

Table 2
Studies Applying smart technologies for seaports.

Author	Smart Technology		
	SG	EMS	IoT
Stoll et al. [21]		✓	✓
Alzahrani et al. [31]	✓	✓	
Niglia et al. [78]	✓		✓
Verma et al. [61]	✓	✓	
Misra et al. [48]	✓		
Parise et al. [47]		✓	
Sarabia and Jacome [79]			✓

study result showed that 25 tidal turbines are capable of meeting the power demands of the port. Misra et al. [7] proposed a microgrid for a port site using renewable energy resources to meet power demands and reduce carbon emissions for seaport activities.

The second criterion for applying smart technologies to seaports is the role of energy management systems for seaports in increasing energy efficiency. For example, Lam et al. [30] investigated the impact of using an EnMS for seaports. These authors argued that implementing a smart EnMS at seaports can have an economic and environmental impact on the port site and surrounding com-munities. Furthermore, Parise et al. [47] argued that an energy master plan at the port site could improve the efficiency of the operating systems at the port. Applying a new smart EnMS will help optimise the energy usage at seaports, such as using a smart grid, microgrid, and/or shore-to-ship power supply.

Acciaro et al. [18] compared two port authorities applying Energy manage-ment systems for seaports and showed that using an EnMS to ports will help reduce energy cost and increase energy efficiency at the port site. Meanwhile, Lamberti et al. [76] analysed the impact of using smart Energy management systems for seaports for touristic harbours by utilising currently installed re-newable energy generators and energy storage. This study showed that selling local energy production to the grid is the optimal solution to recoup the invest-ment costs of the system. The third criterion for applying smart technologies to a seaport is applying new advanced technology. Sarabia and Jacome [79] developed a seaport data space that will help avoid the interoperability of the stakeholder information system.

These results show that the seaport data space improves the decision-making process between seaport departments. Furthermore, Piris et al. [29] investigated the use of AMS that allows vessels to be moored without a robe, which was found to reduce carbon emissions.

3.5. *Regulatory landscape for greening seaports*

With the increased global motivation to mitigate climate change, several countries [80] have implemented new rules, policies and legislation to help to reduce the impact of climate change. The seaport industry is a crucial element of economic growth for cities, and communities [81]. There are a variety of measures and strategies that have been published in previous studies that con-tribute to reducing carbon emissions in seaports, including the following: an exploratory study by Ref. [82] on implementing low carbon port concepts at Chinese ports suggested several strategies to help apply the low carbon port concept, including promoting the awareness of green port activities, enacting rules and regulations of low carbon port emission, using clean and smart energy tech-nology, and supporting the implementation of low carbon ports through policy and financial aspects. Azarkmand et al. [83] develop ‘ed a standardised tool to calculate the emissions from the seaports based on the WPCI and IPCC guidelines. Erdas et al. [39] introduced a methodology to help rationalise the environmental management strategies for seaports to minimise environmental impacts. Finally, Villalba et al. [42] proposed indicators of carbon emissions for port activities, which could be used to develop practical policy measures based on the proportion of carbon emissions for each activity at the port site.

Table 3
Previous studies on greening seaports.[88]; [89]; [90]; [91]; [92]; [93]; [94].

Author	Port decarbonisation Indicators								
	Carbon Reduction	RES	Cost Optimization		Smart Technologies			Law & Policies	Green Port Practices
			Max	Min	SG	EMS	IOT		
Fahdi et. al, 2019 [27]	✓	✓		✓		✓			✓
stoll et. al, 2013 [21]	✓	✓			✓	✓			✓
Brenna et. al, 2016 [60]	✓	✓			✓	✓			
Sarabia et. al, 2019 [79]	✓						✓		✓
Aarsaether et. al, 2017[22]	✓			✓		✓			
Lam et. al, 2017 [30]	✓	✓		✓		✓			
Alzahrani et. al, 2019 [31]	✓	✓		✓		✓			✓
Heng et. al, 2015 [33]	✓								
Alvarez et. al, 2013 [73]		✓		✓		✓			
Niglia et. al, 2017 [78]		✓			✓				
Verma et. al, 2018 [61]		✓	✓			✓			
Haibo et. al, 2019 [34]	✓								✓
Lazaroiu et. al, 2017 [38]	✓	✓	✓						✓
Parise et. al, 2015 [47]						✓			
Zhu et. al, 2018 [35]	✓	✓							✓
Li et. al, 2011 [82]								✓	✓
Yun et. al, 2018 [23]	✓								
Wang et. al, 2019 [24]	✓	✓		✓				✓	✓
Azarkamand et. al, 2020 [83]								✓	✓
Wang et. al, 2020 [43]	✓							✓	✓
Yang et. al, 2019 [88]								✓	✓
Boile et. al, 2018 [89]							✓		✓
Zughbi et. al, 2011 [90]	✓								

Continued on next page

Author	Port decarbonisation Indicators								
	Carbon Reduction	RES	Cost Optimization		Smart Technologies			Law & Policies	Green Port Practices
			Max	Min	SG	EMS	IOT		
Gobbi et. al, 2019 [91]	✓								
Erdas et. al, 2015 [39]	✓				✓			✓	✓
Molavi et. al, 2020 [25]	✓	✓			✓	✓		✓	✓
Hua et. al, 2011 [6]									✓
Moya et. al, 2016 [16]	✓						✓		
Villalba et. al, 2011 [42]	✓							✓	✓
Tovar et. al, 2019 [36]	✓								
Arena et. al, 2018 [44]	✓	✓			✓	✓			
Lam et. al, 2017 [30]									✓
Dulebenets et. al, 2018 [92]				✓					
Trivyza et. al, 2019 [74]	✓			✓					
Johnson et. al, 2015 [45]	✓			✓	✓				
Gutierrez et. al, 2019 [28]	✓	✓			✓	✓			
Twrdy et. al, 2020 [41]	✓	✓							✓
Song et. al, 2020 [75]				✓					
Park et. al, 2016 [93]								✓	
Yang et. al, 2017 [46]	✓			✓					
Piris et. al, 2018 [29]	✓						✓		
Tsai et. al, 2018 [40]	✓								
Pavlic et. al, 2014 [87]									✓
Ramos et. al, 2014 [37]	✓	✓			✓	✓			
Acciaro et. al, 2014 [18]		✓				✓			
Wang et. al, 2019 [26]	✓	✓		✓					✓
Misra et. al, 2017 [48]	✓	✓			✓	✓			
Balbaa et. al, 2019 [62]	✓	✓		✓				✓	
Misra et. al, 2017 [7]	✓								✓
Davarzani et. al, 2016 [94]									✓
Lamberti et. al, 2015 [76]		✓		✓	✓	✓			
Manolis et. al, 2017 [19]	✓					✓			

*RES: Renewable Energy Sources, *SG: Smart Grid, *EMS: Energy Management System, *IOT: Internet of Things

3.6. *Best practice guidelines for smart green ports*

The idea of greening ports has emerged after several initiatives to reduce the number of emissions caused by seaport activities. The concept of a green port involves the integration of environmentally friendly methods of port activities, operation and management [84]. Several criteria can be used to define the measures for implementing the green port concept, such as policies to help reduce carbon emissions from the seaport. Likewise, the use of renewable energy for seaport operations should be increased. Previous studies [32,34,35,41,48] on green ports can be structured into two main categories: first, applications that will lead to green ports, and second the methods and measures that will lead to greening ports.

Fahdi et al. [27] discussed the replacement of rubber-tired gantries by an electric type to help reduce carbon emissions and energy consumption. Stoll et al. [21] demonstrated the application of active house architecture at a seaport, which will help to save energy, reduce carbon emissions and increase the use of green energy. Alzahrani et al. [31] developed a smart microgrid for fishery ports, which helped reduce carbon emissions, reduce energy consumption and increase the use of renewable energy resources. Further research by Haibo et al. [34] proposed an inventory method for energy consumption at seaports, including different measures to help reduce carbon emissions and apply the green port concept. Zhu et al. [35] discussed the application of renewable energy technology that will lead to reduced carbon emissions from seaports. In addition, Wang et al. [26] proposed a framework using hybrid renewable energy technology for seaports. Molvi et al. [28] studied the impact of applying micrograds to seaports. Twrdy et al. [41] investigated sustainability in port logistics and the current status in the port of Koper. Misra et al. [48] developed a microgrid for a port authority in India, which led to reduced carbon emissions through the increased use of renewable energy.

The second category of research on green port practices includes studies that discuss the methodologies, measures and standards that will contribute to applying green port concepts. Jian et al. [85] developed practical guidelines for applying low carbon ports in China. Azrkmand et al. [83] developed stan-dardisation tools to calculate carbon emissions, which will help monitor and reduce carbon emissions from seaports. Meanwhile, Erdas et al. [39] proposed a methodology to analyse the ecological footprint based on the environmental objectives of ISO

14000. Hua et al. [86] proposed a green port indicator and used fuzzy importance-performance analysis to assess the performance of green ports. In addition, Pavlic et al. [87] proposed approaches for the practical ap-plication of green port concepts. Finally, Misra et al. [7] demonstrated the role of smart technologies in helping reduce carbon emissions from port sites.

3.7. Review of seaports decarbonisation projects and initiatives

In the last few decades, governments, global coalitions, and international organisations have moved towards finding more sustainable solutions based on innovative modern technologies to minimise carbon emissions in the industrial sectors. This was primarily undertaken by announcing financial grants for re-search, study and implementation projects to reduce carbon emissions. The seaport industries have entered into digital transformation as part of the global warming agenda with the key objective to reduce carbon emissions around the value chain. Given the knowledge of best practices, it is important to review current decarbonisation initiatives and their adherence to these practices.

Several projects [95–97] have been implemented to improve operations at seaports and terminals. These projects were developed to combat climate change by reducing carbon emissions while reducing energy consumption. Sev-eral research projects [95–97] developed and built smart energy technolo-gies in an attempt to maximise the utilisation of renewable energy resources and to reduce carbon emissions. However, several projects have had differ-ent contributions ranging from rules design and implementation towards the definition of standards for the installation of sustainable strategies for port ac-tivities [98–100]. One of the biggest projects attempting to address digital transformation of seaports is the Stockholm Royal Seaport project which aims to implement and develop a fuel-free seaport district with a budget of around euro 2.2 billion [101]. This initiative also includes developing the largest urban area in Sweden, constructing more than 12,000 new houses and more than 35,000 workplaces.

The Green EFFORTS “Green and Effective Operations at Terminals and in Ports” [96] is a research project that is co-funded by the European Commis-sion aiming to reduce energy consumption and improve clean energy in ports. This project provides strategic planning instruments for ports and terminals to reduce carbon emissions and deliver more intelligent energy management in seaports. The APICE project [102] is financed by the European program, and it aims to establish a knowledge-based approach for air pollution mitigation and sustainable development of ports activities driven by spatial planning poli-cies at the local level, which includes the territory around the seaports. This project aims to help policymakers to integrate a port master plan and associ-ated investments in seaports. The Enerfish project [103] develops integrated renewable energy solutions for seafood processing stations using a new polygen-eration application with renewable energy sources for the fishery industry. The research project improves energy use in the fishery industry by developing opti-misation, simulation, validation, and pilot case studies. The research outcomes of this project are based on developing a distributed energy system that uses the cleaning waste of fish processing industries to produce bio-diesel, which can be used to produce energy for the fish processing industries.

Recently, the Smart Cluster Energy System (piSCES) project [95] has aimed to reduce the costs and carbon footprint for the fish processing industry by developing and testing a new ‘smart grid’ electricity network. The smart clus-ter energy system aims to reduce energy networks’ costs and carbon footprint in the fish processing value chain by implementing smart grid technologies by modelling their energy networks’ usage profile and optimising that against the wholesale energy market and any available onsite generation.

In the selected group of projects that we have reviewed, different sustainabil-ity objectives have been addressed in relation to seaports’ life cycle, all involving different sets of variables and objectives for reducing energy consumption, reduc-ing carbon emissions, and applying renewable energy systems. Table 4 provides a comprehensive list of the projects focused on improving the environmental quality in seaports and terminals.

4. Evolution of seaports environmental regulatory landscape

Climate change has led to the introduction of global policies aimed at decar-bonising industries. According to an IPCC report, since 1950, the observations of atmosphere and ocean currents have gradually increased [107]. Climate is the term for “the typical average weather of a region or city”, while climate change is a “change in the Earth’s overall climate” [108]. In response to climate change, there is an international movement toward environmental sustainability and decarbonisation away from fossil fuels [109].

These initiatives were started by the intergovernmental panel on climate change in 1988 [110]. They were followed by (UNFCCC) in 1994 [10]. In 2005, the Kyoto protocol applied to more than 192 parties [11]. On 12 December 2015, 195 countries agreed to combat climate change in Paris. Important policymak-

Ers vowed to initiate practical steps to reduce the global average temperature and emissions by increasing renewable energy utility. Environmental legislation and policies on renewable energy at the international level aim to reduce CO_2 emissions and increase the use of renewable energy sources [14].

Annunziata et al. [15] highlighted the main three perspectives that govern-ments focus on to reduce CO_2 emission, including the integration of energy efficiency and renewable energy, investments in energy savings, and the devel-opment of zero-energy buildings. Moya et al. [16] highlighted the importance for governments to focus on energy efficiency programs for developing countries to decrease GHG emissions and reduce energy consumption. The main objectives of the EU established in 1997 were to decrease GHG emissions, ensuring the security of the supply chain, and improving the EU’s competitiveness [111]. In addition, the EU sets targets for reducing CO_2 emissions and increasing the use of renewable energy resources [112]. Due to the increasing awareness of global warming and the importance of global decarbonisation plans, many countries have begun to move toward decarbonisation. The United Kingdom was one of the first countries to start implementing a long-term plan to reduce its carbon emissions and increase its renewable energy resources, as shown in Fig. 4.

One of these policies was enacted in 2003 (2003/87/EC). The first initiative began in 1989 to replace fossil fuels with nuclear energy to produce electricity under (NFFO) law. This initiative was followed by a global motivation program, known as the Climate Change Program, which aimed to reduce CO_2 by 15–18% in 2010. In 2002, the government established the Renewable Obligation (RO) law. This act makes it mandatory for the supplier to secure a specific share of electricity from renewable energy or pay the penalty. This policy is known as the emission trading scheme, which is considered to be the main tool for reducing GHG emissions in the EU [113]. This scheme works via a cap and trade mechanism. The cap sets the total amount of GHGs emitted by the installation, while the relevant companies receive or trade their emission allowances. In 2008, the government passed a new act, known as the Climate Change Act. This act requires companies to cut their GHG emissions by about 34% by 2020 and 80% by 2050. The government also developed a budget across several periods to decrease its carbon emissions by 2050.

The Feed-In Tariff (FIT) is an important policy that was applied in Europe in 1980. This tariff was applied in Denmark, Germany and Italy in 1990 [114]. The concept of the FIT is “policy pricing, guaranteeing renewable energy generators a fixed price for the electricity they produce” [115]. The advantages of FIT include a guaranteed price, which will allow householders with solar panels to buy power through renewable energy markets. In 2011, the EU established a new law that requires all members to apply an industrial emissions directive. This law aims to increase the level of protection over human health and the

Table 4
List of projects investigating green seaports and port activities.

Project	Date	Aim	Fund ()	Coordinated by
The Stockholm Royal Seaport [101]	2010–2030	To develop a fuel free seaport district	2.2 Bn	The Stockholm City Council
GREEN EFFORTS [96]	2007–2013	Reduce energy consumption and improve clean energy	3.1 M	Jacobs University Bremen
Greencranes [104]	2012–2014	Demonstrate the feasibility of new technologies and alternative fuels	3.6 M	Ministero delle Infrastrutture e dei Trasporti (MIT)
PRISM [100]	2010–2012	Identify a set of relevant and feasible performance indicators for the EU ports	–	European Sea Ports Organization (ESPO)
CLIMEPORT [97]	2009–2012	Encourages Mediterranean Ports to reducing greenhouse emissions	1.6 M	Port Authority of Valencia
ECOPORT [98]	2009–2012	Improve the quality of ports	2.1 M	Autoridad Portuaria de Valencia
piSCES [95]	2017–2020	Reduce the costs and carbon for fish industries by implementing smart grid	2.2 M	Waterford Institute of Technology
APICE [102]	2007–2013	Develop a knowledge-based approach for air pollution mitigation and sustainable development of port activities	2.2 M	Regional Environmental Agency of Veneto
Enerfish [103]	2008–2013	A new polygeneration application with renewable energy sources	5.4 M	TEKNOLOGIAN TUTKIMUSKESKUS VTT
E-harbour [105]	2010–2013	Create a more sustainable energy model in harbour regions on the basis of innovative intelligent energy networks (smart grids)	–	Municipality of Zaanstad
EFICONT [99]	2009–2011	To incorporate a set of significant energy efficiency improvements for seaprts	–	Ministry of Development
Greenberth [106]	2013–2015	Study in detail the improvement opportunities of energy efficiency in six mediterranean ports	1.6 M	Port Authority of Valencia

environment by decreasing industrial emissions in the EU. This law is based on five criteria: an integrated approach, the best available techniques, flexibility, environmental inspection and public participation. In 2012, the UK established a new approach known as the “Green Deal”, which helps homeowners improve their energy savings and determine the best option to pay for their energy. This was followed in 2014 when the government announced a mega plan to install smart meters in homes between 2014 and 2019, with over 53 million smart meters for gas and electricity now being used. The EU established a new directive (2001/77/EC) to promote the use of electricity from renewable energy resources [11,116]. To increase the deployment and development of RES, in 2009, the EU implemented a renewable energy directive (28/2009/EC) that promotes the use of renewable energy resources to provide 20% of the total power production by 2020 [117]. In 2011, the Europe Commission published a low carbon roadmap for EU members, aiming at reducing GHG emissions by 80–95% by 2050. To achieve this target, each EU member must increase its level of development and deployment of clean technologies [117].

5. Key components to greening seaports

Mitigating carbon emissions at the global level is currently a vital issue due to global warming and the dangers posed by climate change. The projected dou-bling of the Earth’s population in the coming decades necessitates the discovery and application of sustainable, smart and secure technologies that will con-tribute to meeting power demands and mitigating carbon emissions efficiently [118]. The use of smart technology would have a significant effect on people’s lives. The advancements of technology might also affect people’s interactions with smart technology to provide a clean and sustainable environment [119]. Using smart energy technology for seaports can significantly help mitigate car-bon emissions and impact the overall efficiency of systems at the ports level. The technology will also increase the efficiency and competitiveness of shipping, fishing and tourism in the global market. The following section will highlight the state-of-the-art technologies used to mitigate carbon emissions and increase energy use efficiency at seaports.

5.1. Smart grid

Traditional power generator units supplied electricity only to the closest neighbourhoods due to the direct current-based power grid and the limited units of power voltage. Later updates to the power grid system followed, which provided electricity over long distances between power units and buildings using technical tools, such as AC grids. This system is known as a centralized energy system [120]. In addition, the growth of the power necessary to meet people’s needs in the coming decades requires a strong response. The smart grid concept has helped to identify high-quality and cooperative generation and storage op-tions. The objective of a smart grid is to allow participants and decision-makers to more easily determine an ideal operational environment for both utilities and power consumers [121].

The increased public understanding of renewable and sustainable energy resources and population growth and economic maturity in developed and de-veloping countries have resulted in a significant shift in the design of electrical energy systems. This transition focuses on smart, green, controllable and pre-dictable electric system designs [122]. Smart grid technologies can help find a solution for power system problems to work with more sustainable, reliable, safe and high-quality electricity.

A smart grid has a positive effect because it allows renewable energy re-sources to communicate with various city energy resources, improving the power system’s reliability and efficiency, as shown in Fig. 5.

The consumers in a smart grid become active members by utilising energy systems to prevent energy waste/loss and minimising energy consumption via a demand and response approach. Smart grids can also bring more benefits to consumers by lowering electricity costs and increasing revenues from energy sales at peak hours [123].

“A smart grid uses digital technologies to enhance the reliability, stability, and performance (both economic and energy) of the electric system from large production, through distribution networks to electricity users, and an increas-ing number of distributed-generation and storage resources” according to the US Department of Energy [57]. Smart grids, on the other hand, depend on renewable energy sources like solar and wind energy, which are intermittent and unreliable, which is one of the challenges in expanding the reach of smart electric networks, especially in seaports and industrial complexes [124].

This can be dealt with through a set of technologies that greatly contribute to achieving stability and flexibility in the delivery of electricity, including the application of artificial intelligence to predict the quantity of energy that will be generated within the next day and then store it or convert it to another form of energy and then reuse it and meet a need Power whenever customers need it [125]. This effectively contributes to the possibility of connecting the smart electric grid to the energy markets and benefits consumers by lowering electricity costs and increasing revenues from energy sales at peak hours [126].

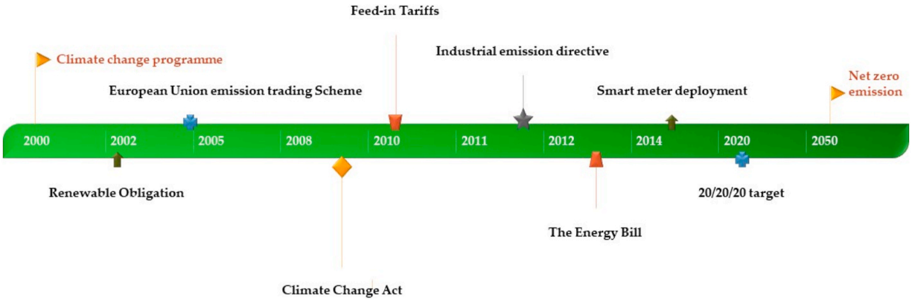

Fig. 4. Timeline of the main motivations for decarbonisation in the UK.

5.2. *Microgrid*

With increases in the level of concern to limit the human-made GHG emis-sions, methods for using energy efficiently and generating electricity from avail-able resources must be found. In light of the promise of the energy transition period, a report on microgrids [127] created an integral proposition for the next generation of power systems [128]. The microgrid is a small-scale localised en-ergy network that involves loads, a network control system, and a variety of Distributed Energy Resources (DERs), including generators and energy storage systems. For DERs and demand responses to communicate in delivery networks, microgrids have been implemented with smart elements [129]. According to the US Department of Energy, a microgrid is characterised as “a community of in-terconnected loads and distributed generation within defined electrical borders that rely on a single controllable entity concerning the grid,” according to the US Department of Energy. A microgrid can attach to the grid and detach from it, allowing it to run in grid-connected or island mode [130]. Microgrids for sea-ports are made up of distributed energy resources (DERs), energy conversion devices, communications networks, control systems, and energy management systems that allow for flexible energy management between organisations and consumers [131,132]. Therefore, a microgrid involves a combination of renew-able energy resources, energy storage, controllers and consumers; it is also a grid-connected and multigeneration system [133,134]. The RES depends on climate conditions, and PV, wind, and tides are intermittent resources [135]. Further, one needs to ensure the system’s reliability, meet power demands and avoid contingencies for the successful operation of a microgrid [136]. Using en-ergy storage systems for microgrids will help solve the problem of intermittent RES [137].

The microgrid’s operation, control, and coordination is a critical issue that can affect the system’s overall efficiency [138,139]. Two studies [136,140] used optimisation techniques to minimise faults and waste and maximise the perfor-mance and profits for both the system and its users [136,141]. Khan et al. [140] focused on minimising the costs of microgrid operation problems and applied different meta-heuristic optimisation techniques.

5.3. *Distributed generation*

The last decade witnessed a significant transition in energy policies due to serious issues that might affect people’s lives, such as the limited quantity of fossil fuels and global warming, alongside a noticeable increase in the popula-tion’s growth rate. Consequently, multi countries have begun to deploy small power generation units to increase the security of supply and meet the power demands [142]. This system is known as a Decentralised Energy System (DES) or Distributed Generation (DG). The role of DG is to provide flexibility and reliability to the grid through the use of small-sized plants and more efficient generation [143]. In addition, DG exploits local energy generation resources and installs energy storage systems at local sites [144]. The main energy policies for DECs are intended to deregulate the energy market and help solve climate change. This is reflected in the deployment of DECs, and the increased compet-itiveness between entities [145]. According to Ref. [146], the shift from centralised to decentralised energy production is happening at a rapid pace. Furthermore, the integration of RES with decentralised energy systems can decrease the reliance on fossil fuels, increase the security of the power supply, and reduce carbon emissions. The concept of DG has many definitions, the first of which was published by Ref. [147], who defined DG from a location perspective as “electric power supply on the consumer side of the metre or inside distribution net-works”. According to Ref. [148], there are three categories of DGs: a) those linked to the distribution network, b) those connected to the consumer side of the me-tre, and c) those disconnected from the grid and localised depending on energy demand. DG consists of the traditional generation and the non-traditional gen-eration. Traditional generation systems include devices such as microturbines. Non-traditional

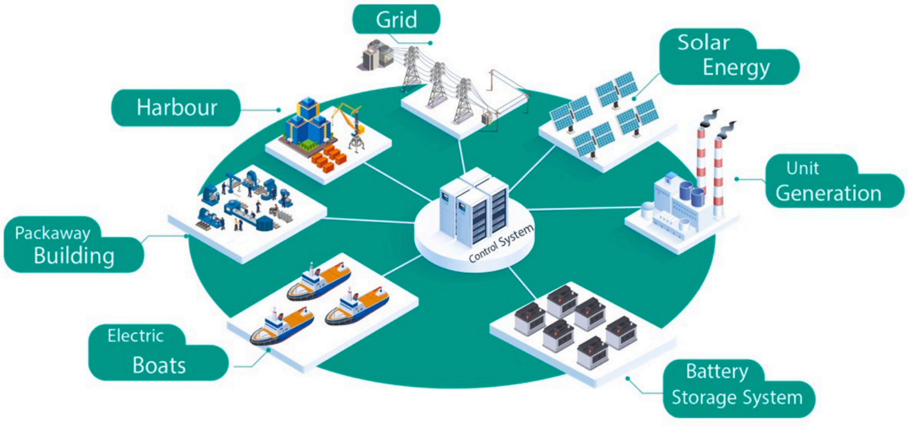

Fig. 5. Smart grid model for port authorities [32].

generation systems include RES, storage devices and electro-chemical devices (fuel cells). We noted several applications of DG. DG can be kept on standby to supply the required power during peak times or in critical situations. It can be used to produce combined power and heat supply with high efficiency at the district level [149].

5.4. Energy management system

The new approach of Information and Communication Technology (ICT) applications for home and building automation networks has increased the fea-sibility of applying smart energy systems in residential and commercial build-ings. This interest correlates to the awareness of environmental impacts from energy generation, and usage [150]. The world's energy demands are projected to increase in the next decades due to population increases and industrial ac-tivities. The industrial sector predicts to increase its energy consumption by 40% by 2040 [151]. Global energy demand forecasts show the urgent need for further strategies to minimise energy consumption and minimise environmen-tal impacts. The energy management system (EMS) is a technique that can optimise energy usage in buildings and industries through various strategies [152]. Increased energy prices and the depletion of primary resources prompted the development of energy management in 1970, according to Ref. [153]. EMS key goal is to minimise energy pricewithout compromising efficiency or quality, all while minimising environmental impacts [154]. The new approach to energy management systems for seaports is focused on finding smart, efficient, secure, and affordable solutions. This latest EMS is part of the distributed energy re-sources scheme. Electrical power generation services that are directly connected to Medium Voltage (MV) or Low Voltage (LV) delivery networks, rather than bulk power transmission systems, are referred to as distributed energy resources (DERs) [155]. The new approaches that manage energy use via DER include smart grid, microgrid and virtual power plant, which are covered in greater depth in the following section.

5.5. Virtual power plant

Due to the increased penetration of DG units and its ability to exchange the energy produced from conventional power plants, advanced technology is needed to meet the power demands of consumers from economic and security perspectives [156]. The increasing deployment of DG and the lack of a passive approach reflect the long-term investment in running DG. There is a great need to begin assimilating an active system that will help DG participate in energy markets [157,158]. In this context, a virtual power plant (VPP) is defined as "a unique power plant that uses information and communication technology to link, monitor, and visualise dispersed generators (ICT)" [159]. A Virtual Power Plant VPP can manage and the power flow between units [160], and it can help optimise energy use and increase the performance of the relevant systems [161,162]. Dispatching and optimisation, management and control, and integration of DG and renewable energy resources are the three key functions of VPPs [163]. A VPP's purpose is to exchange energy with the grid network and to monitor the power supply and demand flow between entities, according to Refs. [160,164].

5.6. Artificial intelligence (AI)

Artificial Intelligence (AI) applications for environmental modelling are in-creasingly used due to the recognition of AI's ability to solve complex problems [165]. AI techniques are used to anticipate, optimise, model, simulate and mon-itor complex systems such as adaptive control, scheduling, optimisation, and complex mapping [166,167]. In the energy sector, in every stage of the energy supply chain, AI plays a critical role (from power generation to transmission, to distribution, to the end-user) [168–171]. AI can increase the energy efficiency of power systems via intelligent energy management systems for sea-ports [172–174]. AI can also help to improve the reliability of the power supply while also lowering the cost of power [175].

5.7. Information and communication technology (ICT)

Information and communication technology (ICT) is considered one of the basic elements in modern society. ICT is also the core element of the industrial sector. ICT, according to UNESCO, is a mixture of informatics technology and other related technologies, especially communication technology [176]. In a smart grid, ICT plays a key role in constructing a highly versatile and secure communication infrastructure as well as allowing protocols to facilitate real-time interactions between producers and consumers [177]. The most commonly used communication strategy is a smart meter and a data concentrator via Power Line Communications (PLC). The second approach combines a data concentrator and a metre data management system; the most widely used system is GPS-GPRS [178].

5.8. Internet of Things (IoT)

Internet of Things (IoT) is a brand-new concept of information technology [179] that has multiple applications and offerings for the industrial sectors. The Internet is a worldwide system that interconnects computer networks based on a standard internet protocol suite, which serves hundreds of millions of users worldwide. Since the Internet is a network of networks made up of millions of private, public, academic, industry, and government networks, industries like seaports and ecosystems will benefit from Internet solutions by implementing a variety of electronic, wireless, and optical networking technologies [180].

IoT aims to allow the trusted exchange of useful data between unseen, em-bedded and uniquely identifiable devices through Radio Frequency Identification (RFID) and Wireless Sensor Networks (WSNs) using sensor devices and multi-ple processors for decision making to facilitate automation [181]. The use of IoT for port activities was described by Ref. [79], who developed a seaport data space that will help avoid the interoperability of the stakeholder information system. The results showed that the seaport data space improves the decision-making process between seaport departments. Another research looked at the use of an Automatic Mooring System (AMS), which allows vessels to be anchored without the use of a robe, and found that it can minimise carbon emissions [29].

5.9. Smart port

The new vision of smart port will involve installing and deploying a new energy model and value proposition based on smart and innovative technolo-gies with low operational and environmental impacts. "Emphasising especially operational and energy efficiency, productivity, and the environmental impact aspect" sums up the holistic definition of a smart port, according to instrumen-tal research studies on smart ports [20].

The smart port approach can impact the overall ecosystem of the seaport by continuously harvesting information on seaport activities using the Internet of Things and making decisions using artificial intelligence and big data tech-nologies. This approach can provide a resilient data storage system and allow different entities to access relevant data based on an agreed governance model that will help optimise operational systems and increase efficiency.

The development of seaports from 1950 to 1990 followed the traditional paradigm of seaports, with progress in logistics operations and infrastructure but limited improvements to information and communication systems. Sea-ports have entered into a digitisation process involving the adoption of new technologies that will increase their level of effectiveness, as seaports are a mul-tidimensional system combining economic functions, infrastructure systems and geographical space and trade [182]. Advanced technology for port operations can also have a powerful impact on port authority and the surrounding com-munities and increase competitiveness between different port authorities. This could lead to the implementation of smart port activities using leading-edge technology [25].

From 2000 to the present, seaports began to enhance their operational sys-tems to become smart ports using advanced technology systems [134]. Smart ports, according to one study by Siror et al. [183] is "a system of port *trans*-portation and activity based on modern knowledge platform that enables mul-tiple and diverse information services for port stakeholders based on the col-lection, processing, release, exchange, review, and use of relevant information". Another definition by Li et al. [184] described a smart port as an integration of all elements of terminal operations, warehousing, logistics, yards and port transportation through a particular network that provides different types of information for daily operations at the port.

Another description of the smart port concept was provided by Ferretti et al. [185], who defined smart ports as a fusion of new smart technologies, such as the Internet of Things, Big Data, automation, and environmentally friendly technology, that come together to form smart infrastructure that connects wired and wireless networks to surrounding objects, such as sensors, to form smart in-frastructure that connects wired and wireless networks to surrounding objects, such as sensors, to form smart infrastructure, to allow the exchange of data between entities, which will help improve the logistics and transportation in-dustries. The idea of a smart port was highlighted by Buiza et al. [20], based on a project called "action plan for the smart port concept in the Mediterranean region" The definition of the smart port concept focuses on three main areas: operation, energy usage and environment [186].

The importance of the energy consumption at seaports relates to the high energy demands of port operations. Efficiently using energy is a challenge for port authorities because greater energy consumption means greater carbon emis-sion production and increased operational costs [187]. Consequently, most port organisations urge port authorities to set port regulations to reduce energy con-sumption and increase green energy resources. This will also help reduce carbon emissions and energy costs for port operation systems. The second element of the smart port definition is the environmental aspect. Various initiatives like ECOPORT [98], PRISM [100] and GREEN Efforts [96] aims to define and set the environmental performance indicators for port authorities to help them re-duce and eliminate the impact of environmental effects.

European seaport authorities consider air quality the most important of the ten environmental priorities for seaports, as air quality affects port operations and shipping activities. As a result, the environmental element is a crucial area that needs to be considered to transform ports into smart ports [188]. The third area of the smart seaport concept is operations. The main operations at sea are loading and unloading the cargo and containers from ships, boats and vessels into warehouses. In the supply chain of the operational systems at seaports, several areas could be optimised to increase the efficiency and effectiveness of port operations, which will help reduce costs, time, labour, and the lifespan of the machine. Molavi et al. [189] added another domain to the smart port index domains, which is safety and security. The importance of safety and security in seaports is real as it considers critical infrastructure. In the last few years, several strategies have been identified to increase the level of safety and security in seaports with increased digitisation and automation [190]. This development in seaports operations has led in the past few years to an increase in the level of cyber attacks and security threats [191]. This issue increases the urgency to consider safety and security for seaports as one of four main strategic smart port domains.

6. Conclusion

Seaports are considered one of the main drivers of the global economy and are a core element of the transportation, shipping, tourism, and fishing indus-tries. However, increased activities in seaports have undoubtedly affected the environment, including high carbon emissions, noise resulting from activities at the seaports, high energy consumption, and high health impacts among the populations of coastal cities near the seaports. This study has reviewed the pub-lished and applied research that has contributed significantly to transforming and promoting the concept of green and smart seaports in various countries. The findings demonstrate that the key factors contributing to decarbonising seaports are applying renewable resources, cost optimisation, deploying intelligent tech-nologies, establishing rules and regulations for greening seaports. Implementing green seaport practices guidelines help seaport authorities move towards using a green seaport approach.

Meanwhile, through an analysis of the research, three main factors con-tribute directly and indirectly to the environment: the consumption of fossil fuels, the high energy consumption of power systems and the lack of the pro-fessional management of resources at seaports. Notably, the seaport's current global status shows a lack of experience in smart seaport approaches. We argue that the intelligent port approach will increase competitiveness between sea-port authorities, which may ultimately lead to the seaport authority's inability to deal with climate challenges for the seaports. There must be a valuable role for business people and investors in optimal investment in modern technologies that reduce carbon emissions, such as renewable energy systems, smart metering devices and other modern technologies. Whilst it is not easy to achieve a green and sustainable seaport without investors' presence, incentives and initiatives must be in place to convince investors of the feasibility of investing in modern seaports. This can be in financial gain, avoidance of environmental legislation penalties and sustainability of the port and the global climate.

As part of the plan to make seaports sustainable, overall decarbonisation of the life cycle must be provided. This will have a tremendous impact on the overall system and contribute to the comprehensive efficacy of seaports and enhance the level of greening, sustainability, and competitiveness between sea-ports. LCA can help quantify the trade-offs and gains to achieve improvements.

However, due to the complexity of seaports within LCA, scalable approaches that factor in dynamic and non-linear considerations should be used. Similarly, the longer time scales of seaport operation make the time dimension another condition to consider in modelling seaport activity. This study finds a need to develop real-time LCA approaches for seaports that combine LCIA models with time-dependent characterisation to achieve environmental sustainability. It is essential to optimise the operation of energy at seaports. This research finds success in projects that consider many variables that influence the total energy management in ports and the importance of using a semantic representation of the seaport's environment as a pre-processing step of smart energy system oper-ation. Therefore, it is recommended that seaport energy systems utilise a grey-box approach to energy systems management that factors in both white boxes (simulation-based) and black-box (data-driven based) approaches. The grey box approach will be underpinned by semantics but informed by real-time feedback. While longer-term operational control approaches are commonly used, the com-bination of different sectors and markets and acute fluctuations in supply and demand increase power-grid operations' complexity. Consequently, time-series based optimisation with a multi-objective approach can accommodate short-term or real-time operation given the appropriate data and computing power. Although many seaports are pledging land to invest in smart energy systems, they can make further efforts by reducing their environmental impact and cre-ating more jobs for the local communities around seaport sites. Consequently, stakeholders, policymakers and seaport authorities must develop policies and legislation to enhance the role of investment in clean energy at seaports and facilitate all capabilities to achieve this aim, which includes building expansion at the seaport sites and their operation.

It is recommended that future works should use AI applications for energy systems in seaports to help predict energy consumption and meet the required power demand through local clean energy resources. AI can also help optimise energy costs by avoiding selling power in hot seasons and managing power in the seaports to achieve maximum profit for seaport authorities. This may be achieved through real-time changes in power usage to match the grid's price to maximise income from selling power or minimise costs in buying power. While energy system optimisation is not a new concept, most implementations have only considered the system singularity. In contrast, we recommend a holistic approach to energy system optimisation through the use of semantic models. This paper finds benefits in implementing a Blockchain model to achieve an optimal energy market where decentralised energy systems can trade freely. Fu-ture research should consider trading practices around the Blockchain model to eliminate third-party intermediate services to reduce monetisation and increase the cyber-security of energy systems. Finally, it is hoped that this article will inform the emerging policy direction of the UK, the European Commission, and beyond and provide insights about the importance of seaports in the net-zero trajectories to address the large-scale energy system challenges. It is essential to appraise current and future actions and initiatives across various policy areas, from energy supply to demand, from technology support to life cycle environ-mental impacts and market implications.

7. Future research directions for decarbonising seaports

Through shipping and import and export operations, seaports are the main arteries to transport materials and goods between countries. They are essen-tial in commercial dealings and necessary to purchase consumer goods such as food, medicine, and others. Maritime transport operations are considered to be vital and strategic pillars on which our modern economies are based. How-ever, the world faces a critical challenge from increased carbon emissions, which has prompted Western economies to reduce carbon emissions through several international agreements and alliances.

Maritime activities can play an effective role in contributing to reducing carbon emissions, which will be directly reflected in the level of performance, quality, and competitiveness of seaports and enhancing the level of sustainability in their local ecosystem. The previous sections have elaborated on the increasing volume of research aimed at decarbonising seaports, including the development and design of applied methodologies to quantify carbon emissions produced from port activities [192], study and analysis of renewable energy sources systems deployment [193], and also improving the efficiency of maritime transport [194]. We argue that decarbonising seaports can profoundly transform port activ-ities, as elaborated in the next sub-sections.

7.1. Total life cycle approach to seaports decarbonisation

Most of the previous studies focus on developing strategies that contribute to reducing carbon emissions in seaports by optimising the energy mix [195], improving the energy efficiency of the equipment and machinery used in ports [196], and mitigating the environmental impact of ships by reducing their speed and scheduling their arrival and departure from seaports [45]. These actions have the potential to contribute significantly to reducing the carbon footprint of modern seaports. In this context, life cycle Assessment (LCA) helps quantify the environmental pressures, the trade-offs, and areas to achieve improvements considering the entire life cycle of seaports, from design to recycling. However, current approaches to LCA do not factor inconsistently (both in the foreground and background inventory systems) life cycle variations in (a) seaport building use, (b) energy supply (including from renewable sources), and (c) building and environmental regulations, as well as changes over the building/seaport and the local neighbourhood lifetime. These include (a) change in the energy mix of seaports or upgrading and retrofitting the energy system(s) in place; and (b) time-increase of energy demand during the lifetime of a seaport due to a wide range of reasons such as changes in activity patterns.

Seaports present the highest complexity within LCA, which precludes the use of linear and static approaches but instead requires scalable approaches that factor in dynamic and non-linear considerations. Seaport processes involve longer time scales than in other industries, and therefore they face very different operational and environmental conditions. Consequently, modelling is essential to understand the resulting pollutant emissions and resource consumption con-sidering the time dimension in port activities. This time dimension is currently missing in Life Cycle Inventory databases. Therefore, using time-dependent characterisation factors, a further combination of Life Cycle Impact Assessment (LCIA) models can lead to more comprehensive and reliable LCA results. Con-sequently, real-time LCA approaches that address temporal and spatial vari-ations in the local seaport ecosystem are required because they would more effectively promote a 'cradle-to-grave' environmental sustainability capability.

7.2. Semantic-based modelling, forecasting and optimisation of seaports energy systems

Various digital services, including complex software, are needed to meet var-ious stakeholder requirements in the complex seaport energy landscape. These digital services are running complex simulations, forecasting weather and de-mand, and continuous demand response management. The importance of these services was further increasing with the adoption of renewable energy and dis-tributed generation to achieve an efficient integration with existing systems. As the renewable energy penetration is rising, the need for digital services is extending beyond the unit level to an intelligent system present centrally that can calculate and mitigate the impact due to various uncertainties at each node occurring due to the complex nature of energy systems as well as its dependence on external parameters like the weather. As a result, energy system manage-ment should be systematically developed, considering management topologies, schemes, and process variables best expressed by semantic models such as on-tologies. Energy system optimisation is a complex problem. Existing approaches are not fit for the future as they consider the whole system a static entity and miss the holistic perspective of emerging energy technologies.

As a result, we advocate implementing the previously mentioned systems approach to energy management, best expressed through semantic models that provide a holistic conceptualisation of energy systems and their socio-technical constituents. This is essential to address various scenarios, including local en-ergy balancing, islanding, and blackout prevention, in an evolving world with high penetration of distributed energy resources. A semantic framework can potentially satisfy the basic requirements of an energy system such as openness, practicality, scalability, resilience and flexibility.

Such semantic-based architecture can be further enhanced by using Artifi-cial Intelligence based algorithms that make the grid self-healing, minimising disruption. There is a need for in-depth research in this direction to ensure the resilience and optimality of future energy management systems through self-healing capabilities. It should focus on various qualities such as i) pro-mote autonomy, connectivity, emergence and diversity ii)balancing local and global objectives iii) dynamic reconfiguration for optimising performance and scalability iv) enabling a demand-responsive energy management system that allows the bi-direction flow of energy. Optimisation based grid planning and longer-term operational control are common approaches in power system man-agement. However, increasing stochastics on the supply and demand side and the coupling of different sectors and markets increases the complexity of power grid operation. It requires multi-objective, time-series based optimisation under increasing uncertainty. At the same time, improving data availability and com-putational power give optimisation based on short-term and close to real-time operation. Furthermore, there is a need to think of combinations of distributed and centralised control strategies to bring the best of them together.

8. Secure and reliable seaports energy services

Seaports are responsible for shipping circa 90% of the global supply chain of goods. They are, as such, critical infrastructures and are potentially subject to a wide range of threats [197]. This is now exacerbated by the digitisation of seaport infrastructures, including energy systems, and a complex value chain involvement. Potential risks to energy systems include blackout or service inter-ruption, malicious command injection, delayed measurements, Denial-of-Service attack, dynamic pricing information altered, and user accounts alteration. The consequences of such cyber security threats can be dramatic. Consequently, there is an urgent need to increase awareness on cyber threats faced by ports worldwide [198] to ensure secure shipping and operations [199]. Conversely, the reliability and quality of supply (QoS) of energy-related services in seaports are becoming a pressing issue due to the increasing need for smart integration of distributed energy resources. A gradual transition is already occurring towards demand responsive energy management, which is enabled by smart metering infrastructures with a bidirectional energy flow and dynamic pricing schemes. Therefore, there is a requirement for secure authentication of users, agents, and transactions at each interface between energy devices. The number of processes is also exacerbated by the increasingly distributed nature of grids and their underpinning communication requirements. Three interesting avenues for fur-ther research include: (a) research to identify and quantify the risk of a breach of privacy and security to the systemic reliability and quality of service (QoS) caused by insecure authentication occurring in a heterogeneous environment, where legacy standards and applications need to remain in operation along-side advanced standards; (b) research to identify and quantify the loss of data, breach of privacy and vulnerability due to the heterogeneous communication in-frastructure (wireless, wired, PLC), and the impact on grid reliability and QoS; and (c) research to develop guidelines for information security management, and inform related legislation and standardisation in the energy domain in seaports.

8.1. Transition towards prosumer-driven seaport energy communities

Seaports are an essential ecosystem, including their local communities. We are gradually experiencing the emergence of sharing economies, with a corre-sponding change in consumption models. These can motivate energy prosumers (local communities around seaports) to participate in a leasing energy market where services are used for a shorter period and are more accessible via commu-nity sharing. Blockchain can incentivise participation in such a sharing economy by providing greater choice for energy consumers and providers while enabling much greater flexibility in switching between multiple market offerings. This sharing economy can decentralise energy production and balance consumption from consumers by not being restricted to energy services or price constraints from a single energy provider. The energy market is transforming towards many suppliers and buyers, so it is important to enabling participants in a seaport ecosystem to exchange an increased amount of traded energy. The interac-tion between these actors and the associated processes requires a high degree of standardisation, which a Blockchain model can facilitate. The utilisation of Blockchain for energy trading can lead to the eradication of brokers, monetising energy excess, and developing energy communities. These brokers and interme-diary parties are usually required to validate or ensure the trustworthiness of information across parties but can be replaced by a more automated Blockchain process. Third-party verification can be eliminated because Blockchain deliv-ers high security and data protection for different applications supported by a transparent ledger that records all transactions. In a Blockchain system, any user can become a trader and offer an energy product or service to a group of consumers. Blockchain technology has, therefore, the potential to leverage the benefits of decentralised energy systems and enable an environment where everyone can trade, pay, and even deliver energy to others. Blockchain can sup-port the creation of economically attractive energy communities utilising the power of the Internet and implement the vision of a perfect energy market. Blockchain identifies an online distributed database that aggregates a collection of blocks connected. It is also a public and decentralised ledger that stores records, structured as a chain and blocks. From multiple Blockchain solutions, smart contracts are instruments that can extend Blockchain's capabilities and have been used in various industries. Smart contracts have often been used to convert business rules into codes, based on which a contract code/script is stored in a Blockchain [126]. Future research will explore adopting energy sharing and trading practices within and around seaports using Blockchain technology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] E.G. Efimova, A.A. Gapochka, Seaports as drivers of regional economic development: the case of saint petersburg and leningrad province, Case Stud. Trans. Pol. 8 (2) (2020) 383–393.

[2] J.-P. Rodrigue, The Geography of Transport Systems, Taylor & Francis, 2016.

[3] A. Azzellino, J.P. Kofoed, C. Lanfredi, L. Margheritini, M.L. Pedersen, A marine spatial planning framework for the optimal siting of marine re- newable energy installations: two Danish case studies, J. Coast Res. 65 (2013) 1623–1628.

[4] J.J. Corbett, J.J. Winebrake, E.H. Green, P. Kasibhatla, V. Eyring, A. Lauer, Mortality from ship emissions: a global assessment, Environ. Mental Sci. Technol. 41 (24) (2007) 8512–8518.

[5] Y. Durmus¸Og˘ Lu, S. Aksoy, C. Denïz, A Study of Renewable Energy in a Port Facility by Using Solar Organic Rankine Cycle Systems.

[6] J. Hua, Y. Wu, Implications of energy use for fishing fleettaiwan example, Energy Pol. 39 (5) (2011) 2656–2668.

[7] A. Misra, K. Panchabikesan, S.K. Gowrishankar, E. Ayyasamy, V. Ra- malingam, Ghg emission accounting and mitigation strategies to reduce the carbon footprint in conventional port activities–a case of the port of Chennai, Carbon Manag. 8 (1) (2017) 45–56.

[8] UNCTAD, Review of maritime transport, Carbon Manag. 1 (1) (2015) 1–122.

[9] S. Solomon, M. Manning, M. Marquis, D. Qin, et al., Climate Change 2007- the Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC, vol. 4, Cambridge university press, 2007.

[10] A. Talberg, S. Hui, K. Loynes, Australian Climate Change Policy: a Chronology, Parliamentary Library, 2013.

[11] J. Dutton, Eu Energy Policy and the Third Package, Energy Policy Group/UKERC working paper.

[12] P. Agreement, Paris agreement, in: Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015: Paris). Retrived December, vol. 4, HeinOnline, 2015, p. 2017.

[13] S. Oberthür, L. Groen, Explaining goal achievement in international negotiations: the eu and the paris agreement on climate change, J. Eur. Publ. Pol. 25 (5) (2018) 708–727.

[14] J. Reynolds, Y. Rezgui, J.-L. Hippolyte, Upscaling energy control from building to districts: current limitations and future perspectives, Sustain. Cities Soc. 35 (2017) 816–829.

[15] E. Annunziata, M. Frey, F. Rizzi, Towards nearly zero-energy buildings: the state-of-art of national regulations in europe, Energy 57 (2013) 125–133.

[16] D. Moya, R. Torres, S. Stegen, Analysis of the ecuadorian energy audit practices: a review of energy efficiency promotion, Renew. Sustain. Energy Rev. 62 (2016) 289–296.

[17] E. Commission, Communication No. 640, 2019. The European Green Deal, com no. 640, 2019. commission of european communities: Brussels, bel- gium).

[18] M. Acciaro, H. Ghiara, M.I. Cusano, Energy management in seaports: a new role for port authorities, Energy Pol. 71 (2014) 4–12.

[19] N. Manolis, I. Ahmad, K. Fotios, P. Palensky, W. Gawlik, Mas based demand response application in port city using reefers, in: International Conference on Practical Applications of Agents and Multi-Agent Systems, Springer, 2017, pp. 361–370.

[20] G. Buiza, S. Cepolina, A. Dobrijevic, M. del Mar Cerb′an, O. Djordje- vic, C. Gonz′alez, Current situation of the mediterranean container ports regarding the operational, energy and environment areas, in: 2015 Inter- National Conference on Industrial Engineering and Systems Management (IESM), IEEE, 2015, pp. 530–536.

[21] P. Stoll, L. Rizvanovic, J. E. Rossebo, Active House Deployment Architec- Ture for Residential Electricity Customers' Active Interaction with the Smart Grid.

[22] K.G. Aarsaether, Energy savings in coastal fisheries: use of a serial battery hybrid power system, IEEE Electrification Magazine 5 (3) (2017) 74–79.

[23] P. Yun, L. Xiangda, W. Wenyuan, L. Ke, L. Chuan, A simulation-based research on carbon emission mitigation strategies for green container ter- minals, Ocean Eng. 163 (2018) 288–298.

[24] W. Wang, Y. Peng, X. Li, Q. Qi, P. Feng, Y. Zhang, A two-stage frame- work for the optimal design of a hybrid renewable energy system for port application, Ocean Eng. 191 (2019) 106555.

[25] A. Molavi, J. Shi, Y. Wu, G.J. Lim, Enabling smart ports through the integration of microgrids: a two-stage stochastic programming approach, Appl. Energy 258 (2020) 114022.

[26] W. Wang, L. Huang, J. Gu, L. Jiang, Green port project scheduling with comprehensive efficiency consideration, Marit. Pol. Manag. 46 (8) (2019) 967–981.

[27] S. Fahdi, M. Elkhechafi, H. Hachimi, Green port in blue ocean: optimization of energy in asian ports, in: 2019 5th International Confer- Ence on Optimization and Applications (ICOA), IEEE, 2019, pp. 1–4.

[28] J.E. Gutierrez-Romero, J. Esteve-P′erez, B. Zamora, Implementing on- shore power supply from renewable energy sources for requirements of ships at berth, Appl. Energy 255 (2019) 113883.

[29] A.O. Piris, E. Daz-Ruiz-Navamuel, C.A. Prez-Labajos, J.O. Chaveli, Reduction of co2 emissions with automatic mooring systems. the case of the port of santander, Atmospheric Pollut. Res. 9 (1) (2018) 76–83.

[30] J.S.L. Lam, M.J. Ko, J.R. Sim, Y. Tee, Feasibility of implementing energy management system in ports, in: 2017 IEEE International Con- Ference on Industrial Engineering and Engineering Management (IEEM), IEEE, 2017, pp. 1621–1625.

[31] A. Alzahrani, I. Petri, Y. Rezgui, Modelling and implementing smart micro-grids for fish-processing industry, in: 2019 IEEE International Con- Ference on Engineering, Technology and Innovation (ICE/ITMC), IEEE, 2019, pp. 1–8.

[32] A. Alzahrani, I. Petri, Y. Rezgui, A. Ghoroghi, Developing smart energy communities around fishery ports: toward zero-carbon fishery ports, Energies 13 (11) (2020) 2779.

[33] Z. Heng, C. Qiushuang, Q. Xiongwen, J. Xiaochuang, X. Ya, Green ship- ping oriented coordinated berth allocation for port group, in: 2015 34th Chinese Control Conference (CCC), IEEE, 2015, pp. 8466–8471.

[34] L. Haibo, L. Wen, S. Xiaowei, Study on port energy consumption inven- tory and monitoring technology, in: 2019 5th International Conference on Transportation Information and Safety (ICTIS), IEEE, 2019, pp. 298–302.

[35] L. Zhu, C. Qin, C. Peng, Analysis on energy saving and emission reduction of clean energy technology in ports, in: IOP Conference Series: Earth and Environmental Science, vol. 121, 2018.

[36] B. Tovar, A. Wall, Environmental efficiency for a cross-section of Spanish port authorities, Transport. Res. Transport Environ. 75 (2019) 170–178.

[37] V. Ramos, R. Carballo, M. A′lvarez, M. S′anchez, G. Iglesias, A port to- wards energy self-sufficiency using tidal stream power, Energy 71 (2014) 432–444.

[38] C. Lazaroiu, M. Roscia, Sustainable port through sea wave energy con- verter, in: 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), IEEE, 2017, pp. 462–467.

[39] C. Erdas, P. Fokaides, C. Charalambous, Ecological footprint analysis based awareness creation for energy efficiency and climate change mitiga- tion measures enhancing the environmental management system of limas- sol port, J. Clean. Prod. 108 (2015) 716–724.

[40] Y.-T. Tsai, C.-J. Liang, K.-H. Huang, K.-H. Hung, C.-W. Jheng, J.-J. Liang, Self-management of greenhouse gas and air pollutant emissions in taichung port, taiwan, Transport. Res. Transport Environ. 63 (2018) 576–587.

[41] E. Twrdy, M. Zanne, Improvement of the sustainability of ports logistics by the development of innovative green infrastructure solutions, Trans. Res. Procedia 45 (2020) 539–546.

[42] G. Villalba, E.D. Gemechu, Estimating ghg emissions of marine portsthe case of barcelona, Energy Pol. 39 (3) (2011) 1363–1368.

[43] L. Wang, C. Peng, W. Shi, M. Zhu, Carbon dioxide emissions from port container distribution: spatial characteristics and driving factors, Transport. Res. Transport Environ. 82 (2020) 102318.

[44] F. Arena, G. Malara, G. Musolino, C. Rindone, A. Romolo, A. Vitetta, From green-energy to green-logistics: a pilot study in an Italian port area, Trans. Res. Procedia 30 (2018) 111–118.

[45] H. Johnson, L. Styhre, Increased energy efficiency in short sea shipping through decreased time in port, Transport. Res. Pol. Pract. 71 (2015) 167–178.

[46] Y.-C. Yang, Operating strategies of co2 reduction for a container terminal based on carbon footprint perspective, J. Clean. Prod. 141 (2017) 472–480.

[47] G. Parise, L. Parise, L. Martirano, P.B. Chavdarian, C.-L. Su, A. Fer- rante, Wise port and business energy management: port facilities, electri- cal power distribution, IEEE Trans. Ind. Appl. 52 (1) (2015) 18–24.

[48] A. Misra, G. Venkataramani, S. Gowrishankar, E. Ayyasam, V. Rama- lingam, Renewable energy based smart microgridsa pathway to green port development, Strat. Plann. Energy Environ. 37 (2) (2017) 17–32.

[49] S. Mekhilef, R. Saidur, A. Safari, A review on solar energy use in indus- tries, Renew. Sustain. Energy Rev. 15 (4) (2011) 1777–1790.

[50] J. Conti, P. Holtberg, J. Diefenderfer, A. LaRose, J.T. Turnure, L. West- fall, International Energy Outlook 2016 with Projections to 2040, Tech. Rep, USDOE Energy Information Administration (EIA), Washington, DC (United States, 2016.

[51] S. Hess, A. Oliva, M. Hermann, G. Stryi-Hipp, V. Hanby, Solar process heat–system design for selected lowtemperature applications in the indus- try, in: Solar World Congress, 2011.

[52] E. Taibi, D. Gielen, M. Bazilian, The potential for renewable energy in industrial applications, Renew. Sustain. Energy Rev. 16 (1) (2012) 735–744.

[53] IRENA, Statistics, Renewable Capacity, 2018.

[54] A. Labouret, M. Villoz, Solar Photovoltaic Energy, vol. 9, IET, 2010.

[55] G. P. Hagopian, N. Bebel, S. P. Larson, Renewable Energy with Photo- Voltaic Systems.

[56] K. Branker, M. Pathak, J.M. Pearce, A review of solar photovoltaic lev- elized cost of electricity, Renew. Sustain. Energy Rev. 15 (9) (2011) 4470–4482.

[57] T.T. Chow, A review on photovoltaic/thermal hybrid solar technology, Appl. Energy 87 (2) (2010) 365–379.

[58] W. Hoffmann, Pv solar electricity industry: market growth and perspec- tive, Sol. Energy Mater. Sol. Cell. 90 (18–19) (2006) 3285–3311.

[59] W. Libo, Z. Zhengming, L. Jianzheng, A single-stage three-phase grid- connected photovoltaic system with modified mppt method and reactive power compensation, IEEE Trans. Energy Convers. 22 (4) (2007) 881–886.

[60] M. Brenna, M. Longo, D. Zaninelli, R. Miceli, F. Viola, Co 2 reduction exploiting res for ev charging, in: 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), IEEE, 2016, pp. 1191–1195.

[61] J. Verma, S. Donghan, K.L. Hai, O.H. Chuah, D. Chaoyu, X. Yang, X. Yan, Impact study for pv and ess integration in jurong port distribution grid, in: Asian Conference on Energy, Power and Transportation Electrification (ACEPT), IEEE, 2018, pp. 1–7.

[62] A. Balbaa, R. Swief, N.H. El-Amary, Smart integration based on hy- brid particle swarm optimization technique for carbon dioxide emission reduction in eco-ports, Sustainability 11 (8) (2019) 2218.

[63] [link], https://ses.jrc.ec.europa.eu/e-harbours-electric, 2013.

[64] I. Dincer, Comprehensive Energy Systems, Elsevier, 2018.

[65] Y. Kumar, J. Ringenberg, S.S. Depuru, V.K. Devabhaktuni, J.W. Lee, E. Nikolaidis, B. Andersen, A. Afjeh, Wind energy: trends and enabling technologies, Renew. Sustain. Energy Rev. 53 (2016) 209–224.

[66] W. Tong, Wind Power Generation and Wind Turbine Design, WIT press, 2010.

[67] S. Peake, et al., Renewable Energy-Power for a Sustainable Future, vol. 4, Oxford university press, 2018.

[68] S. Cavazzi, A. Dutton, An offshore wind energy geographic information system (owe-gis) for assessment of the UK's offshore wind energy potential, Renew. Energy 87 (2016) 212–228.

[69] K.L. Anaya, M.G. Pollitt, Integrating distributed generation: regulation and trends in three leading countries, Energy Pol. 85 (2015) 475–486.

[70] F.O. Rourke, F. Boyle, A. Reynolds, Marine current energy devices: cur- rent status and possible future applications in Ireland, Renew. Sustain. Energy Rev. 14 (3) (2010) 1026–1036.

[71] S. Abolhosseini, A. Heshmati, J. Altmann, A Review of Renewable Energy Supply and Energy Efficiency Technologies.

[72] F.O. Rourke, F. Boyle, A. Reynolds, Tidal energy update 2009, Appl. Energy 87 (2) (2010) 398–409.

[73] E. A. Alvarez, J. F. Francos, A. N. Manso, M. R. Secades, A. Gutirrez- Trashorras, Obtaining renewable energy from tidal currents in the aviles port: new services for citizens, in: New Concepts in Smart Cities: Foster- Ing Public and Private Alliances (SmartMILE), 2013 International Con- Ference on, IEEE, pp. 1–9.

[74] N.L. Trivyza, A. Rentizelas, G. Theotokatos, Impact of carbon pricing on the cruise ship energy systems optimal configuration, Energy 175 (2019) 952–966.

[75] T. Song, Y. Li, X.-P. Zhang, C. Wu, J. Li, Y. Guo, H. Gu, Integrated port energy system considering integrated demand response and energy inter- connection, Int. J. Electr. Power Energy Syst. 117 (2020) 105654.

[76] T. Lamberti, A. Sorce, L. Di Fresco, S. Barberis, Smart port: exploiting renewable energy and storage potential of moored boats, in: OCEANS 2015-Genova, IEEE, pp. 1–3.

[77] S.R. Seaport, Stockholm royal seaport, 2013.

[78] A. Niglia, Securing critical infrastructure with smart grids, in: 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), IEEE, pp. 223–225.

[79] D. Sarabia-Jacome, I. Lacalle, C.E. Palau, M. Esteve, Enabling industrial data space architecture for seaport scenario, in: 2019 IEEE 5th World Forum on Internet of Things (WF-IoT), IEEE, 2019, pp. 101–106.

[80] M. Kanellakis, G. Martinopoulos, T. Zachariadis, European energy poli- cya review, Energy Pol. 62 (2013) 1020–1030.

[81] I. Kotowska, Policies applied by seaport authorities to create sustainable development in port cities, Trans. Res. Procedia 16 (2016) 236–243.

[82] J. Li, X. Liu, B. Jiang, An exploratory study on low-carbon ports devel- opment strategy in China, Asia J. Shipping Logistics 27 (1) (2011) 91–111.

[83] S. Azarkamand, G. Ferr, R.M. Darbra, Calculating the Carbon Footprint in Ports by Using a Standardized Tool, Science of The Total Environment, 2020, p. 139407.

[84] F. Fao, The State of World Fisheries and Aquaculture 2018 Meeting the Sustainable Development Goals, Livestock Primary. Food and Agri- culture Organization of the United Nations, 2018.

[85] H. Jian, Sustainable Development of Port Economics Based on System Dy- Namics [j], Systems Engineering-Theory & Practice vol. 1.

[86] C. Hua, J. Chen, Z. Wan, L. Xu, Y. Bai, T. Zheng, Y. Fei, Evaluation and governance of green development practice of port: a sea port case of China, J. Clean. Prod. 249 (2020) 119434.

[87] B. Pavlic, F. Cepak, B. Sucic, M. Peckaj, B. Kandus, Sustainable port infrastructure, practical implementation of the green port concept, Therm. Sci. 18 (3) (2014) 935–948.

[88] L. Yang, Y. Cai, Y. Wei, S. Huang, Choice of technology for emission control in port areas: a supply chain perspective, J. Clean. Prod. 240 (2019) 118105.

[89] M. Boile, S. Theofanis, E. Sdoukopoulos, N. Plytas, Developing a port en- ergy management plan: issues, challenges, and prospects, Transport. Res. Rec. 2549 (1) (2016) 19–28.

[90] H. Zughbi, P. Zulli, Energy Consumption and Co2 Emissions Benchmarking and Modelling in Port Kembla Steelworks, Chemeca 2011: Engineering a Better World: Sydney Hilton Hotel, NSW, Australia, 18-21 September 2011, 2011, p. 1053.

[91] G.P. Gobbi, L. Di Liberto, F. Barnaba, Impact of Port Emissions on Eu-Regulated and Non-regulated Air Quality Indicators: the Case of Civi- Tavecchia (italy), Science of The Total Environment, 2019, p. 134984.

[92] M.A. Dulebenets, Green vessel scheduling in liner shipping: modeling carbon dioxide emission costs in sea and at ports of call, Int. J. Trans. Sci. Technol. 7 (1) (2018) 26–44.

[93] J.-I. Park, T. Kim, Institutional improvement measures for environmental assessment in the pursuit of eco-friendly ocean renewable energy devel- opment in South Korea, Renew. Sustain. Energy Rev. 58 (2016) 526–536.

[94] H. Davarzani, B. Fahimnia, M. Bell, J. Sarkis, Greening ports and mar- itime logistics: a review, Transport. Res. Transport Environ. 48 (2016) 473–487.

[95] I. Petri, A. Alzahrani, J. Reynolds, Y. Rezgui, Federating smart cluster energy grids for peer-to-peer energy sharing and trading, IEEE Access 8 (2020) 102419–102435, https://doi.org/10.1109/ACCESS.2020.2998747.

[96] J. Van Duin, H. Geerlings, J. Froese, R. Negenborn, Towards a method for benchmarking energy consumption at terminals: in search of perfor- mance improvement in yard lighting, Int. J. Trans. Develop. Integration 1 (2) (2017) 212–224.

[97] A. Carballo-Penela, I. Mateo-Mantec′on, J.L. Dom′enech, P. Coto-Mill′an, From the motorways of the sea to the green corridors' carbon footprint: the case of a port in Spain, J. Environ. Plann. Manag. 55 (6) (2012) 765–782.

[98] B. Akgul, Green Port Eco Poty Project Appl. Proced. Trukey 95 (4) (2017), 042063.

[99] M. Puig, R.M. Darbra, The Role of Ports in a Global Economy, Issues of Relevance and Environmental Initiatives, 2019, pp. 593–611.

[100] L. Fobbe, R. Lozano, A. Carpenter, Assessing the Coverage of Sustainabil- Ity Reports: an Analysis of Sustainability in Seaports, SPONSORS, 2019, p. 609.

[101] A. Kramers, J. Wangel, M. Höjer, Governing the smart sustainable city: the case of stockholm royal seaport, in: ICT for Sustainability 2016, At- lantis Press, 2016.

[102] N. P′erez, J. Pey, C. Reche, J. Cort′es, A. Alastuey, X. Querol, Impact of harbour emissions on ambient pm10 and pm2. 5 in barcelona (Spain): evidences of secondary aerosol formation within the urban area, Sci. Total Environ. 571 (2016) 237–250.

[103] B. Xu, A. Nayak, D. Gray, J. Ouenniche, Assessing energy business cases implemented in the north sea region and strategy recommendations, Appl. Energy 172 (2016) 360–371.

[104] G. Cranes, Report on port container terminals energy profile, Versiones 14 (14) (2013) 2.

[105] H. Ronde, A. Ranne, E. Peirano, I. Byrne, H. Le Duc, Integrated renew- able energy solutions for aquaculture processing; enerfish, in: 2011 Inter- National Conference & Utility Exhibition on Power and Energy Systems: Issues and Prospects for Asia (ICUE), IEEE, 2011, pp. 1–4.

[106] E. Sdoukopoulos, M. Boile, A. Tromaras, N. Anastasiadis, Energy effi- ciency in european ports: state-of-practice and insights on the way for- ward, Sustainability 11 (18) (2019) 4952.

[107] I. P. O. C. Change, Ipcc, Climate Change.

[108] [link], https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-climate-change-58.html, 2011.

[109] S. Howell, Y. Rezgui, J.-L. Hippolyte, B. Jayan, H. Li, Towards the next generation of smart grids: semantic and holonic multi-agent management of distributed energy resources, Renew. Sustain. Energy Rev. 77 (2017) 193–214.

[110] C. C. Mitigation, Ipcc special report on renewable energy sources and climate change mitigation, Renew. Energy 20 (11).

[111] E. Ewea, reportEnergy Policy to 2050–achieving 80–95% Emissions Reductions, A Report by the European Wind Energy Association.

[112] L.C. Kuiper, R. Sikkema, J.A. Stolp, Establishment needs for short rota- tion forestry in the eu to meet the goals of the commissions white paper on renewable energy (november 1997), Biomass Bioenergy 15 (6) (1998) 451–456.

[113] E. Commission, et al., Directive 2003/87/ec of the european parliament and of the council of 13 october 2003 establishing a scheme for greenhouse gas emission allowance trading within the community and amending coun- cil directive 96/61/ec, Off. J. Eur. Union 46 (2003) 32–46.

[114] R. Haas, C. Panzer, G. Resch, M. Ragwitz, G. Reece, A. Held, A histor- ical review of promotion strategies for electricity from renewable energy sources in eu countries, Renew. Sustain. Energy Rev. 15 (2) (2011) 1003–1034.

[115] J. Lipp, Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom, Energy Pol. 35 (11) (2007) 5481–5495.

[116] E. Union, Directive 2009/28/ec of the european parliament and of the council of 23 april 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing directives 2001/77/ec and 2003/30/ec, Off. J. Eur. Union 5 (2009) 2009.

[117] E. Commissie, A roadmap for moving to a competitive low carbon econ- omy in 2050, Europese Commissie, Brussel.

[118] P.E. Labis, R.G. Visande, R.C. Pallugna, N.D. Caliao, The contri- bution of renewable distributed generation in mitigating carbon dioxide emissions, Renew. Sustain. Energy Rev. 15 (9) (2011) 4891–4896.

[119] B. Celik, R. Roche, D. Bouquain, A. Miraoui, Decentralized neighborhood energy management with coordinated smart home energy sharing, IEEE Trans. Smart Grid 9 (6) (2017) 6387–6397.

[120] A.A. Bayod-Rjula, Future development of the electricity systems with distributed generation, Energy 34 (3) (2009) 377–383.

[121] M.L. Tuballa, M.L. Abundo, A review of the development of smart grid technologies, Renew. Sustain. Energy Rev. 59 (2016) 710–725.

[122] J. McDonald, Adaptive intelligent power systems: active distribution net- works, Energy Pol. 36 (12) (2008) 4346–4351.

[123] N. Phuangpornpitak, S. Tia, Opportunities and challenges of integrating renewable energy in smart grid system, Energy Procedia 34 (2013) 282–290.

[124] M. Ourahou, W. Ayrir, B.E. Hassouni, A. Haddi, Review on smart grid control and reliability in presence of renewable energies: challenges and prospects, Math. Comput. Simulat. 167 (2020) 19–31.

[125] S. Leva, A. Dolara, F. Grimaccia, M. Mussetta, E. Ogliari, Analysis and validation of 24 hours ahead neural network forecasting of photovoltaic output power, Math. Comput. Simulat. 131 (2017) 88–100.

[126] I. Petri, M. Barati, Y. Rezgui, O.F. Rana, Blockchain for energy sharing and trading in distributed prosumer communities, Comput. Ind. 123 (2020) 103282.

[127] A.M. Omer, Energy, environment and sustainable development, Renew. Sustain. Energy Rev. 12 (9) (2008) 2265–2300.

[128] D. Zhang, Optimal Design and Planning of Energy Microgrids, Thesis, 2014.

[129] D. Zhang, N.J. Samsatli, A.D. Hawkes, D.J. Brett, N. Shah, L.G. Papageorgiou, Fair electricity transfer price and unit capacity selection for microgrids, Energy Econ. 36 (2013) 581–593.

[130] D.T. Ton, M.A. Smith, The us department of energy's microgrid initia- tive, Electr. J. 25 (8) (2012) 84–94.

[131] Z. Sun, X.-y. Zhang, Advances on distributed generation technology, Energy Procedia 17 (2012) 32–38.

[132] S. Abu-Sharkh, R. Arnold, J. Kohler, R. Li, T. Markvart, J. Ross, K. Steemers, P. Wilson, R. Yao, Can microgrids make a major contri- bution to UK energy supply? Renew. Sustain. Energy Rev. 10 (2) (2006) 78–127.

[133] M.A. Hossain, H.R. Pota, W. Issa, M.J. Hossain, Overview of ac micro- grid controls with inverter-interfaced generations, Energies 10 (9) (2017) 1300.

[134] Q. Jiang, M. Xue, G. Geng, Energy management of microgrid in grid- connected and stand-alone modes, IEEE Trans. Power Syst. 28 (3) (2013) 3380–3389.

[135] O. Ellabban, H. Abu-Rub, F. Blaabjerg, Renewable energy resources: current status, future prospects and their enabling technology, Renew. Sustain. Energy Rev. 39 (2014) 748–764.

[136] P. Ahmadi, I. Dincer, 5.9 Optimization in Energy Management, vol. 5, Elsevier, 2018.

[137] Y. Yang, S. Bremner, C. Menictas, M. Kay, Battery energy storage system size determination in renewable energy systems: a review, Renew. Sustain. Energy Rev. 91 (2018) 109–125.

[138] A. Vinayagam, A.A. Alqumsan, K. Swarna, S.Y. Khoo, A. Stojcevski, Intelligent control strategy in the islanded network of a solar pv microgrid, Elec. Power Syst. Res. 155 (2018) 93–103.

[139] M.A. Hossain, H.R. Pota, M.J. Hossain, F. Blaabjerg, Evolution of microgrids with converter-interfaced generations: challenges and oppor- tunities, Int. J. Electr. Power Energy Syst. 109 (2019) 160–186.

[140] B. Khan, P. Singh, Selecting a meta-heuristic technique for smart micro- grid optimization problem: a comprehensive analysis, IEEE Access 5 (2017) 13951–13977.

[141] H. Farhangi, Smart Microgrids: Lessons from Campus Microgrid Design and Implementation, CRC Press, 2016.

[142] K.J. Chalvatzis, A. Ioannidis, Energy supply security in the eu: bench- marking diversity and dependence of primary energy, Appl. Energy 207 (2017) 465–476.

[143] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, W. Dhaese- leer, Distributed generation: definition, benefits and issues, Energy Pol. 33 (6) (2005) 787–798.

[144] K. Alanne, A. Saari, Distributed energy generation and sustainable devel- opment, Renew. Sustain. Energy Rev. 10 (6) (2006) 539–558.

[145] C.R. Karger, W. Hennings, Sustainability evaluation of decentralized electricity generation, Renew. Sustain. Energy Rev. 13 (3) (2009) 583–593.

[146] P. Paliwal, N. Patidar, R. Nema, Planning of grid integrated distributed generators: a review of technology, objectives and techniques, Renew. Sustain. Energy Rev. 40 (2014) 557–570.

[147] T. Ackermann, G. Andersson, L. Sder, Distributed generation: a defini- tion1, Elec. Power Syst. Res. 57 (3) (2001) 195–204.

[148] L. Mehigan, J. Deane, B. Gallachir, V. Bertsch, A Review of the Role of Distributed Generation (Dg) in Future Electricity Systems, Energy.

[149] W. El-Khattam, M.M. Salama, Distributed generation technologies, def- initions and benefits, Elec. Power Syst. Res. 71 (2) (2004) 119–128.

[150] G. Kini, Energy Management Systems, BoDBooks on Demand, 2011.

[151] S. Bilgen, Structure and environmental impact of global energy consump- tion, Renew. Sustain. Energy Rev. 38 (2014) 890–902.

[152] R. Chaturvedi, S.G. Kumar, P.G. Joshi, Efficiency Improvement by En- Ergy Optimization Program in Energy Intensive Industries a Case Study of Satia Industries Limited, Muktsar (punjab), Thesis, 2016.

[153] G. Petrecca, Industrial Energy Management: Principles and Applications: Principles and Applications, Springer Science & Business Media, 2012.

[154] A. Alzahrani, I. Petri, Y. Rezgui, Analysis and simulation of smart en- ergy clusters and energy value chain for fish processing industries, Energy Rep. 6 (2020) 534–540.

[155] M.F. Akorede, H. Hizam, E. Pouresmaeil, Distributed energy resources and benefits to the environment, Renew. Sustain. Energy Rev. 14 (2) (2010) 724–734.

[156] E. Mashhour, S.M. Moghaddas-Tafreshi, Bidding strategy of virtual power plant for participating in energy and spinning reserve marketspart i: problem formulation, IEEE Trans. Power Syst. 26 (2) (2010) 949–956.

[157] P. Djapic, C. Ramsay, D. Pudjianto, G. Strbac, J. Mutale, N. Jenkins, R. Allan, Taking an active approach, IEEE Power Energy Mag. 5 (4) (2007) 68–77.

[158] A. Abdelaziz, Y. Hegazy, W. El-Khattam, M. Othman, Virtual power plant: the future of power delivery systems, in: European Workshop on Renewable Energy Systems, pp. 1–2.

[159] M. Kenzhina, I. Kalysh, I. Ukaegbu, S.K. Nunna, Virtual power plant in industry 4.0: the strategic planning of emerging virtual power plant in Kazakhstan, in: 21st International Conference on Advanced Commu- Nication Technology (ICACT), IEEE, 2019, pp. 600–605.

[160] O. Nwauka, A. Telukdarie, J. Enslin, Virtual power plant basic require- ments for integration of distributed energy resources driven by industry 4.0, IEOM (2018) 511–523.

[161] L.I. Dulau, M. Abrudean, D. Bica, Applications of virtual power plants approaches, in: International Conference and Exposition on Electri- Cal and Power Engineering (EPE), IEEE, 2014, pp. 1060–1064.

[162] A. Kaur, L. Nonnenmacher, C.F. Coimbra, Net load forecasting for high renewable energy penetration grids, Energy 114 (2016) 1073–1084.

[163] L.I. Dulu, M. Abrudean, D. Bic, Distributed generation and virtual power plants, in: 49th International Universities Power Engineering Con- Ference (UPEC), IEEE, 2014, pp. 1–5.

[164] H. Saboori, M. Mohammadi, R. Taghe, Virtual power plant (vpp), defi- nition, concept, components and types, in: Asia-Pacific Power and Energy Engineering Conference, IEEE, 2011, pp. 1–4.

[165] S.H. Chen, A.J. Jakeman, J.P. Norton, Artificial intelligence techniques: an introduction to their use for modelling environmental systems, Math. Comput. Simulat. 78 (2–3) (2008) 379–400.

[166] A.A. Bazmi, G. Zahedi, Sustainable energy systems: role of optimization modeling techniques in power generation and supplya review, Renew. Sustain. Energy Rev. 15 (8) (2011) 3480–3500.

[167] R.T. Kreutzer, M. Sirrenberg, Fields of Application of Artificial Intelli- genceCustomer Service, Marketing and Sales, Springer, 2020, pp. 105–154.

[168] R.T. Kreutzer, M. Sirrenberg, Fields of Application of Artificial Intel- ligenceEnergy Sector, Smart Home, Mobility and Transport, Springer, 2020, pp. 195–210.

[169] M.W. Ahmad, J. Reynolds, Y. Rezgui, Predictive modelling for solar thermal energy systems: a comparison of support vector regression, ran- dom forest, extra trees and regression trees, J. Clean. Prod. 203 (2018) 810–821.

[170] M.W. Ahmad, M. Mourshed, Y. Rezgui, Tree-based ensemble methods for predicting pv power generation and their comparison with support vector regression, Energy 164 (2018) 465–474.

[171] M.W. Ahmad, A. Mouraud, Y. Rezgui, M. Mourshed, Deep highway net- works and tree-based ensemble for predicting short-term building energy consumption, Energies 11 (12) (2018) 3408.

[172] C.D. Korkas, S. Baldi, I. Michailidis, E.B. Kosmatopoulos, Intelligent energy and thermal comfort management in grid-connected microgrids with heterogeneous occupancy schedule, Appl. Energy 149 (2015) 194–203.

[173] A.I. Dounis, Artificial intelligence for energy conservation in buildings, Adv. Build. Energy Res. 4 (1) (2010) 267–299.

[174] Z. Wang, R. Yang, L. Wang, Intelligent multi-agent control for integrated building and micro-grid systems, in: ISGT, IEEE, 2011, pp. 1–7.

[175] L. Yin, Q. Gao, L. Zhao, B. Zhang, T. Wang, S. Li, H. Liu, A review of machine learning for new generation smart dispatch in power systems, Eng. Appl. Artif. Intell. 88 (2020) 103372.

[176] J. Anderson, T. van Weert, C. Duchteau, Information and Communica- Tion Technology in Education: A Curriculum for Schools and Programme of Teacher Development.

[177] M. Faheem, S.B.H. Shah, R.A. Butt, B. Raza, M. Anwar, M.W. Ashraf, M.A. Ngadi, V.C. Gungor, Smart grid communication and information technologies in the perspective of industry 4.0: opportunities and chal- lenges, Comput. Sci. Rev. 30 (2018) 1–30.

[178] T. Kazičková, B. Buhnova, Ict architecture for the smart grid: concept overview, in: 2016 Smart Cities Symposium Prague (SCSP), IEEE, 2016, pp. 1–4.

[179] G.T. Ferguson, Have your objects call my objects, Harv. Bus. Rev. 80 (6) (2002) 138–144.

[180] S. Madakam, V. Lake, V. Lake, V. Lake, Internet of things (iot): a lit- erature review, J. Comput. Commun. 3 (5) (2015) 164.

[181] M.U. Farooq, M. Waseem, S. Mazhar, A. Khairi, T. Kamal, A review on internet of things (iot), Int. J. Comput. Appl. 113 (1) (2015) 1–7.

[182] A. Hlali, S. Hammami, Seaport concept and services characteristics: the- oretical test, Open Transport. J. 11 (1).

[183] J.K. Siror, S. Huanye, W. Dong, Rfid based model for an intelligent port, Comput. Ind. 62 (8–9) (2011) 795–810.

[184] S. Li, Z. Ma, P. Han, S. Zhao, P. Guo, H. Dai, Bring intelligence to ports based on internet of things, in: International Conference on Cloud Computing and Security, Springer, pp. 128–137.

[185] M. Ferretti, F. Schiavone, M. Al-Mashari, M. Del Giudice, Internet of things and business processes redesign in seaports. the case of hamburg, Bus. Process Manag. J. .

[186] M. Abaie, H.R.; Rastegary, The emergence of smart ports and their im- pactful implications, in: Proceedings of 14th Trans Middle East Confer- Ence, Springer, pp. 128–137.

[187] G. Wilmsmeier, J. Froese, A. Zotz, A. Meyer, Energy consumption and efficiency: emerging challenges from reefer trade in south american con- tainer terminals.

[188] M. Oppenheimer, A. Petsonk, Article 2 of the unfccc: historical origins, recent interpretations, Climatic Change 73 (3) (2005) 195–226.

[189] A. Molavi, G.J. Lim, B. Race, A framework for building a smart port and smart port index, Int. J. Sustain. Trans. 14 (9) (2020) 686–700.

[190] IMO, Third Imo Greenhouse Gas Study 2014, 2014.

[191] H. Boyes, R. Isbell, A. Luck, Code of Practice: Cyber Security for Ports and Port Systems, Department for Transport, London.

[192] S. Azarkamand, C. Wooldridge, R. Darbra, Review of initiatives and methodologies to reduce co2 emissions and climate change effects in ports, Int. J. Environ. Res. Publ. Health 17 (11) (2020) 3858.

[193] N.B. Ahamad, M. Othman, J.C. Vasquez, J.M. Guerrero, C.-L. Su, Optimal Sizing and Performance Evaluation of a Renewable Energy Based Microgrid in Future Seaports, 2018, pp. 1043–1048.

[194] S. Singh, B. Sengupta, Sustainable Maritime Transport and Maritime in- Formatics, 2020, pp. 81–95.

[195] Y. Bicer, I. Dincer, Clean fuel options with hydrogen for sea transporta- tion: a life cycle approach, Int. J. Hydrogen Energy 43 (2) (2018) 1179–1193.

[196] M. M. Kidere, Analytical Assessment of Port Energy Efficiency and Man- agement.: a Case Study of the kenya Ports Authority.

[197] P. Beaumont, Cybersecurity risks and automated maritime container ter- minals in the age of 4ir, in: Handbook of Research on Information and Cyber Security in the Fourth Industrial Revolution, IGI Global, 2018, pp. 497–516.

[198] S. Jones, Addressing cyber security risks at ports and terminals, Port Technol. Int. J. 62.

[199] G.C. Wilshusen, Maritime critical infrastructure protection: dhs needs to enhance efforts to address port cybersecurity, Tech. Rep. (2015).