A review of energy efficiency in ports: operational strategies, technologies and energy management systems

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Abstract

Many ports and terminals endeavor to enhance energy efficiency as energy prices have increased through years and climate change mitigation is a key target for the port industry. Stricter environmental regulations are adopted by authorities to limit pollutants and GHG emissions arising from energy consumption. Increasingly, port operational strategies and energy usage patterns are under scrutiny. To ingrain sustainability and environmental protection of ports, the use of innovative technology appears as a critical conduit in achieving a transition from a carbon-intensive port industry (dependent on fossil fuels) to a low-carbon port model by harnessing renewable energy, alternative fuels (e.g. LNG, hydrogen, biofuel), smarter power distribution systems, energy consumption measurement systems. In this context, this paper conducts a systematic literature review to analyze operational strategies (e.g. peak shaving, operations optimization), technology usage (e.g. electrification of equipment, cold-ironing, energy storage systems) and energy management systems (e.g. smart grid with renewable energy) for improving the energy efficiency and environmental performance of ports and terminals. Research gaps and future research directions are identified. Analysis shows that there is a great potential for ports to achieve further energy efficiency and researchers have many impactful research opportunities.

Keywords: Ports, Energy efficiency, Renewable energy, Electrification, Smart energy management, Sustainability

1. Introduction

The increasing growth of international trade bestows significant importance to maritime logistics as more than 85% of world cargo traffic is transported through sea, and consequently seaports. The energy demand of international shipping, including seaports, has increased by 1.6% per year on average between 2000 and 2015 [1]. The increasing energy demand results in higher energy costs, pollutants and GHG emissions. Energy costs can be a significant overhead for ports and terminals, and reducing these costs might bring valuable cost reductions [2]. Reduction of emissions directly contributes to the sustainability and green perspective of ports [3].

Energy efficiency is mainly about giving the same services with less energy consumption, it is also related to using eco-friendly and sustainable energy to provide these services. Energy efficiency is critical for ports and terminals which aim to reduce energy consumption (consequently emissions) and become greener. In October 2014, the European Council

Abbreviations: GHG, Green House Gas; LNG, Liquefied Natural Gas; QC, Quay Crane; AGV, Automated Guided Vehicle; YC, Yard Crane; ASC, Automated Stacking Crane; YT, Yard Truck; STS, Ship-to-Shore; RMG, Rail-Mounted Gantry crane; RTG, Rubber-Tired Gantry crane; SC, Straddle Carrier; RC, Reach Stacker; ALV, Automatic Lifting Vehicle; IAV, Intelligent Autonomous Vehicle; E-RTG, Electrified RTG; B-AGV, Battery-powered AGV; ARMG, Automated RMG; LED, Light-Emitting Diode; PV, Photovoltaic; CHP, Combined Heat and Power; CCS, Carbon Capture and Storage; KPI, Key Performance Indicator; MW, Megawatt; kW, Kilowatt; kWh, Kilowatt hour.

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endorsed a target of 30% energy efficiency and a target of 27% for the share of renewable energy in total energy consumption in all sectors by 2030 [4]. The top 10 environmental priorities of the European port sector are reported in [5]. Energy consumption was not in the list in 2004, it was in the 3rd place in 2013.

The sustainability and climate-friendly strategies have been moved from awareness to action items in the eyes of port policy makers and port communities, as many ports are located in close proximity to cities around the world [6, 7]. To contribute to the sustainability and green perspective, targets for reducing GHG emissions in port waters, yards, hinterlands are planned to be in regulations [8, 3]. Emission reduction is a direct consequence of the energy efficiency, electrification of equipment, the use of alternative fuels and renewable energy sources. These aspects, along with operational efficiency, constitute a big part of the next generation port concept [5].

There is a positive correlation between port operational efficiency and port energy efficiency. Increasing the operational efficiency of resources (e.g. equipment, berth) would reduce the energy consumption, and thus enhance the energy efficiency [9]. The energy consumption can be in the form of electricity or fuel. In the recent years, there has been a shift towards electrification of equipment along with the use of electricity generated in a port from renewable energy sources. Electrification also replaces fuel to supply power for ships during hotelling at berths. For several equipment, other alternative fuels (e.g. biodiesel, LNG, hydrogen) also gain popularity over fossil fuels as energy source. In this paper, all available and future energy sources are assessed for ports. This study mainly concerns container terminals, but studies about cargo ports (e.g. bulk terminals) and cruise ports are also reviewed.

Energy efficiency is strongly influenced by technological advances in power generation, storage, distribution, conversion and consumption [10]. Energy systems, that ports use, include various components such as batteries, distributors, converters. As new methods arise to enhance the grid intelligence and new devices are designed to efficiently store energy (e.g. flywheels, supercapacitors), the energy efficiency can be further increased. For example, port equipment installed with energy management components can have significant energy conservation by saving energy in hoist down, storing this energy and using it in hoist-up or travelling motions. Energy efficiency in reefer area can be increased with intelligent power distribution systems. Technological advances also contribute to the fuel consumption efficiency. As new fuel friendly engines and fuel cells are designed, ports can benefit from that. Technological advances in harnessing renewable energy are also relevant for ports as renewable sources are increasingly used. In this sense, new technologies including smart grid and microgrid to manage energy demand and supply can enhance energy management in ports. All relevant technological advancements are reviewed in the following sections.

The motivation for this study is to provide a comprehensive overview of *operational strategies, technologies and energy management systems* that aim to achieve energy efficiency for sustainable and green ports. All methods, technologies and alternative energy sources are clarified, and the resulting energy efficiency is quantified. Methods to measure and estimate the energy consumption in ports are presented. Research gaps and research directions are presented for future studies.

Technologies and measures for GHG emission reduction in the shipping industry are reviewed in [11]. There is no comprehensive review for energy efficiency (consequently GHG emission reduction) in ports and terminals. A bibliometric analysis mapping collaboration patterns and research clusters about greening ports and maritime logistics is conducted in [12]. The methodology in this paper is different from [12] since the operational strategies, technologies and energy management systems are explained in detail, and the energy efficiency achieved through these measures are quantified and compared. One hundred forty-six (146) studies are reviewed in which one hundred ten (110) studies are journal articles, eighteen (18) studies are articles published in conference proceedings, sixteen (16) studies are technical reports by ports, research projects and companies, and two (2) are press releases by companies. The composition of studies shows that there is a journal article domination, and the industrial projects from various ports are also well-represented.

The organization of the paper is as follows. In section 2, operational strategies including optimization of operations, peak shaving and others are detailed. In section 3, technological aspects such as cold-ironing, electrification of equipment, advanced energy storage systems, lighting advancements, and others are presented. In section 4, energy management systems including energy consumption measurement, energy supply planning, renewable and clean energy alternatives, smart grid and microgrid are explained. The research gaps in the literature and future research directions are pointed out in section 5. Finally, the conclusions are drawn in section 6.

2. Operational strategies

The operational strategies cover methods that focus on energy-aware planning of operations in ports. The energy-aware planning aims to reduce energy consumption of equipment, reduce the processing time of operations, operate the equipment in non-peak hours, and optimize operations considering energy prices.

2.1. Energy-aware optimization of operations

The operational efficiency of a port depends on how efficiently the available resources are managed. As such, there is a positive relationship between reducing the duration of operations (e.g. ship handling times, transport times of containers in the yard) and the operational efficiency in ports. Operational efficiency results in energy efficiency [9], so most of the optimization studies related to the better planning of port operations contribute to the energy efficiency. In this review, studies that put an emphasis on the energy-aware planning are presented. Most of following studies formulate the problem as a mathematical model with an energy consumption related objective function.

Ports, especially container ports, have three functional areas, namely quayside, yardside and landside [13, 14]. In the quayside, energy-aware optimization of resources (e.g. berths, QCs, gangs, conveyors) are addressed in the literature. The integrated berth allocation and QC assignment problem is formulated with the energy consumption of QCs in the objective function in [15]. The problem aims to find an optimal solution considering the energy consumption and lateness costs of operations. Similarly, QC energy consumption minimization with the marginal QC productivity is studied in [16, 17]. The trade-off between time-saving (minimize lateness) and energy-saving in QC operations is addressed in [18]. Both working energy consumption and non-working energy consumption of QCs are considered. The working energy consumption is a function of the number of moves per hour and the energy consumption during (un)loading. Meanwhile, the non-working energy consumption is about auxiliary units and lighting. The QC assignment is influenced by the queuing behavior of AGVs [19], and it is shown that the optimal number of QCs decreases with the energy consumption per QC per hour [19].

Reducing port stay times gives the opportunity of reducing ship sailing speed at sea [20]. The energy savings through speed reduction near ports can reach up to 25.4% [21]. The concept of virtual arrival, which refers to reducing the approach speed considering port congestion, is studied as a part of energy savings near ports [22]. Virtual arrival and speed optimization are also extended to the ship routes [23].

In the yardside, the planning is mainly about the transport and stacking of containers. Variants of yard allocation problem and yard handling equipment planning [24] are solved in an energy-aware perspective. YC scheduling with energy-consumption is studied in [25], the problem is converted to a variant of vehicle routing problem. Energy-savings of 25.6% are achieved for all YCs compared to the practical results. The energy-aware scheduling of YCs prioritizes positions in the same row [26]. Recently, energy-aware studies gain attention in automated container terminals. A predictive control model is provided for balancing the throughput and energy consumption of a single QC with AGVs and ASCs [27]. A hybrid automation representation is used to simulate the discrete-event and continuous-time dynamics. The suggested method obtains the same makespan with less energy consumption since the method allows vehicles to slow down in the yard. Experiments with one QC, two AGVs and three ASCs show that, in order to load 8 containers in an energy-efficient way, 6.23 kWh of energy is required on average [28]. The behaviors of ASCs and AGVs are simulated with control theory. Results show that 90 containers can be loaded with an approximate energy consumption of 65 kWh [29].

The integrated scheduling of QCs, YTs and YCs is shown to achieve significant energy savings for an acceptable level of lateness [30, 31]. Energy-efficient scheduling for QCs, YTs, YCs is addressed and the relationship between the equipment with respect to energy consumption is mapped in [32]. Single and dual cycle operations are also analyzed for three types of equipment, namely, QCs, YTs, and YCs. Dual cycling operations with collaboration between equipment report a better energy consumption reduction [33].

Energy-aware planning is also studied in gate operations [34] and inter-terminal transport [35] in the landside. At the port gates, small shifts of truck arrival times can significantly reduce energy consumption and truck emissions [34]. Peak workloads of trucks can be reduced with an intelligent inter-terminal transportation schedule [35]. Meanwhile, the efficient scheduling of waterbone AGVs for the inter-terminal cargo routing can reduce energy consumption [36].

2.2. Peak shaving

Since emissions from electricity consumption are significantly fewer compared to fossil fuels and it is economical to use electrified port equipment in many cases, the electrification becomes more popular in ports. An increasing number of new equipment types uses electricity as an energy source in the recent years.

Peak shaving addresses the electricity consumption which fluctuates during the day depending on the workload of the port. The electricity bill composes of two main parts [37], a fixed cost of using the electricity and a variable cost depending on the consumption level. Ports cannot reduce the fixed cost which is predetermined and annually paid, but they can focus on reducing the variable cost which mainly depends on peak electricity consumption and total electricity consumption [10]. The peak electricity consumption accounts for about 25-30% of the monthly electricity bill [37]. If the resources are not well-balanced, a high peak energy consumption (i.e. simultaneous use of all equipment) will result in a high energy cost in the billing month.

Peak shaving refers to operational strategies that aim to reduce the peak energy consumption of the port. There are various methods for the peak shaving. Figure 1 illustrates a number of different methods using the load profile curves where (1) Power sharing: Using any stored energy in the case of peak energy demand periods, (2) Load shifting (i.e. load leveling): Shifting the energy demand in the peak period to non-peak periods, (3) Load Shedding (sometimes called as peak shaving): Turning off non-critical loads during peak periods.

These methods can be implemented in the operations of QCs, reefer containers and electrified equipment. A QC (i.e. STS crane) is one of the biggest electricity consumers in the port [37]. So that, it is suggested to limit the number of QCs lifting at the same time. It is noted that synchronizing the QCs (not to lift at the same moment) reduces the peak electricity demand significantly. However, the average processing and waiting times have been increased [37]. In the case of 6 QCs, having at most 5 QCs lifting at the same time reduces the peak electricity consumption by 11.1%. Meanwhile, the handling time increases by 0.03% and an additional 5.5 seconds of waiting time is measured per container. Using less handling equipment and smoothing the operations in the peak hours help to reduce maximum energy consumption [37].

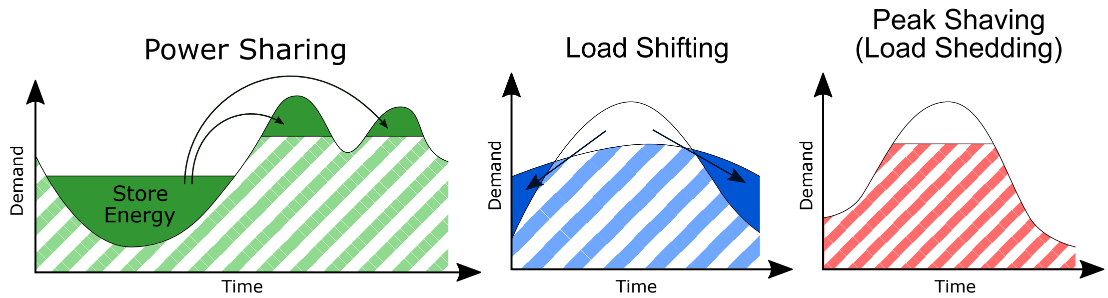

Figure 1: Peak shaving methods (Source: Authors)

For 6 QCs, when the maximum allowable electricity demand is set to 12 MW, the peak demand is reduced by 19.8%. Meanwhile, the average waiting time is only increased by 3.4 seconds per container.

Peak shaving for QCs with dual hoist and twin lift technology is addressed in [10]. Two main technological and operational tools are suggested for the peak shaving, namely the coordination of cranes' duty cycles with a power optimization tool and an energy storage system. A simple postponement for 21 seconds between the start time for each QC (un)loading cycle is implemented, and the peak energy demand is reduced from 10.22 MW to 5.84 MW. The stored energy can be used in the peak periods, and the peak energy demand is further reduced to 2.63 MW [10]. Economical analysis shows that the payback period is seven years with a lifetime of ten and twenty years for ultracapacitors and flywheels, respectively.

The energy consumption of reefer area corresponds to 30%-45% of total energy consumption [38] as reefer containers are plugged to the grid. Depending on the month of the year and the time of the day, reefers require a volatile electricity power. Therefore, the peak shaving methods are significantly important to reduce the peak electricity demand of the reefer area. Many factors such as the time before a reefer is plugged-in, the number of reefer plugs, ship sizes influence the reefer energy requirements [38]. Two peak shaving solutions, namely intermitted distribution of electricity between reefer batches and limited allowance on the electricity consumption for reefer batches, are suggested in [38]. In the first method, electricity is supplied in different timeslots, e.g. 5, 15 minutes slots. Experiments show that the peak energy demand for reefers was 14.8 MW in the base scenario, and it is reduced by 62.8% on average in the first method. In the second method, a maximum limit of 14 MW is allowed. This reduces the peak demand by 7.2%.

Peak shaving methods can also help to reduce the congestion at different areas of the port. Operational peak shaving methods can be applied in the gate operations [39, 40] where appointment systems and truck arrival for non-peak hours are encouraged for the energy efficiency. Operational peak shaving methods are also studied for a shared storage (i.e. warehouse) and a mathematical model is suggested with the objective function of minimizing the peak daily load, consequently energy demand [41]. Results show that the average peak load is reduced by 23.1%.

3. Technologies

Numerous technological solutions are available to enhance energy efficiency and reduce GHG emissions in ports. These solutions include the use of electricity as an energy source (e.g. cold-ironing, electrification of equipment), autonomous vehicles, energy storage devices, reefer cooling technologies, renewable sources and clean fuels, lighting technologies.

3.1. Cold-ironing

Ships mainly have two types of engines, namely main engine (i.e. propulsion engine) and auxiliary engines. The engines alternatively burn diesel oil, heavy fuel oil or LNG, many ships can also burn the combination of them. During docking, most ships turn off their main engines. The energy for hotelling activities, such as power system maintenance, lighting, refrigerating are supplied from auxiliary engines. These auxiliary engines burn fuel in idle position and emit CO_2, SO_2 and NO_x depending on the fuel type.

Cold-ironing, so-called alternative marine power, onshore power supply, shoreside power, is about plugging the vessel to the dock in order to supply the required energy as electricity for hotelling activities. The electricity can be supplied by the grid, renewable sources, LNG or other sources of electrical power [42, 43, 44]. Electricity is used instead of burning fuel, and thus emissions are reduced.

Ports, with higher average ship handling times, have the higher potential for savings through cold-ironing [42]. The reduction in the emissions also differs between regions as regions have different policies (such as sulphur emission control areas) and costs. Through cold-ironing, global carbon emissions, which depend on the emissions intensity of the port electricity supply, are reduced by 10%, while SO_2 emissions are reduced by 2% in the UK ports [42]. In a similar way, CO_2 emissions are reduced by 57.16% in the Kaohsiung port in Taiwan [45].

For a bulk carrier service, a comparison between shoreside power supply and marine fuels shows that shoreside power supply can provide economic advantages for countries in which the electricity price is less than 0.19 USD/kWh [46]. The shoreside power can reduce operating costs and energy consumption by up to 75% [46], and this helps to both shipowners and port authorities.

Cold-ironing can be very influential for cruise ports because large cruise ships require a huge amount of power since many passengers stay on board during hotelling [47, 48]. Three cruise ship routes in different regions are addressed as case studies in [49]. On average, 29.3% of CO_2 reduction (196.6 tons of CO_2) is achieved. CO_2 emission reductions with shoreside power are 99.5% (Oslo, Norway), 85.0% (France) and 9.4% (Fort Lauderdale, US) in the cruise port regions [49].

Cold-ironing technology is a challenging task [47, 50]. Technological barriers and requirements include the proper voltage, the correct connection type, capabilities of power supply companies, the grid characteristics and the security [47]. The power quality and power system reliability issues should be well-assessed for cold-ironing [50]. One generator should be in reserve and ships should be plugged into two sides for higher quality electricity supply [50]. Smart electrical interfaces are also designed to improve the performance of the cold-ironing [51]. The effect of the electric characteristics (e.g. voltages and power quality) on cold-ironing is studied, and the importance of keeping the electrical utility in a good condition is revealed [43].

3.2. Equipment

Ports operate several types of equipment to handle operations. In this section, the conventional equipment types are briefly described, and later the energy consumption of each equipment is detailed. In the quayside, QCs, STS cranes are mostly used to (un)load cargoes [52]. In the yarside, there are vast varieties of equipment types depending on the yard configuration (i.e. automation level, layout design, etc.) [13]. RMGs and RTGs are used for container stacking, while YTs and AGVs are used for horizontal transport of containers. SCs and RSs can both stack and transport containers [53].

Recently, highly automated equipment types are also in use, and they help to improve the efficiency of operations and reduce human involvement [54]. Automated container ports mostly have the equipment such as automated QCs and RMGs. AGVs, ALVs and IAVs can be used for horizontal transport, and ASCs can be used for stacking operations in automated terminals.

Table 1 illustrates possible alternative energy sources, namely diesel, electricity, LNG and hydrogen. Some of these energy sources can be used in a hybrid setting for each equipment. Table 1 shows that there are sufficient alternatives for ports which intend to invest for the equipment. The details of energy saving through the use of electricity or LNG will be discussed in the following sections.

Table 1: Energy source for different equipment (Source: Authors, inspired by [9])

	QC	RMG	RTG	RS	YT	SC	AGV	ASC
Diesel	✓		✓	✓	✓	✓	✓	
Electricity	✓	✓	✓	✓	✓	✓	✓	✓
LNG			✓	✓	✓	✓		
Hydrogen					✓			

In bulk ports, conveyors and pipelines are mostly used to (un)load the cargo on the ship [55]. Meanwhile, silos are used to store the cargo in the yard of bulk ports.

3.2.1. Electrification and technologies for equipment

In this section, the effects of electrification are first discussed and after that technologies to improve the energy efficiency of different equipment are presented. Electro mobility (e-mobility) in ports increases the energy efficient and generates less GHG emissions [56].

For QCs and STS cranes, there are different technologies in order to increase the energy efficiency. Most QCs, STS cranes operate with an alternative current drive. Converting to direct current technology with a proper current factor might be helpful for energy efficiency since direct current can reduce the peak demand and average energy consumption [57]. QCs can recover tremendous energy in the hoist-down movement [58] and this energy can be stored for later use. A hybrid power-train, composing of flywheels and ultracapacitors as energy storage device and main energy sources, might reduce the peak energy demand to 330 kW [58]. The peak power demand of a QC is 1211 kW according to [57] so the peak power is reduced by 72.7% in [58]. In [59], ultracapacitors and supercapacitors are used to optimize the energy storage and a bidirectional converter is used to reconvert potential energy to electric energy, and the peak demand is reduced from 1500 kW to 150 kW. Similarly, the new spreader tandem-twin lift reduces the QC energy consumption [60].

In the yard stacking operations, one of the most commonly used equipment is RTG thanks to its flexibility and productivity. Energy efficiency technologies for RTGs have attracted many researchers. One important method is to electrify RTGs via electric drive systems. Electrification of an RTG can be via bus bar, touch wire, or cable reel systems [56]. E-RTGs can switch between grid power and power from a diesel generator [56] and they perform significantly better than conventional RTGs with respect to energy savings and CO_2 reduction. Table 2 shows an economic and environmental analysis to compare conventional RTGs and E-RTGs conducted by [56, 61] in 2010.

Table 2: Electrification for RTGs [56]

	Energy consumption per move	Number of moves/year	Energy cost/unit	Total energy cost/year	GHG emission per container	Total GHG emissions/year
RTG	2.21 liter/move	1,199,543	24.16/liter	64,047,919	5.96 kg	7,149,276 kg
E-RTG	3.02 kWh/move	1,199,543	2.38/kWh	8,621,835	1.92 kg	2,303,122 kg

E-RTGs obtain 86.60% reduction in energy costs and 67% reduction in GHG emissions (90% reduction according to [62]) compared to diesel-fueled conventional RTGs. Electrification of RTGs should be studied as a mega project for container terminals and the phase in/out schedules for RTG replacement should be optimized with limited resources [63]. Active front-end rectifiers ([64]) can be integrated to RTGs [65].

Energy storage devices, such as supercapacitors [66, 67], batteries [68] and flywheels [62, 69, 70], are used to store the potential energy and consume the stored energy in hoisting and traveling.

Flywheel installment with an undersized diesel-generator is analyzed for an RTG, and fuel savings are expected to reach 35% [69]. Similarly, it is shown in [70] that, after flywheel installment, energy consumption reduction exceeds 30%, the generator obtains a longer lifespan, reduced noise and faster systems response. The use of supercapacitors (along with a hybrid energy source including a diesel-generator) reduces energy consumption by 35% [66]. A power management system considering stochastic loads with random duration results in a 38% reduction in the fuel consumption for RTGs with a flywheel [71]. Another power management system composing of (1) primary converter with an internal combustion engine, generator and the power converter, (2) an energy storage system and (3) electric drives is suggested for RTGs. Experimentally, the fuel consumption was reduced by 20% up to 60% depending on the hybridization [67]. In [72], a power-train hybrid system is developed for RTGs similar to QCs in [58]. Finally, retrofitting RTGs with a smaller diesel generator (i.e. a combination of diesel engine and electric generator) can be an important alternative [62].

Compared to RTGs, RMGs and ARMGs emit fewer emissions since they consume electricity as an energy source [73]. The energy needs of RTG, E-RTG, RMG and ARMG are compared in [61, 74]. Results show that energy consumption and GHG emission is ranked as E-RTG, ARMG, RMG and RTG where E-RTG is the least consumer, while RTG is the highest consumer.

SCs are modernized by hybridization with a diesel-electric generator or an energy storage system. An architecture for hybrid SCs results in a fuel efficiency of 27.1% [75]. In the hybrid SC, traveling motion, hoisting motion, lowering motion consume 52%, 31% and 11% of the total energy, respectively. Sensitivity analyses show that hybridization is impactful on component efficiency, travel distances, laden vs empty travel [75].

In horizontal transport operations, e-mobility advancements strongly influence the electrification and automation of the equipment. AGVs become more efficient, reliable and safe [76]. AGVs, like most of the other equipment, can be diesel-powered, battery-powered or hybrid. The use of a B-AGV fleet is compared to the traditional AGVs, and it is suggested to charge the battery in off-peak hours [77]. Figure 2 shows components of the net present cost for AGV and variants of B-AGV. Results show that the energy consumption is reduced by 64% on average by using B-AGV. Port of Singapore intends to further invest in B-AGVs in the next generation terminal [78].

ALVs, as being able to self-lift the containers, are more environmentally friendly compared to AGVs according to simulation experiments [79]. In [80], IAVs, which are similar to AGVs but with more flexibility in maneuvering within limited space and autonomous pick-up features, are shown to outperform AGVs. In [81], IAVs and YTs are compared for European ports and it is shown that energy cost per IAV is 2916 Euro, meanwhile, it is 21,600 Euro for one YT.

3.3. Reefer containers

Containerized reefer (refrigerated containers) trade, which requires continuous refrigeration of each container to keep the products cool, has been steadily growing and outperforming other market segments in the liner shipping industry in the recent years [82]. In various studies, the percentage of energy consumption from reefer containers ranges between 20% and 45% of the total energy consumption in ports [62, 82, 38]. This suggests the need to increase energy efficiency in the reefer area. There are studies that aim to optimize the design of refrigerated containers to save energy [83].

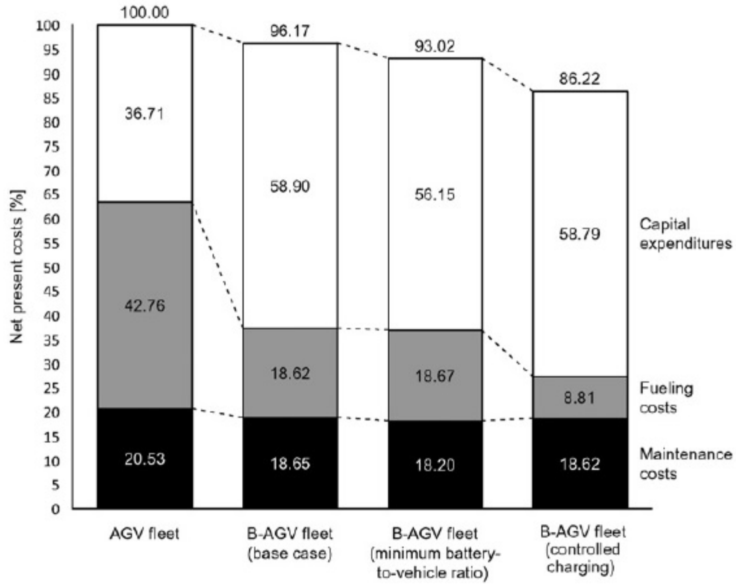

Figure 2: Net presents costs, including fuel costs, by AGV types [77]

Covered areas for refrigerated containers help to avoid heating up of containers [84]. Determining the number of plugs for reefers, determining the location of reefer area (with the aim of minimizing travel distances), formulating a power plan for each reefer cargo, designing better electrical distribution systems and measuring the exact energy consumption for reefer containers are important research perspectives for the energy efficiency in the reefer area [85]. Reefer containers should be visited by reefer operators/technicians for regular checks and energy adjustments. An optimal schedule for these operators aims to reduce the energy consumption and losses considering the travel times [86].

3.4. Technologies in lighting

Lighting consumes roughly 3-5% of total energy in ports. Technologies to improve the energy efficiency of lighting are applicable in many ports. Using LED lamps instead of high-pressure sodium lamps in port storage facilities, administration buildings, outdoor terminal high mast lightning, ensures energy efficiency [87]. It is assumed that 11 hours of light is needed, and an annual electricity savings of 922 MWh is achieved by using LED lamps [87]. The ECT Delta terminal in the Netherlands has saved 300,000 Euro on the electricity in this way [88]. Apart from LED technology, focusing on lighting levels and design of armatures help to save electricity [84].

3.5. Other technologies for energy efficiency

Automated mooring systems as energy consumption mitigation method can be impactful [8, 89]. In this system, ships are mostly moored using vacuum and they lock to berth without many maneuvers. This reduces the energy consumption from the engines.

Advanced technologies, such as start-stop engines for diesel equipment, can allow a reduction of fuel consumption between 10-15% [90]. Reactive power compensation approaches, which imply compensating the reactive power consumed by various electrified equipment, can be used in many ports [90]. By these systems, the power factor is increased while network losses are decreased.

Ports, in the future, can serve in CCS systems with facilities capturing the waste CO_2 from operations and depositing it without releasing to the air [91]. Port of Rotterdam utilizes heat exchangers, water treatment technologies and degassing installations to capture the heat and save energy [92]. The material cycling and disposal potentials for ports help to save further energy [91].

4. Energy management

Energy management system consists of energy demand planning, energy supply planning and smart energy management system linking demand and supply. In order to efficiently implement energy management systems, ports should measure and estimate the energy consumption properly. In addition to that, energy management systems require an established management strategy.

4.1. Measuring and estimating the energy consumption

Energy consumption measurement is made by an instrument or a device. Meanwhile, energy consumption estimation is based on calculations and/or perceptions. The application of energy efficiency methods becomes harder if no detailed energy consumption figure is available. Without any proper information, it will not be clear which operation, equipment or area requires attention. The impact of energy efficiency methods, e.g. environmental or economic effects, cannot be measured properly either. If energy consumption can be measured properly through the day, it is also possible to benefit from cheaper energy purchase prices. As GHG emissions of the port is a function of the energy consumption, a lack of information about the energy consumption will result in ambiguous information about the carbon footprint of the products flowing through the port, and total GHG emissions of the port, consequently. This section introduces studies that analyze the energy consumption (consequently GHG emissions) and various emission modeling methods.

According to [62], reefer containers (43%) and QCs (37%) are largest electricity consumers for ports of Valencia/Kopfer/Livorno. The remaining 20% is mainly shared between yard equipment and buildings. In 2012, the above three ports consumed more than 30 GWh of electricity. In terms of fuel consumption for the mentioned ports, RTGs and YTs constitute 58% and 32% of total consumption which was 7 million liters. Similarly, for a low-automation container terminal, reefer containers and QCs consume 40% and 40% of total consumption, respectively [85]. Meanwhile, the fuel is mainly consumed by YCs (68%) and horizontal transport of containers (30%). In 2013, the average energy consumption per container (dry, excluding reefer cooling) is equivalent to 8.6 liter of diesel where 4.6 liter is due to horizontal transport [82]. In Port of Chennai, 6.3 million liters of fuel are consumed where 59.2% is used by cranes and 25.5% is used by tug boats [93].

Energy consumption changes due to (1) variations in the handling volumes and ship calling patterns, (2) seasonality in energy requirement of reefers containers, (3) fluctuations in the port stay times for import, export, transshipment, reefer containers [9].

In the equipment level, the energy consumption is estimated by simulating operations in the berth and yard [94]. A short-term electric consumption forecast model and an analysis tool for a single electrified RTG is presented [95]. A more sophisticated energy estimation for both diesel RTGs and E-RTGs is conducted in [65] (See [96] for energy consumption of machine tools in manufacturing).

Port industry accounts for 3% of the total GHG emissions worldwide [89]. Table 3 summarizes studies, and the first column shows relevant port and the study, the second column shows the input information for the emission modeling method which is explained in the third column. Finally, the source of energy demand (consequently emissions) is presented in the last column. The studies are chronologically ordered.

Table 3: Emissions assessment, energy consumption for ports (Source: Authors)

Reference: Port(s)	Input	Method	Source of energy demand
Geerlings and van Duin [97]: Rotterdam	Container throughput, Modal split, Terminal Configuration, Terminal layout	a bottom-up based analytical model on land-based emissions	(1) cargo handling, cranes, vehicles, trucks, etc. and operations to tranship containers to another modality
Villalba and Gemechu [98]: Barcelona	Electricity consumption, Fuel consumptions, Waste	a top-down approach focusing on land-based and ships-based emissions	(1) cargo handling, cranes, vehicles, trucks, etc. (2) ship arrival and departure, hotelling, maneuvering
Chang et al. [99]: Kaohsiung	Fuel type, Approaching speed to port	a bottom-up approach on ships-based emissions	(2) ship arrival and departure, hotelling, maneuvering
Gibbs et al. [8]: UK ports	Port stay time, Ship type, Engine type, Fuel type, etc.	a bottom-up based analytical model on land-based and chain-based (including ships-based) emissions	(1) cargo handling, cranes, vehicles, trucks, etc. (1) indirect emission from port electricity demand, (2) ship arrival and departure, hotelling, maneuvering
Froese et al. [90]: EU ports	Number of equipment, Container throughput, Number of lights, Daylight time, Number of reefers, Port stay time, etc.	a bottom-up based analytical model on land-based emissions	(1) cargo handling, cranes, vehicles, trucks, etc. (1) reefer cooling, (1) building, lighting, generators, etc.
Tian and Zhu [100]: China ports	Container throughput, Berth length, Port area, Number of each equipment type, Fuel type, Waste amount, etc.	Intergovernmental Panel on Climate Change (IPCC) method and input-output analysis on land-based emissions	(1) cargo handling, cranes, vehicles, trucks, etc., and heat generation, wastewater treatment, solid waste treatment
Spengler and Wilmsmeier [101]: Chile ports	Electricity consumption, Fuel consumption, etc.	an activity-based cost approach on land-based emissions	(1) cargo handling, cranes, vehicles, trucks, etc., reefer cooling, building, lighting, generators, etc.
EIH [102]: Los Angeles	-	an analytical method on land-based and ships-based emissions	(1) cargo handling, cranes, vehicles, trucks, locomotives, heavy-duty vehicles, etc., (2) ocean-going vessels, tug, etc.
Misra et al. [93]: Chennai	Number of diesel consuming equipment, Engine type, Fuel type, Approaching speed in port, etc.	IPCC and the World Port Climate Initiative (WPCI) methods on land-based and ships-based emissions	(1) cargo handling, cranes, vehicles, trucks, etc., (1) purchased electricity, (1) port tenants use, etc. (2) ship arrival and departure, hotelling, maneuvering
Na et al. [103]: China ports	Berth length, Port area, Number of QCs, Number of YCs, Fuel type, Number of ships arrival, etc.	an inseparable input-output slack-based measure model on land-based and ships-based emissions	(1) cargo handling, cranes, vehicles, trucks, etc. (2) ship arrival and departure, hotelling, maneuvering
Mamatok and Jin [104]: Qingdao	Port stay time, Engine type, Fuel type, Number of equipment (QCs, YCs, tugboats, heavy-duty vehicles, locomotives), etc.	a bottom-up based analytical model on land-based and ships-based emissions	(1) cargo handling, cranes, vehicles, trucks, etc. (2) ship arrival and departure, hotelling, maneuvering

Table 3 refers to two categories of emissions which are (1) land-based emissions (i.e. emissions due to the handling of containers in the port) and (2) ship-based emissions (i.e. emissions due to the berthing, ship arrival and departure, maneuvering of the ships in the port waters). Both emissions belong to the port emission inventory. Many studies [98, 93, 102, 103, 104] consider both (1) and (2) emissions, while some studies solely focus on land-based emissions

[97, 100, 90] or ship-based emissions [99, 105]. Apart from the traditional energy demand sources (such as cargo handling, cranes, vehicles, trucks), container transhipment to other modes is considered in [97], energy required by reefer containers and building is considered in [90, 101], and electric outsourcing and port tenants are considered in [93].

Emission calculation method is mostly based on a bottom-up approach in which all emission contributors proportionally build up the total emission values. The input for the method varies between studies. Traditionally, container throughput, port size, the number of equipment are input in many studies (e.g. [97, 100, 93]). Studies that also address ship-based emissions consider engine type, fuel type, port stay times, sailing speed (e.g. [99, 100, 93, 103]).

There are studies that focus on GHG emissions of equipment and areas [61, 106] considering routing, scheduling and congestion in the yard. The effect of port selection on the CO_2 emissions is also discussed. Liao et al. [107] suggest an activity-based emissions model to measure emissions between the hinterlands and different cities of Taiwan, and show that emissions reduce when transshipment cargoes are transferred to a new port.

4.1.1. Real-time energy consumption monitoring systems

Real-time monitoring of the energy consumption enhances the flexibility of the energy management [108]. However, real-time measuring is essentially more costly in most of the cases as it requires special equipment installment. Real-time energy consumption monitoring systems are technologically attached to real-time operations monitoring [109]. The real-time energy consumption monitoring system can consist of a smart meter and smart energy management systems [110, 111, 112].

A real-time transmission of energy consumption data of yard operations is tested in the Port of Koper [113]. In 2013, the suggested method achieved electricity savings of 281 MWh and fuel savings of 311 tons. A power monitoring system for logging electric data installment is also suggested [57].

4.2. Energy supply

The energy supply for port operations can be from fossil fuels, clean fuels including renewable sources. The energy can also be obtained from the grid in the form of electricity or it can be generated within the port. In this section, renewable energy and other clean fuels are assessed as the energy supply for ports.

4.2.1. Renewable energy

Renewable energy is generated from energy resources that are naturally replenished on a human timescale. These resources include solar lights, winds, tides, waves, and geo-thermal heat [2]. The importance of renewable sources in order to establish a sustainable port is discussed in [84, 91]. An increasing number of ports around the world adopt renewable energy sources. In this sense, "the percentage of energy from renewable resources" is used as a KPI for smart and sustainable ports [114, 115, 2].

Covering the roof of a reefer area with solar panels (i.e. PV installment) is suggested in [116], the obtained electricity might be used for the electrified equipment, reefers, heating/air-con, etc. Another advantage of covering such areas is that the containers would be shadowed, and therefore the electrical energy needed for the cooling would be reduced. The possible use of solar cells and wind turbines for the Port of Chennai in India is assessed [117]. The economic analysis of PVs is conducted with the number of open sky days, the capacity utilization factor, the available area to place PVs. The Jurong Port of Singapore has covered PVs on the warehouse roof space and created 12 million kWh annual energy capacity [118] through a leasing model [119]. Jurong Port does not own the PVs, additional maintenance and upgrade of PVs remain as the responsibility of the lessor.

The report on German maritime sector [120] emphasizes the importance of renewable energy, especially onshore wind energy, solar energy and geo-thermal energy, for German ports. In this respect, Hamburg Port installed more than 20 wind turbines with a capacity of 25.4 MW, and seven new turbines are planned to be installed in 2017 [121]. Hamburg Port has also covered warehouse rooftops with PVs, and expects an electric generation capacity of 500 MWh per year [91]. Other renewable sources such as tidal power generation [122], wave energy [90], geo-thermal energy [91] are subject to investigation for ports.

CHP plants [110, 123], so-called co-generation, can be an important opportunity for ports. CHP must be operated in a heat-controlled manner and it uses the waste heat recovery system (e.g. from the in-house use of port buildings). CHP and the recovery of wastes are subject to analysis in [121].

As a part of Green Efforts projects funded by European Union (www.green-efforts.eu), (1) external supply of regenerative energy and (2) generating energy through renewable sources are suggested for ports [90]. For (1), the port acts like a big negotiator, and it bundles all small consumers around the port and negotiates with the power suppliers. Then, the port distributes the supply energy (from renewable sources) to consumers.

4.2.2. Clean fuels

The sustainability and energy efficiency goals support the selection of port equipment with fewer emissions [3, 2]. In this sense, alternative (clean) fuels, such as biofuels, LNG, LNG dual fuel, hydrogen fuel cells, have utmost importance for ports and shipping. Ports that use alternative fuels for the equipment, buildings, operations will be impactful in lowering pollutants and GHG emissions. It should be also noted that an increasing number of ships will start to use alternative fuels, mainly LNG, due to 0.50% global sulfur cap on marine fuels from 2020.

The use of LNG for port equipment has been considered by several ports. In 2008, the Port of Long Beach assessed LNG fueled yard equipment [124]. As a part of Green Crane project funded by European Union (www.greencranes.eu, [62]), various ports in Europe assessed LNG fuel-based terminal tractors, LNG or dual-fuel RTGs, and LNG dual-fuel RSs. For LNG-based terminal tractors, the expected CO_2 reduction is 16% along with the dismissal of NO_x emissions. According to [103], using LNG reduces CO_2 by 25% compared to the fossil fuels. Depending on fuel prices in each European country, the optimum number of terminal tractors to be replaced might vary [62]. Later in SEA terminals project funded by European Union (www.seaterminals.eu, [125]), hybrid and LNG dual-fuel RTGs are implemented as prototypes. Finally, LNG fueled engines are used in the Valencia Harbor with green efforts projects [90].

As more ships and ports require LNG as fuel, LNG supply network, LNG bunkering infrastructure and LNG storage facilities become significantly important for ports [91, 125].

The Port of Rotterdam introduced clean fuels by mixing biofuels (30%) with the currently used diesel fuel [97]. Meanwhile, the Port of Rotterdam has reached a throughput of 4.8 million tons of biofuels in 2016 and has become the leading import and export hub. In this sense, harbor wastes were used as renewable sources for biofuel production [117].

The use of hydrogen (H_2) fuel cell is an emerging technology for port equipment. Two examples from Germany are illustrated in [126], where the Port of Hamburg tests H_2, which is generated through renewable sources, for cell fueled forklifts and Port of Bremerhaver analyzes upgrading engines of SCs to hydrogen fueled combustion engines. Static hydrogen injection system is investigated for tugboat engines and fuel cells [90]. The Port of Los Angeles and the Port of Long Beach assess the commercial fuel cell in combination with hydrogen as a clean energy source for various equipment [127]. The barriers include difficulties in the supply of H_2, the limited technology maturity level, and the low investment return with current costs.

4.3. Smart energy management systems: microgrid and smart grid

Smart grid is a general term that includes tools to monitor, control, analyze and optimize power through increased communication between all facets of port energy consumers and energy suppliers such as renewable resources and distributed assets [128].

Smart energy management balances energy supply and energy demand in an intelligent way using key technologies. Smart energy management systems (e.g. microgrids, smart grids and virtual power plants) compose of **four** main pillars, namely *(1) energy supply (power generation) management* including on-site renewable energy generation, CHP, grid, etc., *(2) energy storage* capacity with batteries, *(3) energy demand management* with adoption of real-time energy consumption measurement, electrified equipment and on-shore power supply, and *(4) optimal management and communication* of all active resources via optimization methods, load diagram control, peak shaving, utilization management in the grid [90, 110]. Microgrid and smart grid are analyzed for various applications in urban areas, buildings, warehouses in [129, 128].

Figure 3 illustrates components and relations within smart grid for ports. In this figure, there are four sources of energy demand: (1) onshore power supply, (2) QCs, (3) electrified yard equipment (e.g. RMGs in the yard in this case), (4) buildings, warehouses, reefer area. Energy demand sources are marked with a plug in Figure 3. Smart grid is linked to all energy demand nodes and it supplies power which is illustrated by purple. There are three sources of energy supply for smart grid in Figure 3, namely wind turbines, solar panels and grid. Energy storage system is also included to store energy for later use. Figure 3 has smart grid in the center of the system, and it manages centralized and distributed energy generation, multi-directional power flow, real-time data management.

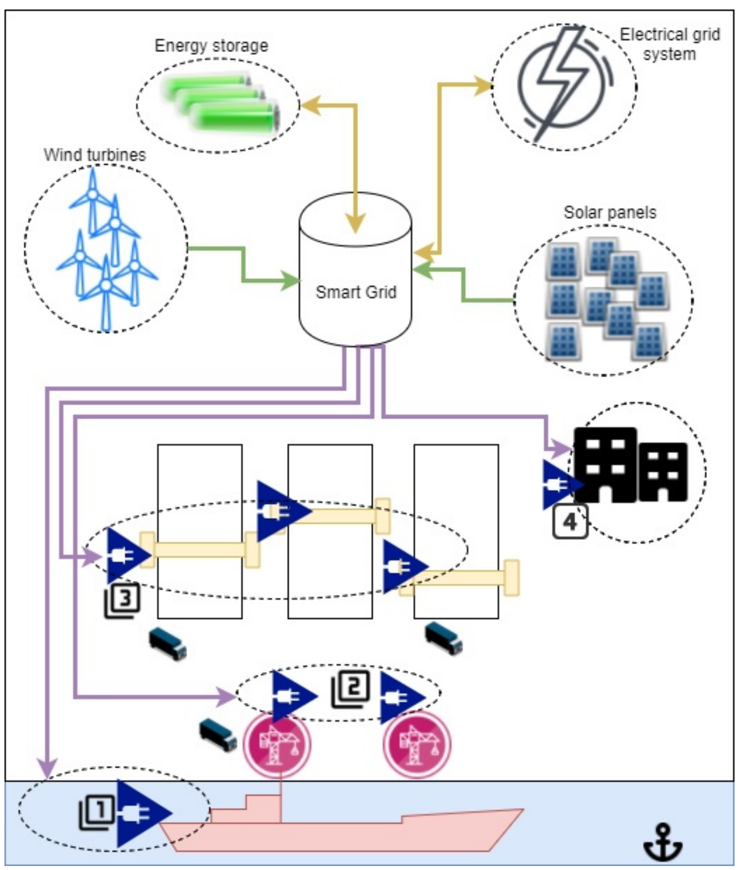

Figure 3: An illustrative example of smart grid at port, container terminal: (1) onshore power supply, (2) QCs, (3) RMGs, (4) buildings, warehouses, reefer area (Source: Authors)

Smart grid offers a port-grid integrated platform consisting of electricity grid technologies [110], sensor technologies, advanced smart meters [130, 131, 132], real-time monitoring systems [133], control tools, battery technologies [123] and communication technologies. It is intended that smart grid and microgrid will replace the traditional grid in the next generation ports of the future [123].

The roadmap for a smart grid project in harbors is presented in [134]. The initial stage composes of (1) load analysis of equipment, (2) smart grid scenario analysis, (3) energy balancing and (4) benefits analysis. These stages help for installation stage which consists of (1) analyzing renewable energy sources and assessing daily fluctuations of energy generation, (2) optimizing peak shaving and demand response planning, (3) planning energy storage and (4) managing tariffs and costs.

Figure 4 illustrates an example of energy supply from different sources when a smart grid is used. In this example from [134], energy sources are wind turbines, PVs, storage batteries (such as li-on and flow batteries) and the grid. In the daytime, PV-generated and wind-generated energy is available, so that the grid is less used. Later in the day, the grid use is peaked when renewable sources are less available.

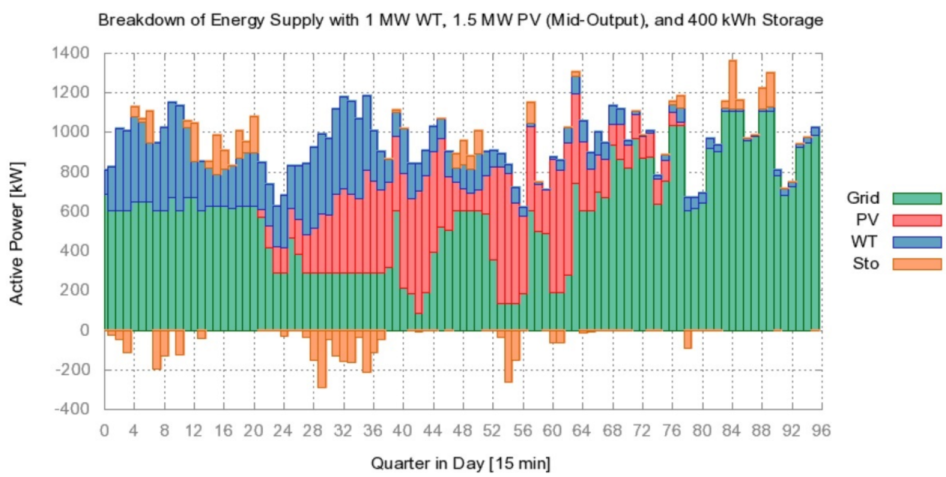

Figure 4: Energy supply breakdown in one day with a smart grid [134]

Energy demand management is of great importance for smart grid. Software architectures are developed to optimize the energy demand control and manage the flexibility for the B-AGVs [135, 131]. The scheduling of the battery charging for B-AGVs is optimized as a part of demand management [135]. The electrical properties of microgrids are also studied [111, 136]. Multi-agent systems are used to address reefer container requirements [111, 137].

Stockholm royal seaport evaluates an urban smart grid project including the harbor and nearby residential area [138]. In this project, the energy generated by renewable sources in the port area and the electricity from grid are stored in the local/centralized energy storage and managed with a visualization-based control system for demand and response. The generated electricity is used by electric cars, on-shore power to ships, and settlements in a smart way [138].

A wise-port energy management system composing of a microgrid and an energy master plan is outlined in [110]. The importance of permanent design, energy efficiency, operational efficiency and architecture efficiency in the energy master plan ([60]) are then discussed. The daily power profiles show that microgrid does not increase daily energy consumption, generates energy safely, and avoids peak energy consumption [110]. Another microgrid project aims to use renewable energy technologies along with direct current in an efficient way [117]. It is planned that daily required electrical energy would be supplied by microgrid where energy storage systems can provide 60% of the total requirement. As a part of e-harbor project funded by European Union (www.eharbours.eu), the feasibility for smart grid installment is assessed for a number of European ports. Finally, virtual power plants are in the project phase for Hamburg Port [91] and Port of Rotterdam.

4.4. Policy frameworks for energy management

In 2014, 27% of the world's total energy consumption was regulated by mandatory energy-efficiency standards. These standards mostly address industries that strongly impact the energy consumption. The ISO 50001 energy management system standards encourage organizations to establish systems and processes to gradually improve the energy efficiency and measure energy consumption. Only a limited number of ports, such as Hamburg Port Authority in Germany, Port of Antwerp in Belgium, Port of Felixstowe in the UK, Port of Arica in Chile, Baltic Container Terminal in Poland, Noatum Container Terminal Valencia in Spain, have been certified with the ISO 50001.

Ports mostly have corporate policies and energy management plans to enlist goals and establish frameworks for energy efficiency. In 2014, 57% of European ports had energy efficiency programs to address the needs [114]. In 2016, this percentage was increased to 75% [4]. The importance of port authority's involvement in energy management system commitments is emphasized in [91]. Later, a port energy management plan is presented, and it covers energy consumption analysis, energy mapping and energy efficiency considerations [4]. The plan highlights the main issues, challenges, and prospects for ports.

There are also studies that focus on environmental management programs and sustainable ports. A port vocabulary is suggested [139] for the ISO 14001 which is about environmental management. Responsibilities of a port authority for enhancing green aspects are listed in [140, 141, 142]. The tools available to port authorities (such as pricing, environmental regulations) and effect of functional parameters (such as handling volumes, cargo composition) are assessed for green port development in [3]. Effects of functional parameters are further analyzed in [143, 104, 5].

5. Research gaps and future research directions

Despite the growth in the number of research papers about energy efficiency in ports, there are still major research gaps to be addressed in future research. Energy efficiency is still a hot research topic as advances in the technology directly impact possible research perspectives [129]. The innovative approaches, economic analyses [132], optimization of various operations, effects of technological advances, and managerial analyses are most significant future research directions. In the following subsections, research gaps and future research potential in each area are presented.

5.1. Operational strategies

Currently, there is a limited number of papers on energy-aware operations planning. There is a need to improve the integration of energy management and real-time operational planning as many studies do not detail the relationship between the total working time, the actual idle time and the energy consumption for each equipment.

In the yard operations, a better model analyzing the relationship between yard traffic congestion and energy consumption is required. Energy-aware routing and scheduling of equipment stands as an interesting research topic since there are many new autonomous and intelligent vehicles, such as AGVs, AIVs, ALVs. As technologies related to speed, maneuvering and sensors improve, new routing problems can be formulated.

Currently, there is no comprehensive work that compares peak shaving methods in different areas of a port using simulation tools. The current peak shaving methods mostly work with predefined rules (e.g. 2 minutes apart loading), an optimal peak shaving rule is also required. What is more, the integration of peak shaving methods into smart energy management can be assessed in economical, environmental and operational analyses.

5.1.1. Integrated planning

The integrated problems of quayside, yardside and landside will attract many more researchers [53, 14, 54]. This review points out that energy-aware planning of integrated planning problems is an even more fruitful research perspective. In this sense, further work is needed to solve the operations planning problems considering the day-ahead energy prices and alternative energy sources.

There is also a strong potential to apply peak shaving methods in the integrated port problems, e.g. yard stacking and routing problems. Power sharing, as a peak shaving method, can be integrated with RTG routing and scheduling problem as the energy storage devices on RTGs can supply the stored energy in different states of movement. The load shifting, as a peak shaving method, can be linked to the pre-marshalling (done by RMGs in some terminals) problem, consequently pre-marshalling can be conducted in non-peak hours of the day.

Reefer area is studied in a limited number of papers. Reefer peak shaving is an interesting future research as reefers consume a high percentage of power in ports. Integrating the energy supply frequency decisions and routing of reefer technicians can bring significant energy savings. Alternative layouts for reefer areas can also be investigated.

5.2. Cold-ironing

The effects of ship port stay times and energy prices on cold ironing can be analyzed. A return of investment analysis is also required due to the different pricing structures of cold ironing. LNG fueled cold ironing technology is also available as a new alternative for ports. Further technical, economic, regulatory and environmental analyses can be provided for such an advancement in future research.

New trade-offs can be analyzed by integrating cold ironing with berth allocation and quay crane assignment problems because the energy demand, consequently the cost of berthing, is different when cold ironing is used.

5.3. Electrification and automation

Conventional yard equipment (such as RTGs, RMGs, SCs) and electrified/hybrid/automated equipment (such as E-RTG, AGVs, ALVs, IAVs, ARMGs) should be compared with respect to energy costs (e.g. peak and average) and environmental aspects (e.g. GHG emissions). The effects of electrification can be simulated with different handling volumes, container terminal types (e.g. import/export, transshipment, reefer focused), seasonality of cargoes, yard sizes, energy prices, etc.

Economic and environmental analyses for fully automated and electrified terminals are also essential [144]. Integrating autonomous and electrified equipment with energy storage devices, smart meters would enrich possible scope for further analysis. It should be noted that there is a room for further technical papers regarding the electrification of equipment with plug-in, non plug-in, hydrogen fuel cells [145].

Battery-powered yard vehicles become more popular in ports. These vehicles require charging intervals in which vehicles must remain idle. A planning need arises for the battery charging scheduling problem. Future research should address the planning of battery charging, the selection of equipment to charge and the routing of the remaining equipment.

The next generation ports will use automation, electrification and smart energy management systems. In this sense, roles of autonomous and/or electrified vehicles in smart grid should be further discussed for port operations. An intelligent energy planning system can be established by considering stochastic energy demand and supply.

5.4. Energy management

Sustainable energy management is an emerging topic for ports [5]. New KPIs can be suggested about energy efficiency and ports can be compared with respect to sustainable energy management. A conceptual framework for energy management systems, similar to the model in manufacturing [146], can be established for ports.

There is no study that conducts a barrier analysis for energy efficiency in ports. The barriers mostly include technological, economic and regulatory aspects. There are also obstacles in supplying clean fuels and other technologies (e.g. LNG, hydrogen fuel cells), so a barrier analysis would be very valuable for the industry and academia.

5.5. Renewable energy and clean fuels

The port industry recently started to use clean energy sources including renewable energy. In the literature, there are mostly technical reports that explain the use of renewable energy. The literature lacks studies that explain the economic contribution, viability, applicability and the best practices.

Studies that reveal and evaluate the current renewable energy projects in ports around the world can be a valuable contribution for the literature. The potentials for renewable energy for different parts of the world can be assessed. In this sense, port regions with the renewable energy potentials can be pointed out. Renewable energy investments are big projects so that an economical investment analysis (e.g. lease models, direct investment) is required.

Hydrogen fuel cells are in focus for many vehicles within the transport industry and ports have started to use them in yard trucks and other equipment. Future advances in this technology will be imported to ports. In this sense, operational, technological, economic and environmental aspects of hydrogen fuel cells can be analyzed in future research.

5.6. Smart energy management

Figure 3 is one of the first figures in the literature which illustrates a conceptual smart grid for ports. There is a great potential in this research direction. Researchers can focus on economic analysis for smart grid, and assess the operational and environmental performance of smart grids through simulation tools.

Balancing energy demand and energy supply in a smart grid is a complicated task [133]. As energy supply through renewable sources is mostly fluctuating (i.e. stochastic) and the energy demand is very hard to predict due to the complexity of operations, a mathematical analysis to configure and design a smart grid is a very fruitful research direction. A method to obtain the optimal equilibrium between energy supply and demand in ports can also bring valuable contributions. Further research will also increase the quality of available data.

6. Conclusion

The number of studies in the field of energy efficiency and eco-friendliness for green ports increases. The topic has a strong industrial relevance since many ports and terminals aim to reduce the energy consumption (pollutant and GHG emissions consequently) and become more sustainable. This paper is the first in the literature to review operational strategies, technologies and energy management systems for energy efficiency in ports. All methods, measures and technologies are reviewed, quantified and compared in this study. Results highlight fruitful future research directions which can help interested researchers and ports to establish their agendas.

Energy savings and emission reductions can be achieved with energy management, state-of-the-art technologies and operational improvements. Currently many ports around the world operate conventional equipment including QCs, RTGs, RMGs, SCs. Meanwhile, some ports have phased in electrified/hybrid equipment such as E-RTG, B-AGVs, ALVs, IAVs. New technologies for intelligent energy storage, energy conversion, energy consumption monitoring and energy management can be installed to the equipment for further energy conservation. Apart from electrification of the equipment, future green ports also analyze the use of LNG, dual fuel and hydrogen fuel cells to power the equipment. Most of above technologies require investments. In order to achieve energy savings and emission reductions without capital investment, many ports focus on operational optimization including peak shaving. For example, energy-aware scheduling of equipment, slight postponement of duty cycles, reduction of simultaneous lifting, and limiting maximum energy use can also bring energy cost reductions. Similar to the equipment, a significant portion of the energy consumption comes from reefer containers in some ports. Ports can improve energy distribution, design better power plans and implement many other methods for reefer containers.

Increasingly, ports invest in harvesting renewable energy. The power generated by clean energy can be used in the port or it can be injected to the utility grid. Still, there are not many ports which have installed smart grids for better energy management. This will certainly catch the attention of the next generation ports. In the future, ports can also install combined heat and power plants and they can also serve as carbon capture and storage facilities.

In this review, it is shown that there are several methods, technologies and management systems for ports to implement. Energy efficiency improvements differ between methods, technologies and systems. Results show that the energy efficiency can reach up to 90%. But, there is no single method, technology or management system that dominates the remainder with respect to energy efficiency, cost of investment and ease of implementation. Ports should initiate the implementation after careful economic, technical and environmental analyses. Increasing the awareness about energy efficiency and encouraging employees for an active involvement is also strongly required.

The future research directions reveal that there is a great potential for further energy savings and emission reductions. As technology advances in relevant areas, more opportunities will realize to further improve the energy efficiency.

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