

Article

Energy Efficiency in European Ports: State-Of-Practice and Insights on the Way Forward

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Received: 31 July 2019; Accepted: 6 September 2019; Published: 11 September 2019



Abstract: The changing energy landscape in Europe, marked with the development of the Energy Union in 2015, had a profound impact also on the European port sector. With European ports becoming key points of energy production, but also being prominent energy users, energy consumption has naturally risen into a top environmental priority for port authorities. To this end, the paper provides a pragmatic and comprehensive overview of the main policies, technologies and practices that European ports have adopted to-date for enhancing their energy efficiency. Addressing a gap that has been identified in relevant recent literature, it gathers actual data and port experiences from many different sources in a first attempt to better facilitate knowledge and experience-sharing activities, that will support ports in collectively moving towards a zero-emission and climate-neutral future. Most importantly, it presents an effort to rationalize research findings, assist in aligning them with practice, shed more light on the exploitation path of this line of research and better inform future research efforts.

Keywords: port sustainability; energy efficiency; energy performance; energy management; green port policy

1. Introduction

In pursuit of a more sustainable future, energy efficiency plays a key role. With the European Union (EU) importing more than half of all the energy it consumes (53.6% in 2016) and total import costs exceeding €1 billion per day, the European Commission (EC) has naturally set energy efficiency as a high and strategic priority [1,2].

To further support and strengthen the process towards reaching the goal of sustainability, the EC has set over time a number of targeted strategies introducing a variety of short, medium and long-term measures, along with specific, quantifiable targets to be met within certain time horizons. More specifically, in May 2014, the EC released its Energy Security Strategy, which comprised of a number of measures aiming to ensure stable and abundant energy supply for European citizens and support the economy of EU Member States [1]. Five months later, and building upon its 2020 Energy Strategy, the European Council agreed on a new 2030 Climate and Energy Framework, setting three main targets: (a) At least 40% reduction in greenhouse gas (GHG) emissions compared to 1990 levels, (b) at least 27% share of renewable energy consumption, and (c) at least 27% improvement in energy efficiency, with the last target being subject to review by 2020, for a potential increase up to 30% [3]. As a next and very important step, the EC formulated the Energy Union, which launched its strategy in February 2015 [4]. The following five interrelated dimensions serve as the cornerstones of

the Energy Union: (i) Energy source diversification and security of energy supply, (ii) higher level of integration of the EU internal energy market, (iii) improved energy efficiency lowering import dependence, (iv) economy decarbonization, and (v) support to research and innovation in low-carbon and clean energy technologies. Very recently, on November 2018, the EC also presented its long-term strategy for moving towards a climate-neutral Europe by 2050. Among its seven strategic priorities, maximizing the benefits from energy efficiency was a key one. More specifically, a 50% reduction in energy consumption was set as a target, taking energy consumption levels in 2005 as a reference basis [5].

Within this context and for supporting the realization of the aforementioned targets, the European port sector has an important role to play [6]. According to a fact-finding online survey that was conducted in 2015–2016 among 86 port authorities scattered across 19 EU Member States, 25% of the responders have more than 50% of their traffic volumes linked to energy commodities (e.g., crude oil, refined petroleum products, coke and coal, Liquefied Natural Gas—LNG, etc.). Furthermore, they represent prominent energy users, and they serve as key locations for energy production from renewable energy sources (e.g., wind, solar, biomass and waste-based energy) [7].

These considerations serve as the main motivation for this paper, which aims to efficiently summarize and present the actions that port authorities in Europe have actually undertaken, policy and technology-wise, to improve energy efficiency and minimize energy consumption. To this end, important environmental benefits may be gained, including mitigation of the associated health implications on port workers, passengers and the surrounding urban community. Important cost savings may also be realized, supporting further investments on new, low-carbon and/or zero-emission technologies. Such a deeper understanding of the industry perspective, along with a comprehensive review of relevant research efforts, can contribute on building a solid foundation to better support port decision-makers into evaluating the transferability of promising policies, technologies and practices, rationalize research findings, assist in aligning them with practice, shed more light on the exploitation path of this line of research and better inform future research efforts.

Within this context, the rest of the paper is structured as follows: Section 2 addresses the policy level and presents, in a descending order with regard to the associated level of commitment, the main policies, standards and strategies that European port authorities have adopted to-date for setting their energy management vision, specifying reduction targets to be achieved, and determining the procedures that need to be followed for monitoring the progress towards achieving those targets. With a greater emphasis being placed on container transport with regard to certain measures (e.g., terminal equipment) considering their higher energy intensity, but with several others being applicable to different types of terminals, Section 3 addresses the technology part, summarizing the main measures that European ports have implemented for reducing energy consumption and improving energy efficiency in their area. Incorporating also a number of new initiatives that have been recently introduced, Section 4 provides key insights and recommendations for European ports moving towards a clean energy future. Section 5 concludes the paper highlighting the key points of the current state-of-the-practice, putting forward the research directions that future efforts and initiatives should converge to.

2. The Policy Side: Energy Efficiency Management and Certification

Ranking seventh in 2009 among the top ten environmental priorities of the European port sector, energy consumption has received increasing attention in recent years. As depicted in Figure 1 below, in the last three years, European ports acknowledged energy consumption as the second most important environmental priority, following air quality [8].

1996	2004	2009	2013	2016	2017	2018
Port development (water)	Garbage / Port waste	Noise	Air quality	Air quality	Air quality	Air quality
Water quality	Dredging operations	Air quality	Garbage / Port waste	Energy consumption	Energy consumption	Energy consumption
Dredging disposal	Dredging disposal	Garbage / Port waste	Energy consumption	Noise	Noise	Noise
Dredging operations	Dust	Dredging operations	Noise	Relationship with the port community	Water quality	Relationship with the port community
Dust	Noise	Dredging disposal	Ship waste	Garbage / Port waste	Dredging operations	Ship waste
Port development (land)	Air quality	Relationship with the port community	Relationship with the port community	Ship waste	Garbage / Port waste	Port development (land)
Contaminated land	Hazardous cargo	Energy consumption	Dredging operations	Port development (land)	Port development (land)	Climate change
Habitat loss / degradation	Bunkering	Dust	Dust	Water quality	Relationship with the port community	Water quality
Traffic volume	Port development (land)	Port development (water)	Port development (land)	Dust	Ship waste	Dredging operations
Industrial effluent	Ship discharge (bilge)	Port development (land)	Water quality	Dredging operations	Climate change	Garbage / Port waste

Figure 1. The top ten environmental priorities of European ports over the last two decades [8].

For successfully addressing such a top environmental concern, port authorities in Europe have been working intensively towards setting-up appropriate policies, devising targeted action plans and establishing proper management frameworks and systems. These are important prerequisites for identifying the right set of solutions and measures to be implemented, considering local conditions and priorities, thus, contributing towards the realization of substantial environmental benefits and cost savings. They also reflect the different level of commitment that port authorities may take for improving their energy efficiency. More specifically, the following sub-sections present the policies, standards and strategies that are commonly adopted as the most effective ones in tackling energy consumption and management concerns in port areas. They are presented in descending order with regard to the overall effort needed, investments required and relevant structures and procedures that need to be in place.

2.1. ISO 50001 'Energy Management'

Introduced in 2011 by the International Standards Organization (ISO) as an effective tool for supporting energy managers on meeting energy consumption reduction goals, the ISO 50001 follows the conventional Plan-Do-Check-Act (PDCA) improvement cycle [9] as follows:

- An energy review (i.e., audit) is conducted first, and the baseline (i.e., reference energy data) is set. Following the results of this process, the overall energy strategy is defined, specific energy-saving targets and objectives are set, performance indicators are determined, and the action plan to be followed is prepared (PLAN);
- Selected measures, either technological or operational ones, which have been incorporated into the action plan are being implemented next (DO);
- Relevant processes, as well as key characteristics of operations that are affecting energy performance, are being monitored and reviewed against the energy policy which has been formulated, and the specific reduction targets that have been set. The relevant results are being reported (CHECK);
- Based on these results, strategic decisions are taken for ensuring the continuous improvement of energy performance and enhancing the Energy Management System (EnMS) (ACT) [9].

ISO 50001 requires a systemic, data-driven and fact-based process to be implemented for supporting the continuous improvement of energy performance. Following its last technical update in 2018,

the standard further specifies the process of establishing, implementing, maintaining and improving an EnMS.

Given the great effort and resources that are required, certification to this standard represents one of the heaviest commitments that a port authority can take for improving its energy efficiency. To this end, its level of adoption within the EU still remains low. The ports of Felixstowe and Antwerp are the first ones that have been certified to this standard, in 2013 and 2015, respectively [10,11]. Only a few ports, mainly large ones (e.g., Valencia, Hamburg), have followed since then [12,13].

2.2. EN 16001 'Energy Management Systems'

A close alternative to ISO 50001, is the European standard for EnMS. Having been introduced a few years earlier, in 2009, EN 16001 actually served as a predecessor to ISO 50001. The two standards share several similarities, but also present a handful of distinct differences [14]. For example, they share the same structure (PDCA cycle), which facilitates their easy integration with environmental management systems, although ISO 50001 introduced three new concepts that were not included in EN 16001.

The first relates to the management responsibility, and more specifically the fundamental role of the so-called top management, which defines the energy policy and main objectives to be achieved, allocating available resources and setting operational roles. To provide support to the top management, an energy management team needs to be established, according to ISO 50001, following the leadership of a management representative. The second concept addresses the 'PLAN' phase and sets in more detail the energy review process for presenting a solid baseline that will allow the monitoring of energy performance using an appropriate set of indicators. The third difference concerns the 'DO' phase, where ISO 50001 puts more emphasis on the design of processes, systems and equipment that may impose an impact on energy aspects, stressing out the need to outline the energy policy that has been set within any new contract and/or communication with energy suppliers.

However, some aspects of EN 16001 were not up-taken in ISO 50001. These include (a) the priority scale of energy aspects, facilitating the identification of those requiring a more thorough examination, (b) the identification of a company's workforce, or others acting on its behalf, whose activities may have an impact on energy consumption, and (c) cost projections related to potential upgrades and estimations of the associated reduction in energy consumption, supporting the re-entry of investments based on energy consumption forecasts [14].

The EN 16001 did not find wide applicability in the European port sector, a fact that can be most probably attributed to the less attention port authorities were paying on energy efficiency at that time (2009) (Figure 1).

2.3. Port Energy Management Plans (PeMP)

The Port Energy Management Plan methodology presents the steps that interested port authorities can follow for developing a Port Energy Management Plan—PeMP (Figure 2), also taking into consideration the emerging development of such internal, voluntary initiatives at the global level (e.g., Port of Los Angeles) [15,16]. Application of this methodology may serve as a preliminary step towards the accreditation of European port authorities to either of the aforementioned standards. The structured methodology was devised within the framework of the 'GREENBERTH—Promotion of Port Communities SMEs role in Energy Efficiency and Green Technologies for Berthing Operations' research project, which was funded by the MED Program from January 2013 to June 2015.

As depicted in Figure 2, a generic energy consumption mapping and assessment method is applied first for setting the baseline. The method resembles in scope the energy efficiency audit schemes that ports often implement on a voluntary basis. It follows a three-level top-down approach, where total energy consumption in terms of direct fuel consumption and purchased electricity is being assessed at the first level. Process blocks (i.e., operations, support/maintenance functions and buildings) are then selected in the second level, and the associated physical processes (i.e., sub-blocks) are mapped. For each activity of a mapped process, the energy consumption is being assessed at the third level,

also considering equipment deployment and time of operation. This process enables the identification of existing gaps, and consequently, the development of targeted recommendations for addressing them. The latter are then communicated to port community stakeholders (e.g., through the organization of focus group meetings) for reaching a clear consensus with regard to the necessary actions to be followed next. Any necessary re-engineering processes are then defined and implemented, while key performance indicators are also determined for the development of the PeMP. In the latter, all actions to be undertaken for enhancing the port's energy efficiency are being described in detail, along with the respective time framework, cost estimates and the allocation of relevant responsibilities to the different actors that will be involved [15].

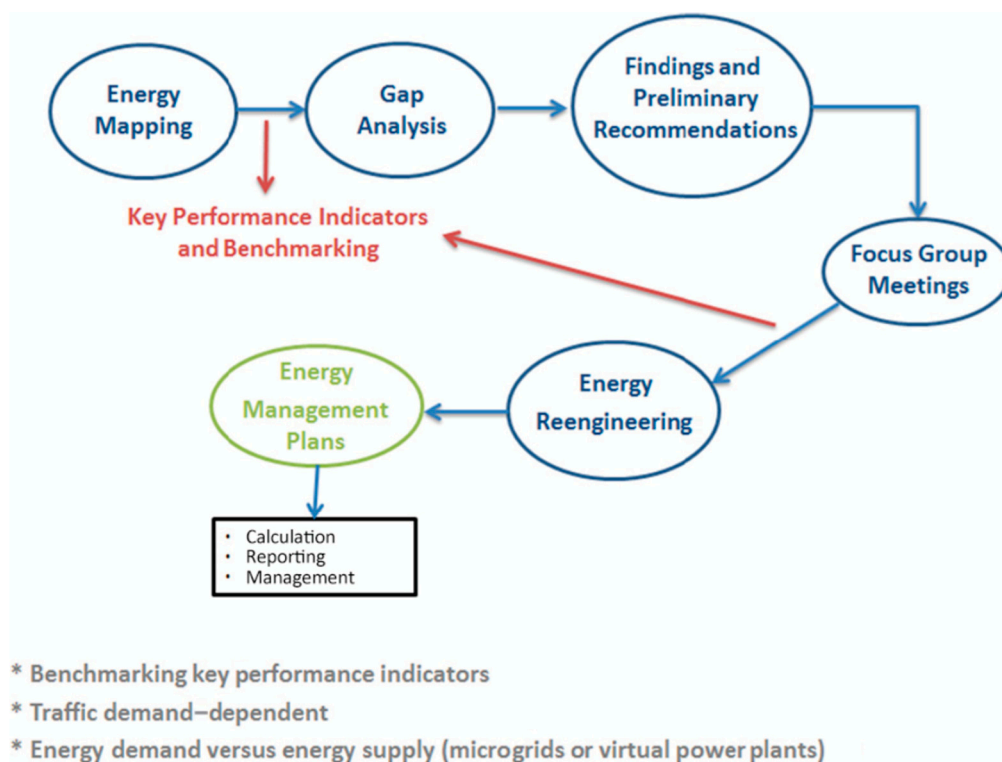


Figure 2. Process for developing a Port Energy Management Plan [15].

This step-by-step approach has been applied and tested in six Mediterranean ports. These are Valencia, Marseille, Livorno, Venice, Koper and Rijeka. Key energy consumers were identified within each port area, and appropriate measures/solutions were selected and proposed to produce significant energy and cost savings. After communicating the proposed measures/solutions to port community stakeholders in each area, a prioritization process took place, and the pilot testing of the ones that received the highest priority was planned. Promising results were reported at the end of each pilot test, supporting full-scale implementation decisions, some of which were actually taken a few months or years later. For example, the port of Livorno established and operationalized the cold-ironing system it had pilot-tested, following the aforementioned approach [17].

Although PeMP does not constitute part of a standard or another certification procedure, it proves to be a valuable intermediate step for port authorities, gradually setting the ground for their future certification to more demanding standards, such as those outlined above.

2.4. Energy Management Addressed via Environmental Management Systems (EMS)

The majority of port authorities in Europe are tackling energy management, mainly through the overall framework of environmental management (Figure 3). Three are the main EMS that have been most widely adopted within the European port network: (a) The Port Environmental

Review System—PERS, (b) the ISO 14001 standard on EMS, and (c) the Eco-Management and Audit Scheme—EMAS (Figure 4).

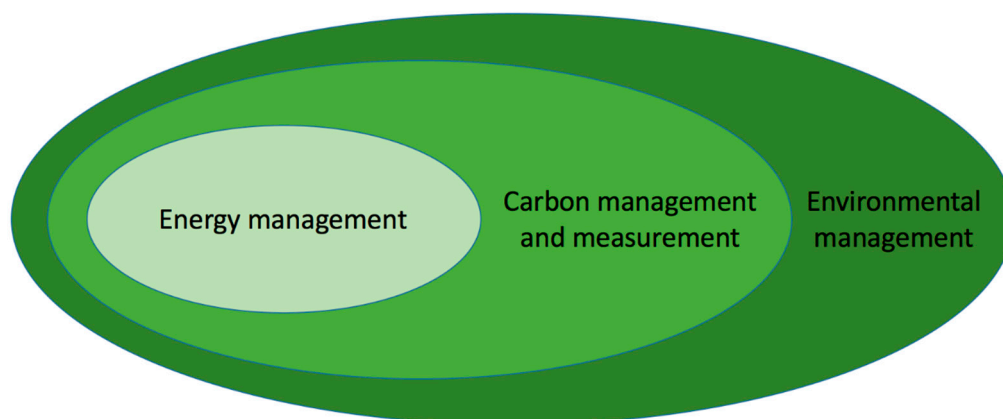


Figure 3. Context within which energy management is usually addressed in ports (adapted from Reference [18]).

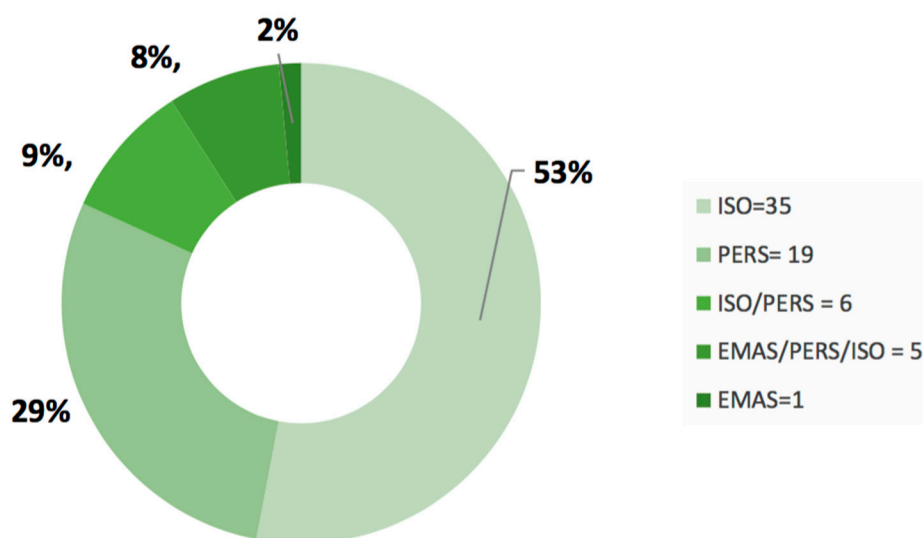


Figure 4. EMS certified ports—members of EcoPorts (i.e., the main environmental initiative of European ports, part of the European Sea Ports Organization) [19] based on Reference [8].

The contribution of EMS to energy management has not been extensively studied and reported in the relevant literature. Quite recently, however, Laskurain et al. [20] addressed this gap by analyzing the contribution of ISO 14001 and EMAS on energy management. According to the results of the content analysis they conducted, ISO 14001 proves to be making little reference on the use of energy, and thus, most certified companies tend to overlook energy aspects and mainly concentrate on more obvious environmental aspects, such as emissions, waste, water quality, etc. Direct and indirect references are being made only in a few sections of the standard (i.e., 3.2.7—Prevention of pollution, 5.2—Environmental Policy, A.6.1.2—Environmental Aspects, 8.1—Operational planning and control) suggesting the reduction of energy consumption, the controlling of energy use for minimizing emissions, and thus, promoting the wider use of clean and renewable energy. EMAS, on the other hand, goes a bit further and introduces a set of core aspects related to energy management. The standard requires certified companies to select the level of energy management and performance they need, and provides them with a set of energy efficiency indicators for monitoring their relative progress. Furthermore, it puts forward a number of best practices that have been implemented in a variety of sectors. However,

with the standard setting no mandatory requirements, its real added-value on tackling energy aspects is very limited [20].

In summary, EMS standards present some major limitations in efficiently tackling energy concerns, since no performance requirements are specifically set and no mandatory, comparable performance indicators are provided, which would facilitate the more accurate differentiation of ports into high and low performing ones with regard to energy management.

2.5. Port Environmental Management Plans (PEMP) and Green Port Policies

Energy efficiency aspects are also incorporated into Port Environmental Management Plans (PEMP) that port authorities often develop on a voluntary basis, while they also serve as a key dimension in the green policy that ports put forward as an overarching approach for tackling environmental aspects in an integrated and coordinated way. However, due mainly to their wider focus, but also the large degree of freedom that often characterizes their development, such planning instruments and policies represent only a small commitment of port authorities to efficient energy management.

Currently, the seven Port Authorities of Venice, Trieste, Koper, Bar, Durres, Thessaloniki and Piraeus, in five Mediterranean countries (i.e., Italy, Slovenia, Montenegro, Albania and Greece) are working towards developing such PEMP's covering a wide range of intervention areas [21]. Within these plans, which are anticipated to be finalized by November 2019, great focus is being placed on the improvement of energy management and the reduction of current energy consumption levels. More specifically:

- Focusing on its buildings, the port of Venice plans to undertake an energy performance diagnostic process, to more accurately determine current levels of energy consumption and better plan appropriate improvements, also taking into consideration any new relevant technologies;
- The port of Trieste investigates the implementation of an onshore power supply (OPS) system at its Ro-Ro terminals, which, according to estimates, is expected to reduce CO₂ emissions by more than 40%. For its efficient planning, both the very recent "Guidelines for the drafting of Energy-Environmental Planning Documents of Port Systems" issued by the Italian Ministry of Environment and the Protection of Land and Sea in December 2018, as well as the "Sustainable Energy Action Plan" of the Municipality of Trieste are being taken into consideration, so that a certain, mutually beneficial degree of alignment can be ensured;
- The port of Bar focuses on (a) the development of an inventory of existing equipment that will include detailed data on energy consumption, and (b) the compilation of a prioritized list of feasible and promising energy sustainability measures for the port as a whole, but also for specific areas/facilities (e.g., buildings, warehouses, storages, etc.) and operations/equipment (e.g., ship loading/unloading equipment, yard operations equipment, terminal vehicles).
- The port of Durres assesses the feasibility of potential investments to be undertaken for the promotion of clean and renewable energy in the port. More specifically, it studies the installation of a photovoltaic system, the conversion of terminal vehicles and equipment from diesel to electric ones, and the implementation of an OPS system;
- The port of Thessaloniki focuses on (a) the development of a new information system for recording, assessing and monitoring, on a real-time basis, the consumption of electricity, natural gas, water and fuel covering all port activities and operations, and (b) the development of a PeMP following the methodology that was briefly presented in Section 2.3;
- A similar energy consumption monitoring system is also being investigated at the port of Piraeus. Such an infrastructure is expected to provide the port with a good, solid basis that will support its future certification to ISO 50001. Along with the system, a series of other measures are also being explored, including the improvement of the energy efficiency of buildings (i.e., frequent maintenance of heating and cooling systems and construction of a 'green' roof on the top of the

new office building of the Piraeus Port Authority), the implementation of a lighting control system, and the electrification of selected terminal equipment.

Within the framework of their green policy, some port authorities in Europe have also introduced modal split clauses in new or in the renegotiation of existing concession contracts for their (mainly container) terminals. Such an obligation can ensure a better environmental and energy performance of the terminal, contributing towards achieving the overall relevant vision and specific targets that the port authority has set. Typical was the case in the port of Rotterdam, where in the proposal request for the concession contract of its Maasvlakte 2 container terminal, the port authority set the minimum desired modal split. Candidates had then to describe within their proposals, the modal split that they could realize as well as the strategy that they would follow for achieving their expectation [22]. Besides modal split, several other environmental instruments are applicable and can be taken into consideration in a terminal concession setting [23].

3. Technological and Operational Measures Adopted for Improving Energy Efficiency

3.1. Categorization

A wide range of technological solutions and operational measures addressing different processes, facilities and equipment, have been implemented in European ports for further improving their current energy performance. The relevant efforts prove to have been further intensified over the last few years considering the higher priority given on energy concerns, as well as the important opportunities that have more recently emerged with regard to the wider exploitation of renewable energy sources, such as wind energy, solar energy and the different forms of ocean energy (e.g., wave and tidal energy).

Two very recent reviews of Bjerkan and Seter [24] and Iris and Lam [25] provide a very good overview and categorization of the main areas where further energy efficiency improvements can be realized in ports, building upon a very large number of relevant bibliographic sources. In certain cases, though very limited in number, targeted pilot and/or full-scale projects that European ports, among others, have implemented are also being reported in brief. More specifically, addressing all different aspects of port sustainability, Bjerkan and Seter distinguish available practices into four categories:

- Port management and policies, where port environmental plans, energy management and monitoring systems, green concession agreements, modal split clauses, green port dues, collaboration schemes between port community stakeholders, and other managerial instruments are being taken into consideration;
- Power and fuel used in ports, considering different forms of renewable energy (i.e., wind, solar, wave and tidal, and geothermal), electrification of vehicles and equipment as well as cold ironing systems, and alternative fuels (i.e., LNG, biofuels, methanol, hydrogen and low-sulfur fuels);
- Sea activities, that include speed reduction of vessels when approaching the port, efficient vessel handling also looking at the impact of port waiting time on energy efficiency at sea considering the relevant relation introduced by Moon and Woo [26], as well as other vessel emission reduction technologies (i.e., scrubbers); and
- Land activities, that include modal split, technological upgrades of drayage trucks, efficient truck and vessel loading/unloading operations, and intelligent traffic management systems.

Narrowing down their focus on port energy efficiency, Iris and Lam discuss (a) current operational strategies, including energy-aware optimization of operations and peak shaving, (b) key technologies, including OPS, alternative energy sources for equipment (electrification in particular), solutions for reefer containers, lighting technologies and a few others that can contribute towards reduced energy consumption (e.g., automated systems, such as for mooring, start-stop engines for diesel equipment, reactive power compensation systems), and (c) energy management, with emphasis on energy consumption measurement and (real-time) monitoring systems, wider exploitation of renewable energy and clean fuels, micro- and smart-grids, as well as key relevant policy frameworks.

The paper builds upon and aims to effectively complement the aforementioned two contributions by adding another important perspective that is not being adequately addressed as explicitly stated in the existing literature [24]. More specifically, both reviews follow a more research-oriented approach highlighting the key research topics that relevant recent efforts have focused on and have contributed to, with limited references being provided on actual implementation cases. The paper aims to address this gap, by presenting a more business-oriented categorization of the main technological and operational measures that European ports have actually implemented to date, and are currently promoting for improving their energy efficiency (Figure 5). Key implementers (i.e., accounting for the largest investments and having undertaken the most effective efforts for promoting their advancements), as well as recent pilot-testers, are highlighted. Valuable insights can be gained to the benefit of interested ports that have pilot-tested selected measures/solutions with promising results, and are currently in the process of devising their full-scale implementation plans, or are at a more initial stage, investigating possible solutions that will best fit local conditions and successfully adhere to the relevant priorities that have been set. To this end, a more solid foundation can be established, supporting port decision makers into better evaluating the transferability potential of promising solutions and technologies.

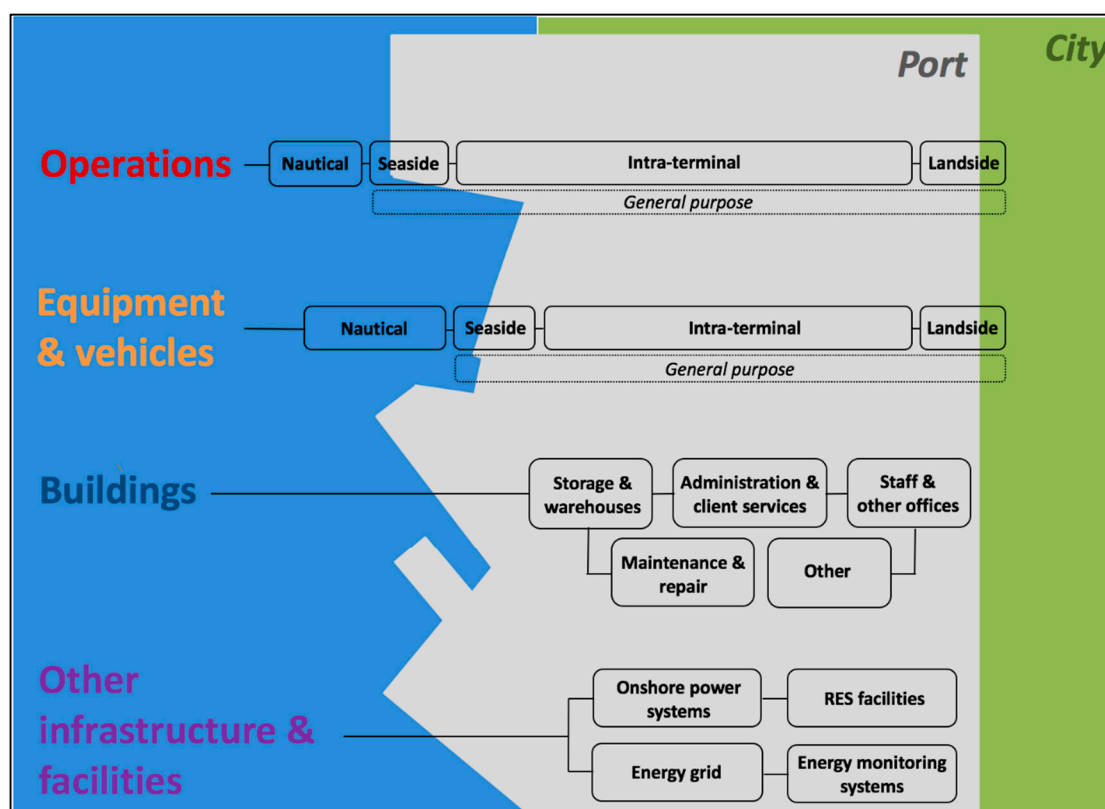


Figure 5. Categorization of energy efficient technologies and solutions implemented in European ports (Authors based on Reference [15]).

The sub-sections that follow aim to provide a comprehensive overview of the range of relevant technologies and solutions that European ports have adopted to date. With a greater emphasis on container transport, publicly available sources were utilized (e.g., ports' websites, published environmental reports, project deliverables, studies, research articles, etc.), supported by different means (e.g., the ports' resources, research programs, etc.) and shared via various communication channels.

3.2. Key Operational Measures

Effectively adapting the process-block approach followed in Boile et al. [15], Table 1 summarizes the key operational measures that European ports have implemented for improving their energy

efficiency. It should be noted at this point, that naturally any process undertaken for optimizing a single or a set of port operations, also induces energy gains, among other benefits that are realized to this end (i.e., time and cost savings), These usually account for the main objective of most optimization efforts. Although the scientific literature on port optimization is vast, with more recent approaches also integrating energy considerations into their methods [27–30], the level to which those have been applied in real operational environments, and even more the extent to which energy aspects are being taken into consideration by the operational planning teams of port authorities and/or terminal operators, is not very easy to determine. Relevant information does not usually become publicly available, nor is it promoted through any other means (e.g., shared through relevant presentations in events targeting port sustainability). To this end, such insights were not included in Table 1. However, it is worth pointing out that the rapidly growing interest of port authorities and terminal operators on improved environmental and energy performance, has been successfully received and well comprehended by developers of terminal operating systems (TOS), who have started to introduce new relevant tools, upgrading their current products (e.g., CHESSCON).

Table 1. Operational measures.

Process Block	Relevant Process	Measure	Key Implementers	Most Recent Pilot-Testers and Supporting Initiative(s)
Intra-terminal	Container handling, transport and stacking	Full or semi-automation of relevant terminal equipment	Rotterdam, Hamburg, Antwerp, Barcelona, Algeciras	-
		Eco-driving of relevant terminal equipment	Copenhagen-Malmö	-
Landside	Port access	Truck appointment system	Antwerp, Gothenburg, Gdansk, Southampton, Felixstowe	-
General purpose	Outdoor lighting	Dynamic (smart) lighting system	Moerdijk	Valencia—SEA Terminals project (2015), Emden—DUAL Ports project (2018)

In Table 1, four relevant measures that have been applied or were quite recently pilot-tested in European ports are included. Two of them (i.e., eco-driving of terminal equipment and dynamic lighting system) are directly oriented towards improving energy efficiency, while the remaining ones (i.e., full or semi-automation of terminal equipment and truck appointment systems) are broader targeting other improvements, but also indirectly contributing towards a lower energy consumption in the port area.

Fully automated as well as semi-automated terminals, can contribute towards more sustainable operations in various ways. The higher optimization of container flows that can be achieved, can result into reduced energy consumption (and, thus, lower costs), while the lifetime of the equipment is also extended allowing better preservation of resources [31]. The port of Rotterdam, and more specifically its Maasvlakte 2 terminal, accounts for the highest degree of automation within the European port network, while increased automation levels can also be found in the ports of Hamburg, Antwerp, Barcelona, Algeciras, London, Liverpool and Thamesport [32]. Overall, container terminal automation is still at a very early stage, with only 1% and 2% of terminals being fully and semi-automated, respectively, at the global level [33].

The rationalization of truck arrivals at ports can also generate multiple benefits. Besides reducing the idle time of trucks waiting outside the terminal's gates, truck appointment systems (TAS) that are used to this end, also contribute towards maximizing the utilization rate of the container yard

equipment, consequently reducing the turnaround time of trucks. The associated energy savings can be important. Quite recently, another very interesting line of work has been published investigating additional energy gains that may be realized from including reefer-related information into a TAS [34]. Considering that reefer container trade is growing at a faster pace than conventional containers, with larger volumes required to be handled, and that those containers actually account for the largest energy consumer in the port area (almost 40% of total energy consumption), minimizing their dwell time through such a system (e.g., by prioritizing the arrival of trucks picking-up such containers) can yield substantial benefits in terms of energy consumption [35,36]. Within the European port network, TAS have been implemented for quite some time now in terminals at the ports of Antwerp (TAMS), Gothenburg (TERMPoint), Gdansk (e.Brama), Southampton (Vehicle Booking System—VBS) and Felixstowe (VBS), with each system presenting its features and capabilities.

Driving terminal equipment in a more environmentally friendly way (e.g., avoiding frequent and/or unnecessary braking and stopping, trying to retain a steady speed, shifting gears at low rpm, etc.) is a measure that can directly result into considerably lower fuel consumption, mitigating also the associated air emissions and improving air quality in the port area. A good balance needs to be retained, however, between environmental and operational efficiency, so that the combined benefit can be maximized. A relevant program was implemented nearly a decade ago in the ports of Copenhagen and Malmö, where machine operators were educated and trained to the principles of eco-driving. As a result, a 10–15% reduction in fuel consumption was reported at the port of Malmö which, in combination with the equipment's lower level of wear-and-tear, resulted in cost savings of up to one million SEK (i.e., nearly € 95.000) [37].

Following the high share of reefer containers in the total energy consumption of ports, as well as the quite equal share of terminal equipment (mainly ship-to-shore cranes), terminal lighting typically represents the third-largest energy consumer (12%) in a container terminal [35]. To this end, quite recently, a number of full-scale implementation, but also pilot projects have focused on the deployment and testing of dynamic (smart) lighting systems covering different areas within the port, effectively meeting real-time operational needs. More specifically, such a full-scale system was installed across the industrial park of the port of Moerdijk in 2017. 1100 LED street lights were equipped with motion sensors that are being managed by a centralized control system, with different light intensities being used according to the needs of different conditions. Operating costs are estimated to have been reduced by 80%, while a 50% reduction has also been reported in maintenance costs [38].

Two other systems have also been pilot-tested within the last four years. The first, the Terminal Dynamic Illumination—TDI, was tested in 2015 at the Noatum container terminal in the port of Valencia, within the context of the SEA Terminals project. The pilot-test, which lasted for approximately 1.000 hours, provided the basis for forecasting future savings which were estimated to be around 80% of the current energy use. Considering the associated costs, those savings are expected to be achieved with a return-on-investment period of under two years [39]. The second system was more recently tested at the port of Emden (2018), within the context of the DUAL Ports project. The LED-based system that was developed, covered a 10-hectare railway reloading point for rolling commodities. Based on European norms for work safety, different light scenarios were programmed within the system for ensuring that adequate light, and of different intensities, is provided for supporting various activities (e.g., loading, unloading, shunting, siding, etc.). Sensors were also used to ensure that the scenarios were automated; while via an online application, remote-control was enabled, allowing the manual on- and off-switch of the available scenarios. The associated energy and cost savings are expected to be important, derived from lower operating hours and maintenance requirements, longer life spans of lamps and the non-necessity of warm-up periods. Light pollution is also expected to be considerably reduced while working conditions, and thus, safety, will greatly improve [40].

3.3. Main Technological Solutions for Port/Terminal Equipment and Vehicles

Table 2 focuses on the second most important energy consumer in the port area, i.e., port/terminal equipment and vehicles. Most of the relevant measures that have been included in the following table relate to new engine technologies (i.e., hybrid, electric, powered with alternative fuels) mainly for terminal transport and stacking equipment. Tug boats and general purpose port vehicles are also addressed. In combination with the dynamic lighting systems mentioned above, the use of LED technology in outdoor port/terminal areas is another rather simple, but very promising, measure.

Table 2. Measures focusing on port/terminal equipment and vehicles.

Process Block	Relevant Equipment/Vehicle	Measure	Key Implementers	Most Recent Pilot-Testers and Supporting Initiative(s)
Nautical	Tug boats	Hybridization	Rotterdam, Luleå	-
		Alternative fuels—LNG	-	Bilbao—CORE LNGas hive project (2018)
Intra-terminal	Terminal transport and stacking equipment	Hybridization	Antwerp, Southampton, Hamburg, Helsingborg	Livorno—SEA Terminals project (2015)
		Full electrification	Piraeus, Felixstowe, Koper, Oslo, Le Havre, Marseille, Hamburg	Valencia—SEA Terminals project (2015)
		Alternative fuels—LNG	-	Valencia—Green Cranes (2013), Barcelona—CORE LNGas hive project (2018)
		Alternative fuels—Hydrogen fuel cells	-	Valencia—H2Ports (foreseen for 2020–2021)
General purpose	Port vehicles	Electrification	Barcelona, Koper	Santa Cruz de Tenerife—e-ISLAND project (2016)
	Outdoor lighting	LED technology	Amsterdam, Barcelona, Bilbao, Värtahamnen	-

The ‘greening’ of terminal equipment is a measure that most port authorities in Europe have undertaken, or primarily consider, for improving their environmental and energy performance. Great emphasis is being placed mainly on the relevant opportunities that terminal transport and stacking equipment provide (i.e., terminal tractors, Automated Guided Vehicles—AGVs, Rubber Tired Gantry—RTG cranes, Rail Mounted Gantry—RMG cranes, reach stackers, straddle carriers, forklifts). Their respective share on the total port energy consumption is substantial, while a large improvement potential still exists, compared to other terminal equipment for which a higher level of energy efficiency has already been reached and possible improvements are more limited (e.g., ship-to-shore gantry cranes) [41].

Relevant investments have been mostly undertaken until now on the hybridization and full electrification of such equipment, with several orders being currently delivered in different European ports. More specifically, following the successful partnership of a global terminal operator (DP World) with a leading terminal equipment manufacturer (Kalmar), twenty-three hybrid straddle carriers were delivered in the DP World Antwerp Gateway terminal over the last two years. Also, in the DP World Southampton terminal, twelve such units were received earlier this year [42]. Compared to the standard units used before, the latter prove to have contributed to a 20% reduction in fuel consumption [43]. Ten hybrid straddle carriers were also delivered in the HHLA Container Terminal Burchardkai at the port of Hamburg within the first quarter of 2019, with one unit being also equipped

with a maintenance-free regenerative energy system [44]. In another container terminal within the same port (i.e., HHLA Container Terminal Tollerort), two hybrid straddle carriers began their operations on January 2019, with the terminal operator expecting to achieve a 15% reduction in fuel consumption compared to the older units that were replaced [45]. Besides straddle carriers, other terminal equipment has also been fitted with such technology. More specifically, following a year of field testing, the fleet of reach stackers at the port of Helsingborg was updated in 2014 with a hybrid unit. During normal container handling conditions, the latter demonstrated savings in fuel consumption ranging from 30% to 50% compared to conventional units [46].

Besides diesel-electric engines, other hybrid technologies have also been tested. More specifically, in 2015, within the framework of the SEA Terminals project, a diesel-powered RTG was retrofitted to a dual-fuel one (i.e., diesel-LNG), which was then tested at the Terminal Darsena Toscana in the port of Livorno. According to the results of the field test, fuel consumption can be reduced by 24%, while important benefits can also be realized in terms of air quality (i.e., 40% reduction of Particulate Matter—PM and 10% reduction of CO₂ emissions) [47].

Full electrification is the option that most port authorities and/or terminal operators are following for the upgrade of their container transport and handling equipment. Ports have started modernizing their fleet with such units, taking another step towards the overarching goal of zero-emission operations. Typical are the examples of the Piraeus Container Terminal and Marseille-Fos, which have now incorporated in their fleets thirty all-electric RTGs and twenty-seven electric straddle carriers respectively, which were delivered in just a four-year period (2013–2017) [42,48]. Very recently (April 2019), the port of Felixstowe also received four electric and remote-controlled RTGs, with additional four units being expected soon, so that its peaks in demand can be better addressed [49]. Relevant orders have also been made and are currently at the stage of delivery at the ports of Koper (i.e., five electric RTGs have been received, with auto plug-in systems and regenerative power systems feeding back energy to the local grid), Oslo (i.e., eight electric RTGs with automation capabilities are being expected) and Le Havre (i.e., twelve electric straddle carriers were delivered early in 2019) [42,50,51].

Other types of terminal equipment have also been taken into consideration with regard to electrification opportunities. More specifically, at the Alternwerder Container Terminal in the port of Hamburg, twenty-five lithium-ion battery-powered AGVs are in operation and are expected to increase to one-hundred units by 2022, which will be served by eighteen charging stations. The energy savings and environmental benefits to be derived will be substantial (e.g., reduction of CO₂ emissions by 15,5 tons and of NO_x emissions by 118 tons). Additional benefits may also be realized during, for example, the stay of AGVs at the charging station, where they can contribute towards stabilizing the energy grid by receiving or providing appropriate amounts of energy [52].

Besides AGVs, the electrification of terminal tractors has also been studied. A first prototype was tested in 2015 at the Noatum Container Terminal in the port of Valencia, within the context of the SEA Terminals project. The real-life trial suggested that important benefits can be gained from the deployment of such equipment in terms of both fuel consumption and air and noise emissions, but further work on batteries was needed at that time [53]. Since then, however, battery research and development has rapidly progressed. To this end, electric terminal tractors have already become available in the market by different manufacturers, but their adoption seems to be limited to U.S. ports, for now, (e.g., port of Long Beach) [54].

In addition to hybridization and electrification, the investigation of the potential exploitation of alternative fuels for powering terminal equipment has also gained increased momentum over the last few years, mainly with regard to LNG, but also to other types of fuels, such as hydrogen. More specifically, an LNG terminal tractor was tested in 2013 at the Noatum Container Terminal of the port of Valencia within the framework of the Green Cranes project. For the testing, an LNG mobile station was also set at the terminal for refueling the tractor, facilitating at the same time the proper training of port workers to the relevant process considering all necessary safety features [55]. According to the feasibility assessment that was conducted, which carefully considered all associated operational parameters,

energy variables (i.e., diesel energy consumption—82.7 kWh/h, LNG energy consumption—91.9 kWh/h), relative costs (i.e., diesel energy cost—0.0693 €/kWh, LNG energy cost—0.0325 €/kWh) and benefits to be derived (i.e., 16% reduction in CO₂ emissions, near zero PM and NO_x emissions), such an investment will only become feasible at that terminal when 19 units are replaced, with the relevant payback period estimated to nine years [56]. Since then, however, a number of LNG terminal tractors have become operational, though in non-European ports (mostly in the U.S. while quite recently 40 such units were also deployed in a Turkish port) [57].

Besides tractors, other types of terminal equipment have been taken into consideration. More specifically, the LNG retrofitting of an RTG was studied in 2013, within the framework of the Green Cranes project, highlighting that fuel consumption savings of 14 L/h (i.e., 58% reduction in fuel costs) and a 34% reduction in CO₂ emissions, can be reached compared to the existing diesel-powered units. More recently, in 2018, the retrofitting of two diesel-powered straddle carriers was also undertaken at the port of Barcelona within the framework of the CORE LNGas hive project [58]. Special attention was placed in this case on retaining the same level of performance, with the relevant analysis indicating important reductions in air emissions and a great efficiency in fuel consumption that can be maximized at high loads and medium speeds [59].

Considerable attention has also started to be placed on the use of hydrogen in ports. Within the framework of the H2 Ports project that was launched earlier this year, the port of Valencia will be the first port in Europe that will pilot-test in two of its terminals the use of a reach stacker (for container loading/unloading), and a terminal tractor (for Ro-Ro operations), which will be powered by hydrogen batteries. The pilot project also incorporates the installation of a new hydrogen supply mobile station that will support those real-life trials [60].

Although, as noted above, such an upgrade of terminal equipment has attracted greater attention, and thus, more investments, a number of port authorities in Europe have also taken some additional steps considering energy improvement opportunities that still exist in relation to other types of port equipment. Tug boats are such a highly indicative example, with the port of Rotterdam constituting a notable case. More specifically, in 2012, Kotug, a locally-based tug owner, refitted its Rotortug 'RT Adriaan' becoming Europe's first hybrid tug with significant reductions reported in fuel consumption (15%) and air emissions (44% of Hydrocarbons, 33% of NO_x and 38% of SO_x). Since then, other hybrid tug boats have been introduced in the fleet of different European ports (e.g., ice-breaker tug at the port of Luleå) [61]. The port of Rotterdam, in particular, further reinforced its fleet with four additional units, fostering the provision of energy efficient nautical activities [62]. Currently, within the framework of the CORE LNGas hive project, an LNG-powered tug boat is also at the last stages of development and will soon become operational fitting into the existing fleet of the port of Bilbao. Such a first case can provide valuable insights to the relevant port authority itself, with regard to the broader deployment of such vessels, but also to other interested ports within the EU that are willing to upgrade their existing fleet with more environmentally-friendly units [63].

In addition to tug boats, and considering the fast development of electro-mobility, some port authorities have also undertaken actions for replacing their current general purpose vehicles (e.g., administration vehicles, security vehicles, etc.) with electric ones that would be supported by recharging stations constructed in the port area. Notable are the examples of the ports of Koper and Barcelona, with the latter investing, in 2017, on 31 electric vehicles (i.e., cars, vans and scooters) and 47 charging points (equipped with both slow and fast chargers) within the framework of its Air Quality Improvement Plan [64,65]. A similar plan was also devised and launched in 2016 at the port of Santa Cruz de Tenerife. The purchase of port electric vehicles and the installation of a network of fast charging points in the port area, complement a series of other energy improvement actions included in the plan (i.e., OPS installation, solar and wind energy production, intelligent public lighting), which collectively are expected to lead into a 85% reduction of CO₂ emissions [66].

Another rather simple, but highly effective, solution, as mentioned above, and with wide applicability within the European port network, is the use of LED technology for the outdoor lighting

of different port and terminal areas. The associated energy savings usually range from 50% to 60%, while in most cases, as mentioned before, such a technology is being coupled with intelligent control systems, featuring different functions and capabilities (e.g., remote-controlling, automation, etc.) [67,68].

3.4. Energy-Efficient Port Buildings

Within the overall great focus that is being placed over the last decade on the design and construction of new, energy-efficient urban buildings (or passive houses as often referred to), as well as on the renovation of existing ones so that the energy performance can be considerably improved, relevant efforts have also been extended in port areas covering, as depicted in Table 3, all different types of buildings (i.e., warehouses and other (cold-) storage facilities, terminal buildings, administration offices, maintenance and repair workshops, etc.). The solutions adopted usually range from sustainable building shells to energy saving systems, solar panels on roofs, small wind turbines, energy efficient indoor lighting, etc.

Table 3. Measures addressing port buildings.

Type	Measure	Key Implementers	Most Recent Pilot-Testers and Supporting Initiative(s)
Terminal office buildings	Passive house concept and eco-building standards	Aalborg, Ghent, Värtahamnen	-
Terminal passenger buildings	Exploitation of thermal energy for heating and cooling	Portsmouth	-
Warehouses	Self-energy preserving warehouses	Immingham	-

A 200 m² office building constructed in 1970 at the port of Aalborg was recently rebuilt and modernized. Energy requirements for heating were reduced by 94%, while the port authority used this project as an opportunity of getting better acquainted with passive house standards, so that relevant efforts could be extended to other port buildings as well [69]. The passive house concept was also adopted for the main building of the Ghent port authority. Advanced insulation and heat recuperation techniques were used for reducing the building's energy requirements to a minimum; while, due to the building's airtightness, sun-blinds that were fitted, as well as its carefully planned ventilation system, no air-conditioning and heating installations were required [69]. High eco-standards (i.e., the Gold Standard of the Sweden Green Building Council Miljöbyggnad) were also used for the construction of the Värta Terminal building at the Värtahamnen port, which utilizes 62 geothermal energy shafts, bored under the terminal, for its heating and cooling [70]. Similar features were also integrated into the passenger terminal building of the port of Portsmouth. More specifically, the latter uses a seawater source heat pump exploiting thermal energy from the sea for heating and cooling purposes, while its roof has been fitted with wind-catchers and automated louvres for better controlling ventilation requirements [69].

Focusing on the more energy-intensive port buildings, an energy-efficient warehouse was built at the port of Immingham in 2015. This warehouse features a solar array on its southern roof, which generates approximately 156 MWh of electric energy per year, covering all its energy requirements and fitting any excess energy back to the electrical grid [71].

3.5. Other Infrastructure and Facilities Supporting Port Energy Efficiency

A number of other infrastructure, systems and facilities, not properly fitting into the previous categories, although certain overlaps may be spotted, have been developed and implemented in different ports in Europe for providing further gains in energy efficiency. These range from energy monitoring and onshore power supply systems to smart energy grids and different devices that are being used for efficiently exploiting various forms of renewable and clean energy (Table 4).

Table 4. Measures related to other port infrastructure and facilities providing further energy efficiency gains.

Other Infra-Structure/Facility	Relevant Process	Brief Description	Key Implementers	Most Recent Pilot-Testers and Supporting Initiative(s)
Energy monitoring system	Multiple	System monitoring (also in real-time) the energy consumption of port equipment, buildings and other facilities (e.g., reefer containers) for supporting decision-making and implementation of measures for improving energy efficiency	Valencia, Koper, JadeWeserPort	Thessaloniki—SUPAIR project (2019)
OPS system	Vessel berthing	System established onshore providing electric power (preferably renewable) to vessels during berth, for supporting their activities, replacing the use of auxiliary engines	Ystad, Oslo, Rotterdam, Gothenburg	Kristiansand—LoCOPS project (2018)
Wind turbines (onshore)	RES production	Wind turbines installed in the port area for generating renewable energy and covering energy needs of the port	Rotterdam, Antwerp, Amsterdam	-
Wind turbines (offshore)	RES production	Wind turbines installed on the offshore area in the outer port for generating renewable energy and covering energy needs of the port	Oostende	-
Solar panels (onshore)	RES production	Solar panels installed in different areas of the port (e.g., often in rooftops of buildings and warehouses) for generating renewable energy and covering energy needs of the port	Rotterdam, Amsterdam, Gothenburg	-
Solar panels (offshore)	RES production	Floating solar panels installed for generating renewable energy and covering energy needs of the port	-	Rotterdam—Program of Rijkswaterstaat (2019)
Wave energy converters (WEC)	RES production	Devices which convert the kinetic and potential energy associated with a moving wave into useful mechanical or electrical energy. Eight main types can be identified while in ports they are often installed at breakwater walls	Naples	Civitavecchia—ENEPLAN project (2017), Heraklion—BMW-funded project (2018), Leixões and Las Palmas—SE@PORTS project (2019)
Tidal stream generators and/or barrages	RES production	Tidal stream generators make use of the kinetic energy of moving water to power turbines, while barrages exploit the potential energy in the difference in height between high and low tides	-	Dover—Pro-Tide project (2015)
Geothermal power plants	RES production	Geothermal power plants are used for generating electricity through the use of Earth's internal thermal energy. Three main types exist, i.e., dry steam, flash cycle steam and binary cycle plants	Marseille	-
Biomass production plants	Clean energy production	Biomass production involves using garbage or other renewable sources (e.g., corn, other vegetation, wood pellets, etc.) for generating electricity	Rotterdam	Koper—Greenberth project (2015)
Smart (micro-) grid	Energy management	Electricity network based on digital technology that can cost-efficiently integrate the behavior and actions of all generators and consumers connected to it	Antwerp	-

As it has been stressed out previously, energy monitoring systems are an important prerequisite for establishing a better understanding of the ports' energy profile and performance, thus, assessing any relative progress achieved at different periods of time. Such systems may be broader in scope, i.e., covering different facilities, operations and port areas, or may be more specific focusing, for example, on monitoring the real-time energy consumption of a specific building (often warehouse). Typical examples of such systems can be found in the ports of Valencia (SEAMS), Koper (Scada) and JadeWeserPort (PEMCT). More specifically, SEAMS—Smart Energy Efficient and Adaptive Management System, which has been implemented at the Noatum Container Terminal of the port of Valencia, following its pilot-testing within the framework of the SEA Terminals project, integrates relevant

information from the machines and equipment used at the terminal (i.e., lighting, STS cranes, terminal tractors, RTGs, reach stackers and forklifts). To this end, 27 different real-time Key Performance Indicators (KPIs) are generated supporting better terminal planning, with the energy consumption dimension included [53]. The Scada system at the port of Koper is broader, because (through the metering and communication equipment that was installed in all transformers of the port and terminals) multiple points of energy consumption are being monitored, facilitating relevant decision-making [64]. Same to Scada is the approach followed by the PEMCT—Port Energy Consumption Monitoring Tool in the JadeWeserPort, where information on the utilization of different energy sources and consumption patterns can also be easily extracted for better informing planning decisions. The latter can also benefit from estimations on CO₂ emissions and balances that the system provides [72].

Although mainly applied for reducing air emissions in the port area [73,74], OPS systems can also be regarded as an energy-efficient solution, since the operation of marine diesel auxiliary engines is being substituted with electricity that is being provided onshore for covering the vessels' energy needs during berthing. If the electricity mix also comprises of a share of renewable energy (generated possibly at the port) the gains are even greater.

In Europe, the port of Gothenburg was actually the first to implement such a system back in 2000, with several other ports following since then. The largest capacities of installed power units are currently provided at the ports of Ystad and Oslo for cruise vessels (6.25–10 MW and 4.5 MW respectively) and at the ports of Rotterdam and Gothenburg for RO-PAX and Ro-Ro vessels (2.8 MW and 1.25–2.5 MW respectively) [69]. Last year, however, another larger facility (i.e., a system integrated into eight containers that can deliver up to 16 MV.A of electric energy) was constructed at the port of Kristiansand, with support being provided by the LoCOPS project. Considering the system's characteristics, which has been installed at the cruise terminal, some of the currently largest cruise vessels in the world can be successfully accommodated [75].

The development of proper infrastructure in ports for efficiently exploiting different forms of renewable energy, and covering an important part of the ports' energy needs, has gained increased momentum over the last few years. The relevant technologies have advanced to a more mature stage of exploitation, and thus, major investments have been undertaken across Europe, and a considerable productivity share has already been reached. According to a recent survey of the European Sea Ports Organization (ESPO) conducted in 2015 among 86 of its members, 38% of the responders have invested in wind energy, while smaller percentages are reported for other forms of renewable energy, i.e., 31% for solar, 26% for biomass and 2% for wave energy [7].

The largest investments on wind energy can be found in the ports of Rotterdam (200 MW), Antwerp (45 MW) and Amsterdam (28.2 MW), while quite smaller is the relevant capacity of the installed power units in other ports (e.g., Hirtshals—16.8 MW, Zeebrugge—8.5 MW) [76–78]. Especially in the case of Rotterdam, the wind energy produced at the port accounts for 10% of the total wind energy capacity in the whole country. A couple of offshore wind installations can also be found in Europe, with the one at the port of Oostende being the most indicative. It consists of a medium sized wind turbine with an installed capacity of 100 KW, aiming to provide electricity for adequately supporting the activities in one of the port's terminals [79].

Given their considerably lower cost and their relatively easier installation process, solar panels have been more widely implemented in European ports. Indicative large systems, mostly installed on the rooftops of warehouses and office buildings, can be found in the ports of Amsterdam (i.e., 11 GWh of generated electricity per year, with units mounted on the building of a logistics service provider), Rotterdam (i.e., 750 MWh of generated electricity per year, with units mounted on the top of a cold storage warehouse), and Gothenburg (i.e., 55 MWh of generated electricity per year, with units mounted on top of the head offices of the port authority) [80–82], while smaller installations can also be located in various other ports. It should be highlighted at this point, that the port of Rotterdam has also taken another very important step with regard to the exploitation of solar energy in ports. Earlier

this year, it implemented a 100 MW floating solar power system, fostering the ground for relevant future investments being undertaken offshore [83].

Different forms of ocean energy, mainly wave and tidal energy, have found to-date little applicability in European ports, which can be partly attributed to the fact that these technologies have not yet reached the required level of maturity, with relevant research being still ongoing. With regard to wave energy, the most noticeable development can be located in the port of Naples, where the OBREC (Overtopping BReakwater for Energy Conversion) system has been installed, since 2016. A typical such system of 5 m long, which is not much more expensive than building a traditional breakwater, can produce electric energy of up to 12.6 MWh/year, with a minimal environmental impact being imposed, while the system also facilitates the recirculation of water inside the harbor [84]. A pilot application of another WEC (REWEC3 plant) has also been recently undertaken at the port of Civitavecchia, while another project is on-going at the port of Heraklion, where five WEC modules with SINN power technology will be tested. Additional tests have also been planned to be undertaken in the near future at the ports of Leixões and Las Palmas within the framework of the SE@PORTS project, aiming to advance the current Technology Readiness Level (i.e., TRL 3) of existing WECs [85–87].

The exploitation of tidal energy in ports (i.e., tidal streams) has not yet been investigated to a considerable extent, with only one pilot project undertaken at the port of Dover in 2015, taking into consideration the favoring conditions that exist there [88]. Since then, however, no further investigation of the applicability of this technology in any other European port was found.

A bit better is the case with regard to the exploitation of geothermal energy. Besides several small-scale applications that have been developed for covering the needs of individual port buildings, as it has been mentioned in the previous sub-section, the most notable large-scale case can be found at the port of Marseille where Thassalia, the first marine geothermal plant is located. The latter uses the sea's geothermal energy for supplying heat and cooling to different port buildings connected to its grid, leading to a 70% reduction of the associated GHG emissions [89].

The production and exploitation of biomass have also been investigated in a few European ports. The port of Rotterdam, in particular, which aims to position itself as a major hub for biomass in Europe, looks at 20% to 30% biomass co-firing in its power plants on the Maasvlakte terminal. Those plants are expected to provide a large steady supply of biomass (mainly wood pellets) which besides distribution will also be used for covering some of the port's energy needs. The port authority of Rotterdam believes, therefore, that a great future lies ahead with regard to biofuels, bio-energy and bio-based chemicals [90]. At a smaller scale, a few years ago, the potential of exploiting waste biomass for (a) heating and hot water preparation, and (b) biogas production, was also investigated at the port of Koper within the framework of the Greenberth project. For the first application, primary energy savings were calculated to 14.1 MWh per year, with the payback period for the relevant investment approximated to nearly four years. For the second application, different types of waste were taken into consideration, i.e., fruits and vegetables, soybeans and cereals, organic fraction of municipal solid waste, and feedstock manure, with the relevant generation of electric energy estimated to almost 66 MWh/year and the payback period to nearly eight years [91].

For efficiently managing the energy produced from many of the aforementioned sources that might be available in a single port, smart (micro-) energy grids have been developed which, through the use of intelligent software, can ensure that different energy sources are efficiently integrated into the grid, energy consumption costs are reduced, the resilient and reliable operation of the electric grid is ensured, and the energy awareness of port consumers is increased. A good example of such a smart grid can be found in the port of Antwerp, where 11 wind turbines are efficiently connected to the grid [92], while in the port of Rotterdam, a novel block-chain enabled approach is currently under investigation [93].

4. Discussion

The proper setting of the current state-of-practice on port energy efficiency, policy and technology-wise, has enabled to extract a handful of useful observations and provide a set of targeted recommendations that can support European ports into further advancing towards a climate-neutral future.

Considering the policy instruments implemented, the overall commitment of ports on energy efficiency still lies low. The majority of European ports prove to be addressing energy aspects only through the broader framework of environmental management, with efforts allocated on the issues covered by the latter often varying, usually at the expense of the ones related to energy. Heavier commitments, often expressed through the certification of ports to energy-specific standards, such as ISO 50001, are still very limited mostly attributed to the considerable investments that are required for setting-up appropriate energy management and monitoring systems, supported by well-structured relevant processes and procedures that also need to be in place. The latter also implies the need for properly training the port personnel who will bear the relevant responsibilities, so that potential gains can be maximized and future progress can be better supported.

The aforementioned gap might be effectively addressed if an energy-specific voluntary certification scheme is introduced, as an intermediate step, similarly to the case of PERS which many European ports have used as a basis for better preparing themselves towards their future certification to ISO 14001 and/or EMAS [94]. Such a scheme would guide ports into better understanding their energy landscape, existing performance and current needs, identifying areas and operations of increased consumption, as well as locating any opportunities that might be available for realizing further improvements. It would also assist ports in gradually incorporating the processes and procedures that are necessary for regularly assessing the progress achieved, setting consequently the next actions to be undertaken. In addition to PERS, EcoPorts may also provide and promote such an energy-specific voluntary scheme, while expansion opportunities at the global level might also be possible through the recently established World Ports Sustainability Program (WPSP) of the International Association of Ports and Harbors (IAPH) [95].

On the operational and technology side, it should be stressed out that the information collected and presented herein was highly fragmented and not easy to locate. Although several ports are promoting their sustainability efforts through specific tabs on their websites, the information included therein is often too generic and not very regularly updated. Better is the case for some ports, though these are more limited in number, which issue environmental reports on a regular (typically annual) basis, where further details are being provided to any interested stakeholder of the extended port community or even beyond. Several other sources were utilized to this end, considerably increasing, however, the time and effort required, should this process be repeated for assessing the state-of-practice at any other period of time in the near or more distant future.

A centralized information point, collecting relevant information on a regular basis and through a structured format, would facilitate the faster and better understanding of the point on energy efficiency where European ports stand at each time. Furthermore, better access to more detailed information would support undertaking additional targeted knowledge and experience-sharing activities. Moreover, ports that are interested in investing in energy-efficient solutions can be better informed with regard to potential risks that they need to carefully consider, as well as of problems that they may encounter during implementation. The WPSP serves as a good starting point, but another Europe-wide and more energy-specific portal may be established, which could be interoperable and easily fit relevant information back to the WPSP. The Eltis portal, which accounts for the urban mobility observatory in Europe [96], could be taken as a basis, with regard to its structure and functions, for the development of the aforementioned portal, considering its successful operation over the past few years as well as the proven value it has added to several local authorities within the EU.

Within the aforementioned process, it would be extremely valuable to also identify how and to what extent energy-efficient operational measures proposed in the relevant scientific literature have

been actually taken into consideration and/or up-taken by the ports' operational planning teams, better understanding the path towards research exploitation, thus, also informing back the research community of the areas where further research, with a great business exploitation potential, is needed. Promising approaches and technologies (e.g., virtual arrivals, peak-shaving, temperature control solution for reefer containers, block-chain solutions for smart grids, etc.) have not yet been fully exploited, and it remains to be seen if, how, and to what extent these will fit into the real operational environment, while research on others (e.g., use of hydrogen as fuel, exploitation of ocean energy, etc.) is still much needed for advancing them into higher Technology Readiness Levels (TRLs) so that they can soon enter the market and become operational.

5. Conclusions

With the Energy Union as a flagship, but also a number of key supporting policies and initiatives already in place, the European Commission has set energy efficiency and security as a high priority in its strategic agenda. With almost 40% of all commodities handled in European ports being sources of energy, but also ports themselves accounting for key locations of energy production, but at the same time also representing prominent energy users, they have a very relevant and important role to play. This has been well comprehended by port authorities in Europe which, for the last three consecutive years, have acknowledged energy consumption as the second most important environmental priority.

To this end, port authorities have undertaken considerable efforts, setting-up appropriate policy frameworks, adopting new operational practices and investing in new technologies, for realizing additional energy savings and further improving their current energy performance. However, there is still a long way ahead. Heavier commitments on energy efficiency need to be taken, and as mentioned above, a relevant voluntary certification scheme may successfully drive this process, leading to more European ports being certified, at the end, with well-recognized global certification standards, such as ISO 50001.

Despite also providing a competitive advantage, sustainability is a common goal that everyone should contribute to, considering that climate change impacts are universal and not limited to a specific region or country. Therefore, information sharing, joint undertakings as well as cooperation schemes are particularly appropriate for efficiently tackling sustainability issues and should be favored and promoted by all stakeholders, since the benefits to be derived can be substantial. This should also be the case for port energy efficiency in Europe. Although ports tend to cooperate within the framework of different research projects funded under various European, regional and/or bilateral programs, additional forms of cooperation prove to be limited, and the relevant information is highly fragmented. An independent, centralized information portal, integrating various information sources into a single access point may set the proper ground for enhanced cooperation and information-sharing between ports so that their planning activities and action plans on energy efficiency can be better informed. Furthermore, experiences from other regions of the world (e.g., U.S., China, etc.), which may be efficiently collected by following the same approach that was adopted herein, facilitating the more detailed comparison of the relative progress and advancements achieved, as well as new contributions from the research community, can also be promoted through such a portal, supporting knowledge transfer and wider exploitation of research results.

Author Contributions: Conceptualization, E.S.; methodology, E.S. and M.B.; investigation, E.S., A.T. and N.A.; formal analysis, E.S. and A.T.; resources, A.T. and N.A.; writing—original draft preparation, E.S.; writing—review and editing, M.B. and A.T.; visualization, E.S. All authors reviewed and approved the final version of the manuscript.

Funding: Research for this paper was carried out within the context of the 'SUPAIR—Sustainable Ports in the Adriatic—Ionian Region' research project, supported by the Interreg ADRION Program that is being funded under the European Regional Development Fund and the IPA II Fund.

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

Abbreviations

The following abbreviations are used in this manuscript:

AGV	Automated Guided Vehicle
CO ₂	Carbon Dioxide
EC	European Commission
EMAS	Eco-Management and Audit Scheme
EMS	Environmental Management System
EnMS	Energy Management System
ESPO	European Sea Ports Organization
EU	European Union
GHG	Greenhouse Gas emissions
IAPH	International Association of Ports and Harbors
ISO	International Standard Organization
KPI	Key Performance Indicator
LED	Light Emitting Diode
LNG	Liquefied Natural Gas
NO _x	Nitrogen Oxides
OPS	Onshore Power Supply
PDCA	Plan-Do-Check-Act
PEMP	Port Environmental Management Plan
PeMP	Port Energy Management Plan
PERS	Port Environmental Review System
PM	Particulate Matter
RES	Renewable Energy Source
RMG	Rail Mounted Gantry crane
RTG	Rubber Tired Gantry crane
SO _x	Sulphur Oxides
STS	Ship-To-Shore
TAS	Truck Appointment System
TOS	Terminal Operating System
TRL	Technology Readiness Level
VBS	Vehicle Booking System
WEC	Wave Energy Converters
WPSP	World Ports Sustainability Program

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