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TOWARDS GREENER CONTAINER TERMINAL

Master of Science Thesis
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ABSTRACT

Ville-Petteri Savolainen: Towards greener container terminal
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Tightening global and national environmental targets are pressuring terminal operators to transition towards more sustainable operations. This green transition doesn't happen without challenges. A wide range of different size terminals do exist and there is no universal solution available. Consequently, understanding current operations and careful investigation of available green technologies are crucial preliminary steps in order to achieve successful foundation for future projects.

The purpose of this study is to first identify key challenges the terminal operators face in relation to decarbonization and sustainability. After that potential technological solutions to the challenges are presented. Furthermore, the study examines energy consumption and management within container terminals. Finally, port electrification planning framework is introduced to guide terminal operators through the initial phases of electrification. The structured framework is intended to provide a clear roadmap for navigating through the different challenges.

Four principal challenges are identified as prevalent across most container terminals. Terminals are significant energy consumers so energy management and energy efficiency improvement should be top priorities for terminal operators. Effectively managing energy use reduces cost and minimizes waste. The second challenge is the different environmental impacts that terminals cause. Emissions, noise pollution and garbage waste are examples of the impacts that all require mitigation strategies. Rising energy demand is forcing terminal operators to consider renewable energy integration. However, challenges arise from its intermittent production and required infrastructure upgrades. The fourth challenge is the lack of stringent decarbonization regulations. This creates uncertainty for the terminal operators as to whether to invest in sustainable solutions now or later.

Several technological solutions have been developed to address these aforementioned challenges. They differ from each other in terms of maturity, needed investment and potential impact on the operation. Electrification has been noted as one of the more potential technologies to achieve sustainability and operational efficiency. Electrification is not an easy transformation for terminal operators. Therefore, the port electrification planning framework presented in this study is meant to help in the preparation phase of the projects. The framework is divided into four clear phases that are further divided into steps. With the framework the terminal operators can make more informed decisions and ensure that critical factors are taken into consideration before starting electrification projects.

Keywords: Electrification, energy efficiency, energy management, container terminal

TIIVISTELMÄ

Ville-Petteri Savolainen: Kohti vihreämpää konttiterminaalia
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Kiristyvät globaalit ja kansalliset ympäristötavoitteet painostavat terminaalioperaattoreita siirtymään kestävämpään toimintaan. Tämä vihreä siirtymä ei tapahdu ilman haasteita. Terminaaleja on erikokoisia, eikä yleispätevää ratkaisua ole saatavilla. Näin ollen nykyisen toiminnan ymmärtäminen ja saatavilla olevien vihreiden teknologioiden huolellinen tutkiminen ovat ratkaisevan tärkeitä alustavia askeleita tulevien hankkeiden onnistuneen perustan luomiseksi.

Tämän tutkimuksen tarkoituksena on ensin tunnistaa terminaalioperaattoreiden kohtaamat keskeiset haasteet hiilidioksidipäästöjen vähentämisen ja kestävän kehityksen suhteen. Sen jälkeen esitetään mahdollisia teknologisia ratkaisuja haasteiden ratkaisemiseksi. Lisäksi tutkimuksessa tarkastellaan energiankulutusta ja –hallintaa konttiterminaaleissa. Lopuksi esitellään satamien sähköistämissuunnittelukehys, joka ohjaa terminaalioperaattoreita sähköistämisen alkuvaiheissa. Jäsennellyn kehyksen tarkoituksena on tarjota selkeät suuntaviivat eri haasteiden ratkaisemiseksi.

Neljä pääasiallista haastetta tunnistetaan vallitseviksi useimmissa konttiterminaaleissa. Terminaalit ovat merkittäviä energiankuluttajia, joten energianhallinnan ja energiatehokkuuden parantamisen tulisi olla terminaalioperaattoreiden tärkeimpiä prioriteetteja. Energiankäytön tehokas hallinta alentaa kustannuksia ja minimoi hukkaa. Toinen haaste on terminaalien aiheuttamat erilaiset ympäristövaikutukset. Päästöt, melusaaste ja jätteet ovat esimerkkejä vaikutuksista, jotka kaikki edellyttävät lieventämisstrategioita. Kasvava energiankulutus pakottaa terminaalioperaattorit harkitsemaan uusiutuvan energian integrointia. Haasteita aiheuttaa kuitenkin sen epäsäännöllinen tuotanto ja tarvittavat infrastruktuuripäivitykset. Neljäs haaste on tiukkojen hiilidioksidipäästöjen vähentämistä koskevien määräysten puute. Se luo epävarmuutta terminaalioperaattoreille siitä, tulisiko kestäviin ratkaisuihin investoida nyt vai myöhemmin.

Useita teknologisia ratkaisuja on kehitetty vastamaan näihin edellä mainittuihin haasteisiin. Ne eroavat toisistaan maturiteetin, tarvittavien investointien ja toiminnan potentiaalisten vaikutuksien suhteen. Sähköistäminen on mainittu yhtenä potentiaalisimmista teknologioista kestävän kehityksen ja toiminnan tehokkuuden saavuttamiseksi. Sähköistäminen ei ole helppo muutos terminaalioperaattoreille. Siksi tässä tutkimuksessa esitetty satamien sähköistämissuunnittelukehys on tarkoitettu auttamaan hankkeiden valmisteluvaiheessa. Kehys on jaettu neljään selkeään vaiheeseen, jotka on jaettu edelleen askeliin. Kehyksen avulla terminaalioperaattorit voivat tehdä tietoisempia päätöksiä ja varmistaa, että kriittiset tekijät otetaan huomioon ennen sähköistyshankkeiden aloittamista.

Avainsanat: Sähköistys, energiatehokkuus, energian hallinta, konttiterminaali

USE OF AI IN THESIS

Artificial intelligence has been used in this thesis:

☐ No
☒ Yes

I hereby declare, I have used the following artificial intelligence applications in this thesis during the thesis process: ChatGPT (GPT-4o mini), Gemini 2.5 Pro

Purpose of the use of AI:

AI was used to check and improve grammar and rephrase text. AI was also used to get new ideas and to help in structuring chapters.

Parts of this work, where AI was used:

Chapters 2-7

I acknowledge that I am fully responsible for the entire content of my thesis, including the parts generated by AI, and accept accountability for any violations of ethical standards in publications.

PREFACE

The completion of this work ends a certain period in life. This study provided me with an opportunity to delve into a topic of interest to me, which in part motivated me to finish the study early in comparison to the original plan.

Thanks for the interesting topic belongs to the target company. I would like to thank Sami and Mikko from the target company. The bi-weekly reviews motivated to keep writing the study forward and comments were received when necessary. Also the coordination of studies and work has been extremely flexible for the past three years, thanks for that. From university side I would like to thank Professor Pertti Järventausta for his quick responses and great suggestions on how to develop the study further.

Finally, thanks to family and other closest ones for providing support whenever needed. Future seems to be bright!

Tampere, 22.5.2025

Ville-Petteri Savolainen

CONTENTS

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ABBREVIATIONS

AGV	Automated Guided Vehicle
AI	Artificial Intelligence
ASC	Automated Stacking Crane
BESS	Battery energy storage system
CAAP	Clean Air Action Plan
CapEx	Capital Expenditures
CARB	California Air Resources Board
CHE	Container Handling Equipment
ESPO	European Seaport Organisation
ESS	Energy Storage System
EU ETS	European Union Emissions Trading System
GHG	Greenhouse gas
GSC	Green Shipping Corridor
HESS	Hybrid energy storage system
HVSC	High Voltage Shore Connection
IAPH	International Association of Ports and Harbors
IGV	Intelligent Guided Vehicle
IMO	International Maritime Organisation
IoT	Internet of Things
LNG	Liquefied Natural Gas
MCS	Megawatt Charging System
OpEx	Operational Expenditures
OPS	Onshore Power Supply
PM	Particulate Matter
Reefer	Refrigerated container
RES	Renewable Energy Sources
RMG	Rail-mounted Gantry
ROI	Return on investment
RORO	Roll-on/Roll-off, as in cargo, vehicles that are rolled on and off
RTG	Rubber-tired Gantry
STS	Ship-To-Shore crane
TCO	Total Cost of Ownership
TEU	Twenty-foot equivalent unit
TRL	Technology Readiness Level
WPCI	World Ports Climate Initiative
WPSP	World Port Sustainability Program
ZEPA	Zero Emission Port Alliance

1. INTRODUCTION

Ports are pivotal to the economic, environmental, and social sustainability of cities and urban areas, with their influence reaching far beyond their immediate waterfront locations. Serving as critical nodes within urban logistics networks, ports facilitate the seamless flow of goods and commodities into and out of urban centers. Operation of ports significantly contribute to urban economic growth by generating employment, increasing local tax revenues and supporting trade-related industries. [1]

The role of ports is evolving beyond traditional cargo handling and logistics due to mounting environmental challenges. So far regulations and legislation have mainly concerned the shipping sector, but it is evident that sooner than later it will expand to port operations as well. Ports and shipping are closely linked and therefore initiatives to reduce maritime emissions must encompass more than seagoing vessels themselves [2]. Decarbonization and energy transition of the transport sector has already started. Achieving decarbonization in alignment with the Paris Agreement's objectives to limit global warming is a critical priority [1][3]. The urgency is reflected in numerous directives and initiatives led by organizations, such as International Maritime Organisation (IMO) [2][4], International Association of Ports and Harbors (IAPH) and the World Port Sustainability Program (WPSP) [5][6][7]. In addition, regional organisations and frameworks, such as the European Seaport Organization (ESPO) and the European Commission's Climate Law emphasize the critical need for sustainable transformations within the maritime sector. [8][9][1]

The energy demand of ports has been increasing steadily over the last decades due to increasing growth of international trade. Naturally, this growing energy demand leads to elevated energy expenses, along with higher greenhouse gas (GHG) emissions and the release of other pollutants. Rising energy costs impose a significant financial strain on ports so cutting these costs could bring valuable cost reductions. [10] Likewise, the advancement of green port initiatives not only reduces harmful gas emissions but also enhances efficiency. Energy efficiency refers to minimizing energy consumption while maintaining the same level of useful power. Port authorities are prioritizing this concept and recognizing that substantial energy savings can be achieved through the enforcement of policies, technological innovations and the incorporation of renewable energy sources (RES). [10][11]

Port operational efficiency and energy efficiency are positively correlated. Enhancing the efficiency of operational resources like equipment and berths contributes to reduced energy consumption and therefore improves overall energy efficiency. Energy consumption in ports typically involves electricity and fuel. In recent years, there has been a notable shift towards the electrification of port equipment, coupled with the adoption of electricity generated on-site from RES. Electrification also serves as a substitute for fuel in providing power to ships during docking at berths. [10]

1.1 Commissioning organisation

This research is being carried out for a company that is a market leader in material handling equipment and services in ports, terminals and distribution centers. The target company is familiar to the author through an almost three-year-employment. The author has worked with manual and automated container handling equipment (CHE) in the product management team.

The target company offers its customers various material handling solutions. The company operates in the port and terminal industry, which includes marine terminals and inland intermodal terminals. The company also plays a significant role in distribution centers, manufacturing industry and heavy logistics. The company's offering includes straddle carriers, reach stackers, empty container handling equipment, terminal tractors and forklifts. Wide range of automated equipment and process automation solutions are part of the offering. In addition, customers are offered spare parts and comprehensive care and maintenance services.

The target company actively strives to develop more sustainable, environmentally friendly solutions for customer needs. The company is a pioneer in the development of electric material handling equipment. The company's vision is to help customers achieve their sustainability and productivity goals through zero-emission equipment, a broad range of services and solid industry experience. The purpose of this study is to provide the company with additional information about the challenges faced by current and potential customers in relation to sustainability.

1.2 Research objectives and scope

This research is driven by the need to support the transition towards sustainable port operations and the needs of the target company. By exploring innovative approaches and best practices, this research aims to serve as a tool for the terminals and provides

valuable information to the target company about the challenges terminals face. The research objectives of this research are:

1. To identify key challenges terminals face related to decarbonization and sustainability.
2. To find current and emerging technologies that can solve the challenges present.
3. To find out ways to maintain and improve the energy efficiency of terminal through smart microgrid.
4. To develop a framework of the steps terminals can solve in advance to ensure smooth transition to electrified container handling equipment without compromising efficiency.

Objective 4 is the main research objective of this study. The purpose of the rest of the objectives is to serve as background information and lead the way to the actions.

To address the objectives above, this thesis focuses on the following research questions:

1. What kind of challenges do terminals have today in terms of reducing greenhouse gas emissions?
2. What are the primary sources of environmental impact in container terminal operations?
3. What role can different technologies play in reducing emissions and energy consumption?

This thesis is limited to container terminal operation in an imaginary marine port that wants to prepare for the future. The port in question is presented in chapter 2.3. This study doesn't encompass broader maritime or logistical systems outside terminal operations. The results of this research can be generalized to other major medium/large ports. The scope of this thesis is affected by the case company and limited resources and time. From a technological point of view, experimental technologies are only shortly mentioned. The focus of this research is mainly on the proven technologies and how those can be applied to container terminals.

1.3 Research methods

The main method of collecting information for this study was through a literature review of relevant articles and books. For searching strategy browsing and snowballing, which is also known as citation chaining, was used. Browsing means general browsing of material about the specific topic using databases. Citation chaining means a process of

browsing the references of a good article to find more relevant material to the topic. A wide range of keywords and phrases were used when searching for material. Searches were broadened or narrowed with Boolean operators AND and OR. Peer reviewed scientific articles were the main source of information used in this study.

Some internal company documents and informal discussions with case company experts were also used to gather extra knowledge on the topic. The author has taken part in electrification meetings where different benefits and challenges of CHE electrification have been discussed. The author has got also internal notes from company experts where terminal operators' concerns related to electrification can be seen.

1.4 Structure of the thesis

This thesis consists of six chapters. In chapter 2 the concept of container terminal is explained. Different types of container terminals and terminal equipment are also presented. Chapter 3 focuses on introducing the most relevant challenges that terminals face today from different perspectives. Promising technological solutions to the challenges and limitations are presented in chapter 4. Chapter 5 focuses on understanding and answering energy efficiency challenges by energy management techniques. These chapters 2-5 are based on literature review, internal company documents and informal discussions with case company experts.

Chapter 6 presents a framework model that is intended for terminal operators. The idea of the model is to emphasize relevant things that should be taken into account when considering container terminal electrification. The framework model introduces steps that terminals can do in advance to maintain or improve energy efficiency and to ensure smooth transition to electrified container handling equipment. In chapter 7 the key takeaways and future research opportunities are discussed.

2. CONTAINER TERMINALS

This chapter clarifies the meaning of the term container terminal. In subchapter 2.1 the difference between port and terminal is explained. Also, primary terminal types are presented. Subchapter 2.2 explains container terminal equipment that is in the core of the terminal operation. Subchapter 2.3 focuses on explaining the operations happening on the terminal premises starting at the pier side. In subchapter 2.4 the chosen terminal in this study is presented.

2.1 What is a container terminal

Ports are complex facilities that usually contain at least one terminal. A terminal is a designated area within a port. Larger ports often include a diverse range of terminals designed to handle different types of cargo. The configuration of these terminals defines the port's role and functionality, with some ports operating as multifunctional hubs while others are specialized. Terminals are generally categorized into three primary types [12]:

1. General cargo terminals: These handle unitized cargo, which is transported in batches and processed through specialized terminal types, such as break-bulk terminals, neo-bulk terminals, and container terminals. **Container terminals** have become the most prominent unitized cargo facilities.
2. Bulk cargo terminals: These manage loose cargo transported in quantities dependent on the vessel's capacity and the terminal's storage facilities. Terminals are divided into two categories: liquid bulk (e.g. petroleum, natural gas) and dry bulk (e.g. coal, iron).
3. Passenger terminals: These terminals handle passengers. It constitutes a relatively small segment of modern port activities, but is significant in regions with extensive ferry operations, such as the Aegean Sea and Indonesia. Many ferry terminals also handle roll-on/roll-off (RORO) cargo. Roll-on/roll-off cargo means vehicles that are rolled on and off a vehicle carrier.

Container terminal is a terminal facility that is dedicated to the transshipment, handling and temporary storage of containers, facilitating the transfer of goods between at least two modes of transportation. Its infrastructure typically includes quays, yard areas, and various equipment, such as cranes. Auxiliary support facilities like administrative offices,

maintenance buildings and warehouses play an important part in the terminals daily operations. [12] Handling containers inside a container terminal premises is defined as container terminal operations.

2.2 Terminal equipment

A container terminal utilizes a range of intermodal equipment to enable its operations. Commonly used equipment includes gantry cranes, straddle carriers, and ship-to-shore cranes. The selection of the needed equipment is influenced by several factors, such as capital investment, operational costs, requirements, cargo volume, stacking density and desired productivity levels. Next common types of CHE will be presented in more detail [12]:

Forklift: Industrial vehicle equipped with two forks attached to a beam. It is designed to lift and transport materials over short distances. They vary widely in size and lifting capacity, ranging from 1 up to 85 tons. Forklifts are usually used for lifting and moving pallets and doing warehouse lifts. [13] They can only handle loaded 20-foot containers or empty containers but are not really meant for container handling operations. [12] Kalmar medium diesel forklift is presented in figure 1.

Figure 1: Kalmar medium forklift [14]

The signature forks can be clearly seen from figure 1. Steel and wood handling are typical operations where forklifts are used.

Straddle Carrier: Versatile machine that is suitable for a range of intermodal operations, including stacking containers and loading and unloading trucks. Straddle carrier is designed to transport containers in horizontal direction by lifting them from the top. [12] Figure 2 shows 3-high Kalmar hybrid straddle carrier.

Figure 2: Kalmar hybrid straddle carrier [15]

A key component of straddle carrier, spreader, can be seen in figure 2 hanging from the top frame. The spreader is used for grabbing the containers. Straddle carrier's stacking height varies depending on the type of the machine itself. 3-high and 4-high options of the machine are available. 4-high machine has capability of stacking up to four units high. Key advantage of straddle carrier is its ability to move containers independently, without requiring additional equipment. Straddle carriers are often employed for moving containers from quayside to the yard stacking areas. [12][13]

Reach Stacker: Is a truck-based equipment utilized in intermodal operations. Reach stackers are equipped with an overhead attachment mounted on a telescopic boom, enabling them to lift, move and stack loaded and empty containers. Figure 3 shows an example of Kalmar electric reach stacker.

Figure 3: Kalmar electric reach stacker [16]

They can stack up to three loaded containers or four to six empty containers. Their design allows them to reach over multiple rows of containers. [12][13] Kalmar electric reach stacker can reach 4 rows deep when stacking or lifting containers. [16]

Terminal Tractor: Is a specialized semi-tractor used for transporting containers on semi-trailers within cargo yards, warehouses or intermodal terminals. Figure 4 presents Kalmar TX electric terminal tractor.

Figure 4: Kalmar TX Electric Terminal Tractor [17]

The tractor itself can be seen in figure 4. The trailer is attached to the tractor when transporting containers. While terminal tractors require a relatively low capital investment and can transport containers at high speeds, their functionality is limited to containers already loaded on the trailer. As a result, additional CHE is necessary for unloading and loading containers onto these vehicles. [12][13]

Rubber-Tired Gantry (RTG): Is a piece of intermodal equipment that is widely used in high-density terminals for loading and unloading railcars and trucks. Design features a cross-beam supported by vertical legs mounted on rubber tires. Figure 5 shows Konecranes battery powered RTG.

Figure 5: Konecranes B-RTG [18]

The design allows the gantry to move, and stack loaded containers efficiently. The spreader that is attached to the trolley can be seen in figure 5. The spreader is used to pick up and move containers from place to place. RTG can stack up to four full containers of five empty containers. RTGs can span up to four rail tracks or six containers rows, making them suitable for stacking operations in areas with densities up to 1000 twenty-foot equivalent unit (TEU) per hectare. RTGs have higher acquisition costs compared to smaller alternatives, but they offer lower operational costs and fit well into container yard operations. [12][13]

Rail-Mounted Gantry (RMG): Is a fixed, widespan intermodal equipment that is designed for operations over six to ten rail tracks or eight to twelve container rows. They are usually utilized at port terminals to manage large container stacks. Nowadays RMGs are increasingly used in modern intermodal rail terminals for operating over multiple train tracks. [12] Figure 6 shows the Kuenz version of a RMG crane.

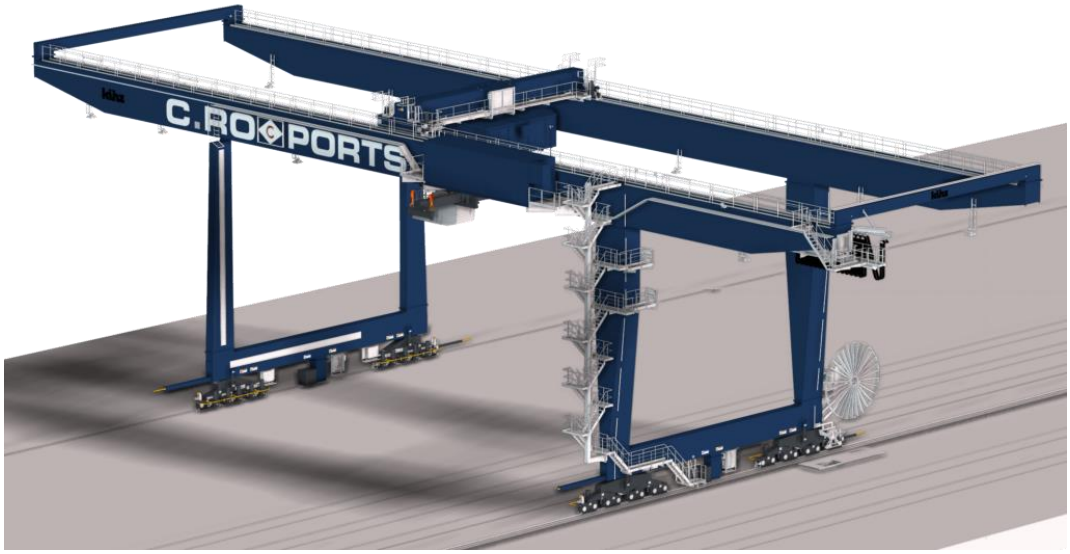

Figure 6: Kuenz RMG crane [19]

As the name suggests, the gantry moves on rails and its mobility is therefore limited to the tracks. RMG is often considered as the biggest CHE. Automatic versions of RMG do also exist.

Ship-To-Shore crane (STS): Known also as container crane, is a large dockside gantry crane. It is used exclusively for loading and unloading intermodal containers from containerships. These cranes vary in size depending on the class of ship they are intended to accommodate. Outreach and lifting height can be customized depending on the operational needs. [12] Figure 7 presents Liebherr STS cranes at work in the Port of Cape Town.

Figure 7: Liebherr STS cranes [20]

Modern STSs can lift up to 150 tons in a single operation. Many cranes can perform twin lifting, which means lifting two containers at the same time. Companies are also testing triple-lift systems, further enhancing operational efficiency. [12]

Automated Stacking Crane (ASC): Is a fully automated crane primarily used for stacking containers in the yard area or loading and unloading trucks and trains. ASCs are capable of handling containers directly from or to the stack, with the ability to traverse over multiple rows of containers. [21] Figure 8 shows Kuenz ASCs in operation.

Figure 8: Kuenz automated stacking cranes [22]

ASCs can maximize the highest possible capacity as well as stacking density. Automation helps in minimizing human error and improving terminal safety. [23] Automation can also improve productivity because breaks are not needed. ASC is very similar to RTG but is installed on to rails.

Automated Guided Vehicle (AGV): Is used for carrying containers between the quayside and stacking yard. Often STSs lift containers from ships to vehicles such as AGVs. Figure 9 shows Konecranes Gottwald lift AGV carrying two containers.

Figure 9: Konecranes Gottwald lift AGV [24]

AGVs are simple low mass vehicles that usually rely on magnetic rails underground to navigate and drive automatically. Their powertrain is almost always electric. [12] AGVs can carry different sizes of containers up to two containers at a time. Some AGV models, like Konecranes Gottwald lift AGV, can also lift and place containers independently. Intelligent guided vehicle (IGV) is more advanced machine compare to AGV. It can navigate with lidars, radars and cameras and there is no need for marker rails underground. However IGVs are not very widely adopted yet.

2.3 Container terminal operations

Container terminal layout consists of different areas. Each area has a specific functional purpose, and various CHE is used for enabling the operations. Figure 10 below illustrates the commonly seen functional areas of the terminal with usual CHE working on those

areas.

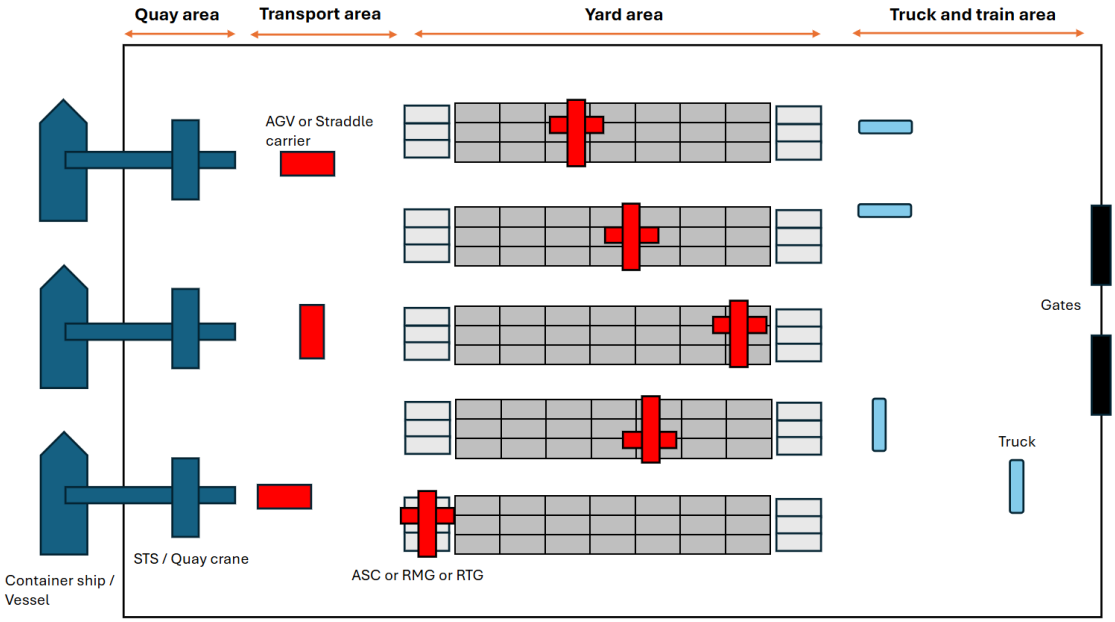

Figure 10: Functional areas of a container terminal

The area where the container ships can dock, is called the quay area. It is also known as the docking area. STS cranes are placed on the edge of the quay, and they act as an interface between the container ships and the quay. AGVs or straddle carriers move the containers back and forth between the terminal areas. They often work on the transport area of the terminal. On the yard area yard cranes such as ASCs, RMGs or RTG handle the stacking operations. This varies between different terminal types. In some terminals straddle carriers take care of all the container transporting and stacking. In that case the functional areas are often called just seaside and yard side. Trucks or trains are served on the truck and train area, where containers are imported or exported. In the following, a little more detailed description of the functional areas will be given.

2.3.1 Quay area

The seaside operational area of a container terminal is the quay, where vessels and barges dock. Loading and unloading of containers at the quay are conducted using STS cranes, known as quay cranes. Some vessels are equipped with onboard cranes to facilitate independent transshipment operations. That practice has largely been discontinued due to the good availability of advanced terminal equipment. Depending on the vessel size up to six STS cranes may be employed simultaneously. [25] Newest and largest containers ships can have width up to 24 containers and length of 24 bays. [12] STS

cranes with an outreach up to 70 meters are required to handle those ships. Skilled crane operators are essential for QC operation.

The handling of a single container during loading or unloading is referred to as a “move”. When unloading a container, the STS crane spreader is positioned on the container, secured by twistlocks and lifted by the crane’s hoist. The crane trolley then transports the container to the quay, where it is lowered onto the ground or a transport vehicle such as AGV. The container is released from the spreader by unlocking the twistlocks, after which the spreader is hoisted back to its initial position. The loading process follows the same steps in reverse order. [25]

The productivity of a STS crane is typically measured by the number of moves it performs per hour. Moves per hour is a key indicator of the terminal efficiency. [25] One move corresponds to the transfer of a container between vessel and a transport vehicle at the quay. In operations, modern STS cranes achieve about 30-50 moves per hour. [26] Manufacturers are constantly trying to improve crane productivity with technological improvements. Advanced STS cranes may be equipped with dual-trolley systems. One trolley operates on the vessel side, and the other handles horizontal transport vehicles. With dual-trolley system the containers are transferred between the trolley at a platform located between the crane’s uprights. Even some triple spreader experiments have been conducted. [25][26]

2.3.2 Transport area

The area under the STS crane is called apron. It is known also as loading and unloading area. This seaside transport area serves as the interface between the STS crane and the storage zone or yard area, where containers are temporarily stored. Containers are either brought to the apron to be loaded onto a container ship or unloaded and immediately transported to the yard area. [12]

The transport process is primarily carried out using straddle carriers, terminal tractors or AGVs. [12][25] Straddle carriers are more suitable for this operation since they can pick up the containers from the ground. STS cranes can place the containers on the ground and continue their operations. There is no need for complicated synchronization between the cranes and the straddle carriers. In addition, straddle carriers enable the direct movement of containers between the quay area and the yard area stack, enhancing operational efficiency [12]. Whereas with terminal tractors or AGVs synchronization is needed to avoid crane waiting. They can’t lift containers themselves so loading and unloading operations from the crane are demanded. However, the use of terminal tractors can be attractive due to low costs and high flexibility. [25] The use of AGVs instead of terminal

tractors or straddle carriers is seeing rising interest. The main advantage of AGVs is the reduced labor costs and the increased safety due to elimination of human workforce. [25] Automatic straddle carriers and terminal tractors do also exist. They show great potential in operations because they don't need human workforce and can work around the clock seven days a week.

2.3.3 Yard area

When moving containers through the transport area, they are transported to the yard area. The yard area is commonly known as the container storage area. The container storage functions as a temporary place accommodating containers while they await loading onto their assigned container ships or collection for inland distribution [12]. The size of the storage yard is directly proportional to the scale of the container ships handled by the terminal. Specific areas within the yard are also allocated for the storage of empty containers and refrigerated (reefer) containers [25]. Reefers can be stacked like normal containers but need electricity so electric plugs are needed at the stacking area [12].

Container storage areas are generally divided into export and import container stacks. In shared terminals, storage areas can be further subdivided based on shippers. The stacking density within the yard depends on the type of equipment used and the yard configuration. [12] Terminal operators are seeking options to increase stacking densities and optimize the terminal layouts as the vessels are getting even bigger. The bigger vessels are putting pressure on terminal infrastructure as well as equipment.

Container storage can be configured in different ways, but two fundamental models exist. The fundamental models are linear layout and block layout. Configurations can differ from each other but are still based on either one of those two models. In linear yard configurations, containers are typically stored on linear stacks of two to three containers in height. [12] Linear layout is common when using straddle carriers for yard operations. Even though straddle carriers can stack up to four containers the upmost tier is often left empty to allow circulation [25]. Container rows are separated from each other so that straddle carriers can access each row. Block layouts offer higher stacking density compared to linear layouts because smaller clearance between container rows is needed. However, with block layouts yard cranes are needed for the operation. They require more investments as cranes are more expensive compared to straddle carriers. Block layouts allow to stack up to six containers in height but usually the upmost tier is left empty. [12][25]

2.3.4 Truck and train area

Moving on from the yard area, truck and train area is presented. Port terminals are critical interfaces between maritime and inland transportation networks. The terminal gate functions as the primary entry and exit point for truck drivers. The drivers must provide documentation, such as bill of lading, for container pickup or delivery. Inspections are nowadays mostly done through cameras and intercom systems. The idea is to verify truck driver's identity, the truck, the container and the chassis. All information is pre-registered in the terminal's management system. [12]

For truck operations, vehicles are directed to designated areas depending on the yard equipment in use. If straddle carriers are employed, trucks are sent to a parking area to wait for service. If yard cranes handle the yard operations, trucks proceed directly to the assigned blocks. If containers are stored on a chassis in the yard, trucks don't need to be served. With trains the tracks extend into the terminal. Gantry cranes typically serve trains in terminals that are operated by such equipment. Straddle carriers can also be used for loading trains, but it is not very convenient. [25] Upon departure, trucks undergo inspection to ensure the correct container is transported inland.

To optimize operations, terminal operators have increasingly adopted advanced information technology systems, such as appointment scheduling systems. Their purpose is to enhance gate throughput and reduce delays. During high-traffic periods potential pickup delays remain. Efforts are made to mitigate these issues and improve gate efficiency and congestion. [12]

2.4 Chosen imaginary terminal

Figure 11 shows a container terminal where various green technologies and equipment are in use. This study focuses on figure 11 type of marine terminal in the following chapters when explaining different challenges and technological solutions unless otherwise mentioned.

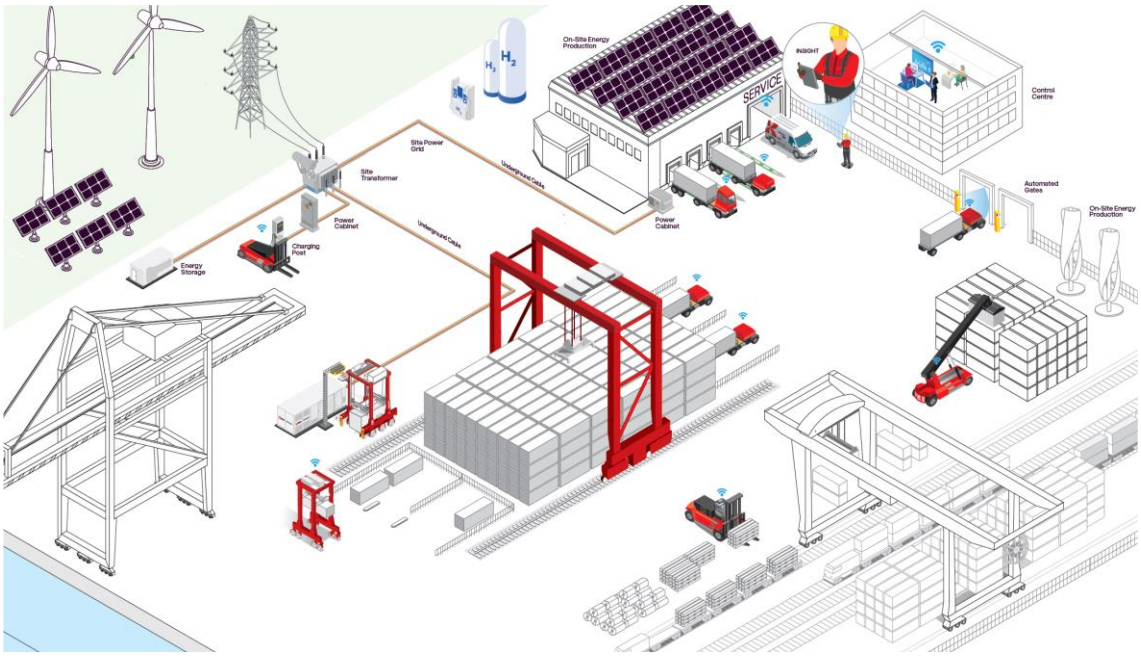

Figure 11: Terminal equipped with emerging green technologies

Integration of renewable energy sources is a key step towards more sustainable terminal. Renewable energy sources like wind turbines and solar panels supply power to the terminal operations. The solar panels are mounted on the roof of the warehouse building and nearby yard area. Wind turbines are located near the terminal. Own distributed generation has been integrated to the energy mix. Hydrogen storage tanks and energy storage systems (ESS) are depicted for energy storage and usage during peak demand. Terminal has an energy management system that helps reduce costs with energy arbitrage and load-shifting. Electric CHE can utilize the produced renewable electricity. The control center oversees terminal operations using advanced monitoring systems and automated scheduling software. Digitalization is an ongoing megatrend in the container terminal industry right now. The equipment used is equipped with wireless communication systems enabling real-time data exchange and remote control in the case of automated vehicles. Equipment is outfitted with sensors for collision avoidance, container positioning and energy usage monitoring. The electricity for the terminal is supplied with underground cables to maximize grid reliability.

3. SUSTAINABLE DEVELOPMENT CHALLENGES

Container terminals face multiple challenges as they adapt to growing trade volumes, environmental expectations, and technological advancements. Key issues include the need for emissions reduction and adherence to stricter environmental regulations as terminals contribute to noise, air, and water pollution and impact marine ecosystems. The shift toward electrification and renewable energy integration increases energy demands. Terminals are required to manage intermittent renewable energy supplies and invest in large-scale energy storage solutions. Grid infrastructure might also need upgrades at smaller size terminals. Space constraints and the complexity of modernizing infrastructure to accommodate advanced equipment pose significant challenges. At the same time rising throughput and larger vessels increase energy requirements for operations and refrigerated containers. In the following subchapters 3.1-3.4 the main challenges are discussed.

3.1 Energy efficiency

Container terminals are significant energy consumers, relying heavily on electricity and diesel fuel for their operations [11]. The sources that consume energy are either stationary or mobile. The mobile sources include CHE, and the stationary sources include reefers, warehouses, buildings, lights, generators and yards [27]. Effective energy management is therefore essential. The ongoing trend towards port electrification aims to enhance automation, improve energy efficiency, lower energy costs and reduce GHG emissions. Port electrification also results in higher electricity demand. In some cases, it is necessary to upgrade existing substations if the local grid can’t handle the increased load. The need for agile power infrastructure and comprehensive energy management systems is real. [11]

Energy efficiency measures in container terminals encompass both operational and technical strategies to optimize energy use and integrate renewable energy sources. Container terminals consume energy on necessities and at the same time some of the energy is wasted, making it crucial to minimize wasted energy. [11] The ideal situation would be to increase the terminal productivity while consuming less energy. It must be noted that the efficiency of electric powertrain is even more than twice that of traditional diesel powertrain. Transition to electric CHE therefore helps reducing wasted energy. In 2024, energy efficiency was ranked as the second highest environmental priority within

the European port authorities right after climate change [8]. As ports modernize, the following challenges remain as critical focus areas to ensure sustainable and environmentally responsible development [28]:

- Reliable and resilient energy supply
- Grid stability and power quality challenges
- Rising energy costs
- CO_2 reducing environmental requirements

The challenges faced by modern ports can be addressed through the deployment of renewable energy sources and ESS and the effective implementation of advanced digital technologies, such as the Internet of Things and Big Data technologies. [11] These systems enable enhanced monitoring and analysis of container terminal operations, contributing to improved energy efficiency. Challenges arise when thinking about space for energy storages and charging stations. Many terminals do not have any additional spaces, and leftover space might be rather used as a new container storage. This space concern of the terminal operators has been spotted repeatedly in company internal documents and it has been heard directly from customers.

Building resiliency in ports requires decentralized networks and integrated power systems, which enhance adaptability and reliability. Integrated power systems technologies should be prioritized to ensure seamless connectivity between technology and data. [11]

3.2 Environmental aspects

As mentioned in the previous chapter, climate change was the number one environmental priority in European port authorities 2024 report. Other major environmental priorities were air quality (3), noise pollution (4), ship waste (6) and garbage / port waste (7) [8]. These are all major challenges that terminals need to tackle. Environmental impacts of port activities include habitat disturbance, biodiversity loss and the depletion of non-renewable sources [29]. Carbon emissions occur throughout all stages of container processing, from the ship's arrival at the port to the final delivery by container trailers to inland facilities [30]. Despite variations in the scope of operations across ports, environmental impacts can be broadly categorized into four main areas [29]:

- impacts caused by cargo handling within the port area
- impacts arising from other port activities, such as different industrial operations
- impacts caused by the vessels berthing at the port

- impacts associated with hinterland transport modes

Environmental aspects are inherently linked to port operations and can result in both direct and indirect negative consequences. The degree of these impacts varies depending on the specific activities undertaken within the port.

The crucial initial step is the establishment of monitoring stations to continuously assess emissions and air quality. Data forms the basis for decision-making and targeted actions. Mitigation measures for air pollutants are most effective when focused on the use of alternative fuels for ships and CHE. Shore-side electrical power, known as cold ironing, can significantly reduce emissions in local port communities by providing alternative energy source for berthed vessels. Economic incentives, including tax rewards or bonuses for vessels and container terminals utilizing cleaner fuels, can also promote emission reductions. [30]

Many ports are already taking actions to actively reduce GHG emissions. The Port of Tianjin and the Port of Shanghai have revised their regulations to mandate the installation of Onshore Power Supply (OPS) or shore-side electricity systems at all newly constructed terminals. Also, existing terminals need to be retrofitted with OPS. The Port of Hamburg, the Port of Helsinki and the Port of Antwerp are implementing stringent measures to mitigate the environmental impacts of port operations. For example, authorities in Hamburg have committed to reducing CO_2 emissions by expanding the use of RESs and phasing out coal-based energy. In a comparable effort, the Port of Singapore provides a 25% fee discount to vessels that are using alternative energy sources to reduce GHG emissions. The Maritime and Port Authority of Singapore has also invested nearly $70 million in green port initiatives. [11][28]

From a different perspective, continuous noise generated by diesel-powered auxiliary engines used by berthed ships poses a real risk to human health. As auxiliary engines are the primary source of noise pollution in ports, the Port of Helsinki has introduced adaptive measures, requiring vessels to refrain from using auxiliary engines for electricity generation while moored. They have installed OPS to reduce emissions, noise levels and improve air quality. They also have movable air quality monitoring station at their premises every other year. [31]

3.3 Renewables integration

The rising global energy demand and environmental challenges posed by traditional fossil fuel usage is driving terminal operators into considering alternative energy sourcing

methods. Integrating RESs into container terminal operations presents numerous challenges despite its potential to enhance sustainability and reduce GHG emissions. These challenges primarily stem from the technical and operational complexities with transitioning to clean energy systems. However, the adoption of renewable energy is still accelerating due to its environmental benefits and economic viability. [11]

RESs such as solar and wind power are inherently intermittent as they depend on weather conditions and time of day. This variability poses challenges for container terminals, where operations require a continuous and stable energy supply. Ensuring reliability often necessitates the use of ESS and backup power from traditional energy sources. Another challenge involves over-generation periods, during which the energy produced by RES exceeds the port's demand [11]. That situation also needs storage for the surplus energy and disconnection of fuel-based generators [11]. [32] Successfully integrating RES into container terminal operations requires harmonization with existing grid systems and equipment. This might involve deploying smart grid technologies to help balance supply and demand while ensuring seamless compatibility with older equipment.

Most existing container terminals were designed to rely on traditional energy sources such as diesel and grid electricity. Retrofitting terminals to accommodate renewable energy systems, such as installing solar panels and wind turbines, requires significant investments in infrastructure upgrades. These upgrades may also need changes in terminal layouts. An energy management system installation should also be considered. The upfront capital expenditure for renewable energy infrastructure is high. Although long-term operational costs may decrease, terminals often face financial constraints that make it difficult to allocate resources for these investments. This is a problem particularly in developing countries. Also, port operators are running businesses, so they are more interested in making short-term profit than investing in sustainable solutions [33]. Naturally renewable energy systems also need space. That can conflict with the limited land availability at port terminals. Space constraints and intermittent production came up as concerns when discussing with target company experts. In addition limited space leads to limited production. Ensuring scalability without compromising operational efficiency is a key hurdle.

One challenge associated with RES integration is the issue of low system inertia. This issue arises when the port's grid is not connected to a robust external grid equipped with large-capacity synchronous generators. [11] Inertia in grid refers to the energy stored in the rotating masses of large generators and certain industrial motors, which enables

them to maintain their rotational motion. This stored energy plays a critical role in stabilizing the power grid during disturbances, such as a sudden failure of a major power plant. When such an event occurs, the inertia can temporarily compensate for the lost power, providing a brief response period of a few seconds. Since RESs are inverter-based that naturally lack inertia, concerns have arisen regarding the role and necessity of inertia in future grids. [34] Low inertia is a primary cause of grid instability. To address this, control system enhancement, such as virtual inertia control with virtual synchronous generator has been proposed. [35]

3.4 Regulation and policy

The absence of stringent decarbonization regulations creates uncertainty for ports regarding investments in sustainable technologies. The lack of comprehensive policies and regulatory frameworks undermines the sustainability performance of container terminals, leading to hesitancy in making significant investments. Even where regulations exist, they are often inadequately enforced by national and local governments or port authorities, resulting in limited accountability. Without effective enforcement, ports may refrain from adopting new technologies, as the cost-benefit ratio remains unfavorable. [1]

Current regulatory and fiscal frameworks further exacerbate the issue. For instance, existing tariff structures fail to reward ports for investing in renewable energy. Alamoush et al. points out that ports that would like to install wind or solar power may even face barriers from restrictions on electricity trading, which might prevent surplus energy from being sold to the national grid for future use. [1] The environmental performance of container terminals is largely influenced by the regulatory policies implemented by port authorities. These policies often vary across ports and terminals, as they are tailored to the specific local, geographical and political contexts. For instance, global ports, Antwerp, Rotterdam and Singapore have taken into use pricing, monitoring and measurement strategies to enhance environmental sustainability within their jurisdictions. [11]

One widely implemented approach is the use of incentive- and penalty-based pricing policies. These policies reward stakeholders who demonstrate environmentally responsible practices while penalizing those who do not comply with environmental standards. This dual-pricing strategy has proven effective in promoting sustainable behavior in the maritime sector across the aforementioned ports. [11]

Port decarbonization policies can be developed either independently or as part of broader environmental frameworks. Port policymakers are responsible for designing and executing implementation strategies that encourage terminal operators, vessel operators

and land transport operators to adopt technical and operational measures for reducing GHG emissions. Port business and management models, regulatory enforcement and port revenues can vary between different ports. That is the reason why the allocation of funds for environmental and climate initiatives is managed by various authorities. Port governance structures can take the form of public (government-operated), mixed public-private (landlord) or private which means private corporate-managed model. Within these port governance models regulatory functions are led by port or public authorities such as municipal, central or federal governments. [36] Many seaport organizations emphasize the necessity for port authorities to implement regulations aimed at reducing energy consumption while promoting the use of RESs. Increased energy consumption leads to higher GHG emissions and operational costs. [37] Minimizing operational costs would consequently improve ports revenue. Alamoush et al. describes that port policy-making can be understood as a two-tiered system: the first tier consists of governments and public authorities operating at higher level and the second tier encompasses the partial role of port authorities operating at lower level [27].

Some actions have already been taken mainly regarding maritime transport. However, they indirectly affect also ports and their operations. FuelEU Maritime Regulation took effect on 1 January 2025. The regulation facilitates the transition towards a more sustainable transport sector by mandating the progressive adoption of renewable and low-carbon fuels, as well as the utilization of OPS in ports, beginning in 2030. [38]

The FuelEU Maritime Regulation requires all ships exceeding 5000 gross tonnage calling at EU ports to reduce the GHG intensity of their onboard energy use. This reduction will be achieved incrementally, starting with a 2% decrease in 2025 and culminating in an 80% reduction by 2050, compared to 2020 levels. Furthermore, the regulation introduces zero-emission requirements for passenger and container ships while berthed. Starting from 1 January 2030, such ships will be mandated to utilize OPS or other zero-emission technologies in EU ports covered under the Alternative Fuels Infrastructure Regulation (AFIR). In 2035 this regulation covers all EU ports that have OPS installed. [38]

Maritime transport emissions have been added to the EU Emission Trading System (EU ETS) scope starting from 2024. Even though maritime transport is quite an energy-efficient mode of transport, it produces a lot of GHG emissions due to increasing cargo volumes. Practically, shipping companies must purchase and use EU ETS emission allowances for each tonne of reported CO_2 or CO_2 equivalent emissions falling within the scope of the EU ETS framework. [39] It can be just a matter of time when container terminal emissions in EU are also added to the EU ETS.

4. TECHNOLOGIES FOR SOLVING CHALLENGES

Several proven technologies have been developed during recent years to address the decarbonization and sustainability challenges that terminal operators face. These technological advancements primarily focus on enhancing operational efficiency, reducing GHG emissions and promoting more sustainable practices. Technological solutions that include for example hybridization, electrification and energy storage systems, are presented in subchapters 4.1-4.7.

4.1 Hybridization

Hybridization of CHE and non-road mobile machinery has really become a popular option when thinking about emission reduction. Generally, in the container handling operation the average power demand is lower than the peak power requirements. Hybridizing vehicle powertrains enables downsizing of internal combustion engines while incorporating onboard energy storage and electric drivetrains to meet peak power demands. At the same time regenerative braking energy can be harnessed to use. The primary objectives of hybridization include improving overall systems energy efficiency, reducing fuel consumption, and minimizing emissions. [40]

Leading ESS that can be used onboard are supercapacitors and batteries. ESS can be integrated into CHE, providing up to 20-50% reduction in fuel consumption compared to traditional diesel-electric machines. The adoption of hybrid gantry cranes has increased in parallel with the growth of global marine cargo transport. The cranes offer significant potential for energy recovery from hoisting and braking operations through the integration of energy storage technologies. The recovered energy can either be fed back into the main utility grid or stored for further use. [11]

The operational cycle of straddle carriers exemplifies a power-intensive application where power demand and regenerative energy fluctuate rapidly. The average power demand is significantly lower than peak power requirements, necessitating ESS with high power charging and discharging capabilities. Supercapacitors are particularly suitable for such applications due to their ability to handle short-term power needs effectively. A series hybrid powertrain topology is a viable solution for most mobile machines due to its flexible component placement and the absence of a direct mechanical connection

between the traction motor and the internal combustion engine. The conversion of a diesel-electric powertrain into a series hybrid configuration is relatively easy. Only ESS and its associated control and management systems are needed. [40]

Different CHE manufacturers offer hybrid versions of straddle carriers. Konecranes offers its Noell Straddle Carrier with diesel-battery-hybrid powertrain. The machine is built on the design of diesel-electric straddle carrier. The powertrain meaning diesel engine is downsized in the hybrid version. Battery units are used instead of brake resistors to enable complete recuperation of energy from gantry and hoist motor. The diesel engine charges the batteries that power the machine. Konecranes advertises that hybrid straddle carriers can cut emissions up to 40% and offer fuel savings up to 35%. [41][42]

Kalmar has also hybrid straddle carriers in its offering portfolio. They hybrid variant features li-ion batteries and a more efficient smaller diesel engine. The engine has start-stop functionality and it only runs when the batteries require charging. Energy from deceleration and spreader lowering are converted into additional electrical power to the battery. The operator can also benefit from lower noise levels during operation. Cabin noise is said to be 50% lower compared to diesel-only machines. Kalmar says that their hybrid straddle carriers are able to reduce fuel consumption and emissions up to 40%. [43][44]

4.2 Electrification

The electrification of port equipment is also driven by the need to reduce GHG emissions and enhance energy efficiency. Electrification takes the terminal operators one step closer to zero emissions compared to hybridization. Transitioning to electric alternatives offers multiple potential advantages, including reduced operational costs, improved air quality, lower maintenance requirements and enhanced worker safety by minimizing noise and vibration pollution. The transition to fully electric operations doesn’t happen without challenges. High initial capital investment, grid capacity and energy demand, and charging infrastructure and downtime are some of the key concerns for the terminal operators.

Electrification is already widely used in STS cranes, RMGs, ASCs and some RTG variations. These cranes are often powered with directly grid connected busbar or cablereel technology. STS cranes can feed electricity back to the supply grid when they are grid connected. With the increasing electrification of CHE, terminals experience significant electricity consumption, resulting in elevated energy expenses. In container terminals with mainly electric equipment, electricity costs constitute a considerable share of total

operational expenditures. The overall electricity consumption of a container terminal is primarily influenced by the operational efficiency of different types of equipment. Main electricity consumers are power supply systems for vessels and reefers, STS cranes, as well as CHE such as yard cranes and straddle carriers. [45]

Several technologies are usually associated with port electrification. Battery electric CHE is often the first technology that comes to mind. Electric straddle carriers, AGVs, terminal tractors and forklifts are increasingly winning the market share. Konecranes offers electric straddle carrier, sprinter carrier, AGV and forklift in its portfolio. Straddle and sprinter carriers are said to have high-capacity batteries that enable maximum continuous operating time. Charging of straddle and sprinter carriers happens at the automatic motorized charging station that is connected to the terminal mains. With AGVs they are either charged automatically or the battery is replaced automatically in a battery-exchange station depending on the battery type. [42][46][47][48]

Other industry players have also some electric offering. SANY offers electric terminal tractors with battery fast charging or swapping options [49]. Hyster offers forklift trucks ranging from 1.5 to 18 tonnes with lithium-ion battery technology [50]. Kalmar has electric options available in straddle carriers, reachstackers, forklifts ranging from 5 to 33 ton and terminal tractors [51][52][53][54]. Straddle carriers can be chosen with high energy or high power battery. High energy battery provides half-shift operation time while high power battery is meant to be charged fast during operation. Charging options available are CCS charging or automatic pantograph charging. [51] Lithium-ion batteries are used in reachstackers, forklifts and terminal tractors [52][53][54].

Port electrification in general also encompasses the integration of additional power generation and energy management solutions. OPS, ESS and energy management will be discussed in later chapters. Technologies such as distributed energy resources, microgrids and electrified CHE differ in terms of technological maturity and market availability. Ports exhibit varying levels of risk tolerance and willingness to invest in emerging technologies. Financial incentives could mitigate investment risks and encourage adoption. A thorough understanding of technology readiness and availability is essential for strategic planning in electrification initiatives. [55]

Table 1 presents common challenges and benefits from electrification. While all ports can derive benefits from electrification, the approach to implementation varies depending on several factors. The factors can be for example, the port's geographical location, electricity generation sources and electricity cost. Ports that are already producing electricity

from RES might get bigger benefits from electrification compared to those relying on utility grids. [55]

Table 1: Potential port electrification challenges and benefits (adapted from [55])

Challenges	Benefits
Equipment availability	Air quality
Equipment costs	Noise reduction
Operational requirements	Water quality
Electrical infrastructure requirements	Potential cost savings
Electrical supply	Technological advancement
Regulatory complexity	Resilient critical infrastructure
Business impacts	Energy independence

Let's go through the benefits first. The transition to electrification contributes to improved air quality in and around port areas by notably reducing emission of harmful pollutants such as sulfur dioxide and nitrogen oxides. This reduction enhances public health outcomes for residents in port cities and surrounding communities. Electrification plays a vital role in preserving marine ecosystems by minimizing the discharge of pollutant into surrounding waters. By decreasing water contamination, electrification fosters a healthier aquatic environment, benefiting biodiversity and fisheries. Electrified CHE and vessels operate with significantly lower noise levels compared to diesel alternatives. This noise reduction enhances the working conditions for port personnel and improves the quality of life for nearby residents. [55]

Although the initial capital investment for port electrification can be substantial, long-term economic benefits can be realized through lower energy consumption, reduced maintenance cost and decreased reliance on fossil fuels [55]. This means that the operational costs will be reduced over time. Kalmar says that battery-powered straddle carriers achieve equal or even superior total cost of ownership (TCO) over the equipment lifetime when compared to diesel-electric or hybrid machines. Main reasons are notably lower operational costs and energy costs. [56] Ports that are equipped with on-site electricity generation capabilities may have opportunities to sell surplus energy back to the grid, creating additional financial incentives. Investments in electrification drive advancements

in energy storage, renewable energy integration, and electric transportation technologies. These innovations not only support port sustainability but also contribute to broader technological progress, fostering economic growth and industrial development. [55]

Electrified ports with microgrid systems benefit from increased resilience to power disruptions and grid failures. Microgrids can enable ports to maintain critical operations during adverse conditions, ensuring continuity and reducing economic losses. The adoption of on-site renewable energy generation diversifies the port's energy supply, reducing dependence on external energy sources. Energy independence enhances a port's capacity to respond effectively to unexpected disruptions and at the same time contributes to overall operational stability. [55]

Let's walk through the common challenges associated with electrification. The availability of electric alternatives for port equipment remains limited in the current market. Even when electric options exist, they may not meet specific regulatory or funding requirements. Furthermore, global supply chain constraints can lead to substantial procurement delays for critical electrical components. The capital cost of electric equipment can be more than double that of traditional alternatives. In some cases, the financial justification for the additional expenditures is difficult to establish. As technological advancements drive cost reductions, the adoption of electric equipment is expected to accelerate. [55]

Electric equipment does not always serve as direct replacements for fossil-fueled equipment due to differences in charging infrastructure, battery lifespan and power output. Reliable equipment is crucial for port operations to minimize downtime and associated economic losses. Ports must carefully assess the compatibility of electric CHE with their operational needs. With electrification new electrical loads appear, often necessitating substantial upgrades to utility infrastructure. The cost of electrical infrastructure modifications can be even bigger and unpredictable if terminal doesn't prepare for it. Financial support may be available through grants or utility programs, but it is not guaranteed. [55] Terminal operators are very concerned about the downtime of the machines during charging. Case company experts have told the author that some operators believe that up to 30 % more electric machines are needed to achieve the same productivity compared to diesel-electric or hybrid machines. However, that's not the truth with every CHE manufacturer. The author has seen operation data-based energy flow simulations from case company that show that the difference in productivity is actually pretty small between the machine types. Terminal operators are pushing CHE manufacturers to develop even faster charging options to minimize CHE downtime.

Port electrification in larger scale has the potential to drastically increase electricity demand that can in some cases exceed the existing capacity of local utility providers. Innovative solutions such as demand-side management, distributed energy resources and port microgrids could alleviate grid stress and ensure stable supply. According to internal company documents on of the biggest concerns of the terminal operators is the electrical infrastructure. The need of charging should be carefully assessed. Meaning that is there only need for charging the specific CHE or also cars and more equipment in the future. ESS can help with weaker electrical infra but the truth is that the infra updates are needed at some point in the future.

The extent to which ports can control electrification initiatives varies depending on their governance structure and regulatory landscape. The regulatory landscape for port electrification is diverse at national and international levels, which poses additional compliance challenges for ports that serve a broad customer base. Ports should evaluate how electrification policies will affect their customers. Sustainability-focused customers can be happy while some customers could shift operations to ports with less rigorous policies. [55]

4.3 Digitalization

Digitalization has been a megatrend in the port industry during recent years. The digitalization of ports and terminals is being implemented globally, and it enhances the competitiveness of the entire maritime logistics chain [57]. The integration of digital technologies in smart ports is essential for addressing challenges such as port congestion and navigation complexities. These challenges arise due to the increasing volume of vessels and other equipment within terminal facilities. Digital solutions in general enable the identification, monitoring and aggregation of critical data to enhance both environmental and operational efficiency. [11] Data-driven decision making is gaining even more interest, and it helps ports and terminals to make more informed decisions. General management can get up-to-date business information on site or fleet performance. Operations management can identify potential bottlenecks and improvements to maximize equipment utilization. Maintenance management and health and safety management can also monitor equipment health and processes remotely.

Advanced digital technologies, including remote sensors and big data analytics, contribute to reducing emissions, minimizing operational costs and decreasing the likelihood of system failures [11]. Beyond improving terminal efficiency, digital technologies also contribute to the safety and well-being of front-line workers [57]. Additionally, digitalization is

said to enhance information security, warehouse management and smart energy systems [11]. With digitalization, cyber security comes as an important factor. Digital technologies may leak sensitive port information which compromises competitiveness [1]. Digitalization and automation are closely linked to each other. Digitalization serves as a fundamental pillar of full automation, and it enables broader and faster connectivity of machines. At the same time, it can generate extensive datasets for further analysis. Different sensors can be installed in machines to monitor the health of critical components in real time to enable predictive maintenance. [57] Digitalization can be linked to electrification by developing systems that can automatically assign machines to go charging based on machines state of charge, free charging stations, operational needs and so on.

Smart ports are characterized by the integration of advanced technologies and digital solutions aiming to enhance sustainability and overall efficiency and effectiveness of operations. Multiple innovations such as Internet of Things (IoT), artificial intelligence (AI) and blockchain technology are utilized. [58] The integration of real-time networking and AI-driven predictive analytics can reduce maritime accidents. By leveraging advanced data analytics, the best transportation routes can be optimized. Digitalization in traffic management reduces vehicle waiting times as well as emissions. [59] Truck appointment systems can be used to optimize truck arrivals and therefore reduce congestion. By streamlining port area logistics, digitalization supports environmental sustainability initiatives and sustainable development goals by lowering carbon footprints and improving air quality.

In electricity systems, digital technologies such as machine learning and smart meters can facilitate the integration of higher shares of variable RES. These technologies enable a more effective alignment of electricity supply and demand from different decentralized sources. In end-use sectors, digitalization enhances efficiency in buildings and transportation while supporting the transition to low-carbon alternatives. [60]

Recent advancements in digital technologies and widespread connectivity have accelerated the digital transformation of the energy sector. Since 2015, grid-related investments in digital technologies have increased by more than 50 %. The distribution segment has become a focal point, representing over 75 % of total digital investments. Additionally, investment in electric vehicle charging infrastructure has seen substantial growth, doubling in 2022 compared to the previous year. However, more efforts from stakeholders are required to fully harness the potential of digitalization in driving clean energy transitions. Development of supportive standards and policies that foster innovation are needed. [60]

The challenges with port digitalization primarily stem from system incompatibility, resource constraints, cyber security risks and resistance to technological adoption. Different stakeholders operate within distinct business ecosystems and utilize diverse solutions and equipment that adhere to varying operational principles. This kind of fragmentation results in data exchange issues between different systems and operational inefficiencies and bottlenecks appearing. Smaller ports are particularly affected due to their limited resources. [61]

Resistance to digitalization and possible cybersecurity threats poses the greatest barriers to the adoption of digital technologies. The handling of cargo movement and content data needs improved security measures due to its sensitive nature. Operators within port environments may underestimate the need for robust cybersecurity systems. Ports and the businesses operating inside the port areas often perceive themselves as part of a closed community with fewer external threats compared to organizations outside. [61] Ports and operators need to understand that long term benefits from digitalization are inevitable even if some parts of the investment might not become immediately useful. A digitalization strategy and planning should be well conducted before diving headfirst into digitalization effort.

4.4 Cold ironing

To mitigate emissions from vessels and ships at berth cold ironing, known also as alternative maritime power or OPS, has been introduced as a sustainable solution. This practice involves connecting vessels to an external electrical power source while docked. At the same time the need to operate onboard auxiliary engines is eliminated. Vessels are typically equipped with two types of engines: the main engine, which provides propulsion and auxiliary engines, which supply power for onboard operations. The engines run traditionally on diesel oil, heavy fuel oil, or liquefied natural gas (LNG). While docked, vessels generally shut down their main engines, relying instead on auxiliary engines to sustain hotelling functions such as lighting, refrigeration and power system maintenance. Auxiliary engines also burn fuel, leading to different emissions. The shore-side electricity can be sourced from the local grid, RES or other electricity sources. Substituting onboard fuel combustion with shore-supplied electricity, the OPS reduces emissions and environmental impacts. [10][62]

The implementation of OPS comprises three primary components: the onshore power supply system, the shore-to-ship connection system, and the onboard power receiving system. The OPS infrastructure connection and interface equipment is internationally standardized by IEC/IEEE 80005-1:2019 [63]. The standard sets general requirements

for high voltage shore connection (HVSC) systems. Once a vessel is connected to the OPS its auxiliary engines and boilers can be turned off, thereby reducing emissions. [62] According to previous research, OPS presents substantial potential for reducing GHG emissions and air pollutants [64]. However, the extent of the reductions depends on the energy mix supplying the electricity [65]. Environmental benefits are maximized when the electricity is generated from renewable sources. Also, ports with longer vessel handling times have a greater potential for emission reductions through cold ironing [66]. Figure 12 shows a typical OPS system and its components. Starting from the shore side electricity is coming from the power grid. Then the high voltage is stepped down with the transformer. Frequency converter matches the frequency to the required frequency by the ship which 50 Hz or 60 Hz. Then on the ship side an onboard transformer is needed to convert the voltage to usable level on the ship. [67]

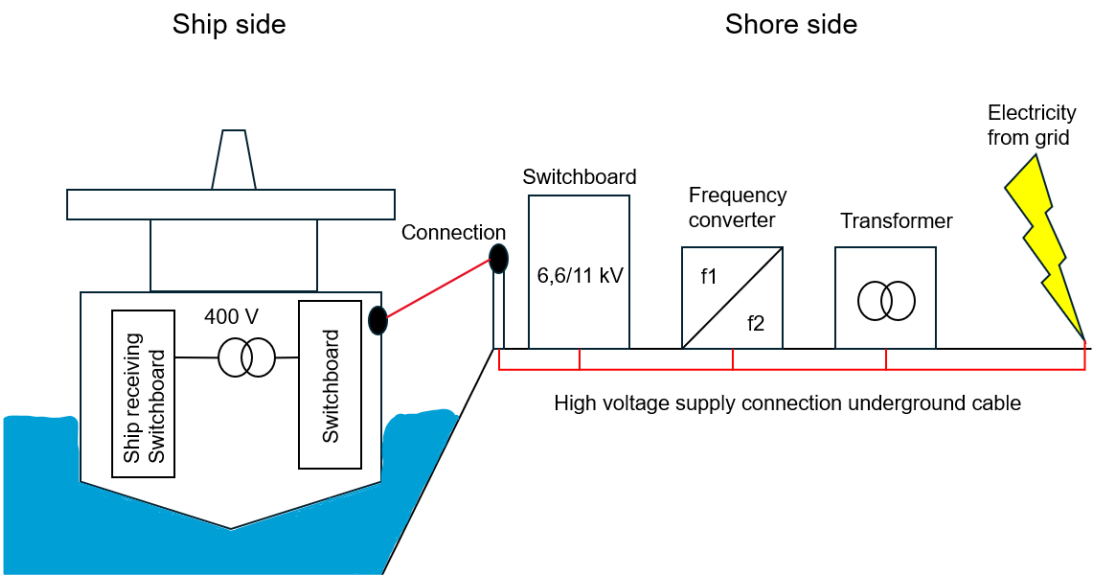

Figure 12: Typical onshore power supply setup, (adapted from [67])

Although the fuel consumption of berthing vessels constitutes only a small fraction of the total energy usage over a vessel's lifetime, the cold ironing offers significant environmental and operational benefits. In addition to reducing CO_2 emissions and pollution, the temporary shutdown of vessel's generators mitigates noise pollution during berthing. Reduction in emissions and noise positively impacts coastal marine ecosystems and nearby communities. The widespread adoption of cold ironing requires well-defined regulatory frameworks and financial incentives to address the substantial initial investment costs. [62] The FuelEU Maritime Regulation is a good example of proper regulation.

According to the World Ports Climate Initiative (WPCI), only 28 ports worldwide currently utilize OPS in various terminals indicating a relatively low adoption rate. This statistic is

from 2018, so some ports have probably adopted OPS afterwards. [68] Interest is OPS increasing due to stricter environmental regulations.

Despite its advantages the implementation of OPS faces several obstacles. Technical challenges include ensuring proper voltage levels and connection type while the ability of the local power utility to meet port energy demands and concerns regarding grid stability further complicate implementation. Before deploying cold ironing, port authorities should conduct comprehensive assessments of power quality and the reliability of the local electrical grid. Incorporating a backup generator is recommended to maintain a stable power supply for vessels while they are connected to OPS. The integration of smart electrical interfaces can also enhance the efficiency and reliability of OPS. [62][10]

4.5 Reefer containers

Reefer containers are thermally insulated enclosures equipped with integrated refrigeration units that regulate internal temperature and humidity by continuously circulating cooled air. Typically, warm air from within the container is drawn into the refrigeration unit, where it is cooled before being recirculated as cold air to maintain the desired storage conditions. When the containers are stacked at the yard, the sunlight increases the cooling needs which leads to rising energy consumption. [69] Reefers are plugged-in during transport in a ship and during storing them at a stack. Power-out periods happen when the ship arrives at the port and when the reefer is transported away from the terminal.

The reefer trade necessitates continuous refrigeration to maintain product integrity. Studies indicate that reefer containers account for 20% to 45% of total port energy consumption, highlighting the necessity for enhanced energy efficiency within reefer storage areas [70][71]. Several studies have explored design optimizations for reefers to minimize energy consumption, including the implementation of covered storage areas to prevent heating of the containers. [10] An innovative approach to enhance energy efficiency of reefer storage was presented in a study by Moros-Daza et al. The underground reefer container storage system is designed to mitigate heat exposure by positioning reefer containers in subterranean storage facilities and thereby shielding them from direct sunlight. By leveraging naturally cooler underground environment, this method significantly reduces the additional energy required to counteract heat influx from surrounding conditions. That way overall energy efficiency in reefer operations improves. [69]

Key research directions for improving reefer energy efficiency include optimizing the allocation and number of reefer plugs, strategic placement of reefer storage areas to minimize travel distances, improving electrical distribution systems, and developing power plans tailored to specific reefer cargo needs. Also, regular inspections and energy adjustments by reefer technicians are crucial for minimizing energy losses [72]. Technological solutions such as reefer monitoring systems (RMS) and sun protection roofs – ideally fitted with photovoltaic panels – can significantly reduce energy consumption. Insulating gaps between adjacent reefers with elastic seals can mitigate external air infiltration, further enhancing energy efficiency in reefer storage areas. [10][37]

4.6 Energy storage systems

With the growing emphasis on port electrification and decarbonization, ESS have emerged as key technologies to enhance energy efficiency, support grid stability, and integrate renewable energy sources. These systems can be broadly categorized into stationary energy storage solutions and onboard energy storages for port equipment and different container terminal operations.

Stationary ESS in container terminals primarily serve as buffers to manage fluctuations in energy demand. Excess renewable energy can be stored in them and provided as backup power during peak load periods. Among the most widely adopted technologies are battery energy storage systems (BESS) which offer high energy density and reliability. Lithium-ion batteries are favored due to their efficiency, long cycle life and rapid response capabilities. Beyond conventional battery storage, supercapacitors present an alternative solution for applications requiring rapid charge-discharge cycles and high-power output. They have lower energy density compared to batteries, but they excel in applications that demand quick energy bursts. Flywheel energy storage systems have also gained some attention for their ability to store kinetic energy and provide instantaneous power support. Battery storages and supercapacitors are presented in subchapters 4.6.1-4.6.2.

In addition to stationary ESS, onboard energy storage solutions are increasingly being integrated into port equipment. These mobile ESS enhance energy efficiency by enabling regenerative energy capture and reducing reliance on fossil fuels. Onboard energy storages were mainly discussed in subchapters 4.1 and 4.2.

4.6.1 Battery storages

Battery energy storage systems are deployed in power systems, often utilizing lithium-ion and lead-acid battery technologies. While alternative battery chemistries exist, they

are not as common due to cost and efficiency. BESS enables the storage of electrical energy from the power grid, which can be later discharged based on system demands. Generally, BESS is implemented to fulfill two primary functions: energy scheduling and backup power supply. [55]

BESS facilitates energy arbitrage by storing electricity when energy costs are low, demand is low or when there is surplus generation. When prices are higher or demand is elevated, electricity can be discharged back to use. [73] A common example is the storage of excess solar or wind energy generated during the day for discharge during peak evening hours. Similarly, electricity can be purchased when time-of-use tariffs are lower and utilized during high-demand periods to optimize cost efficiency. [55]

Additionally, demand reduction and demand charge mitigation are essential applications of BESS, where stored energy helps regulate power consumption and prevent peak demand surcharges. By acting as a buffer, BESS can absorb short-term, high-power loads, such as the charging of electric machines and shore power for ships. This capability reduces strain on the electrical grid, mitigates the risk of overloading infrastructure and minimizes the need for costly grid capacity upgrades. [55]

BESS plays an important role in enhancing grid resilience by serving as a backup power source during grid outages. Depending on its capacity, BESS can supply power for short-term disruptions or sustain critical port operations for extended periods. A key requirement for backup power applications is grid-forming capability, which allows the BESS to establish and maintain its own electrical network when isolated from the grid. Although not all BESS solutions have this functionality. When integrated with a larger microgrid, BESS can support electrified CHE and reefers, ensuring continued operations during power interruptions. [55]

It is worth mentioning that BESS can offer additional grid services beyond their primary functions, potentially mitigating costs through direct participation in energy markets or by deferring infrastructure upgrades. While the financial return of BESS from a pure energy cost perspective may not always be optimal, their economic viability depends on power market conditions and other factors. Justification for BESS deployment often extends beyond financial returns. Bess is frequently implemented to provide backup power and defer costly capital investments. For example, storing excess on-site solar energy can reduce dependence on electricity generated from high-carbon sources and that way improves economic and environmental sustainability. [55]

4.6.2 Supercapacitors

Supercapacitors, also known as ultracapacitors, are a type of electrochemical energy storage device that can store and deliver energy at exceptionally high rates, providing high-current bursts over a short time. Compared to traditional battery storage they exhibit excellent cycle life, high specific power and superior performance in extreme temperatures, particularly in low-temperature charge and discharge conditions. The high capital cost and low energy density of supercapacitors result in a higher unit cost of stored energy ($/kWh) compared to batteries. Due to their rapid charge-discharge capability, supercapacitors are widely utilized in applications such as electric vehicles and power supplies. Power quality management and frequency regulation are also common applications where supercapacitors are used. The high self-discharge rate and cost make them less suitable for long-duration energy storage. [74][75]

In the context of renewable energy integration, voltage oscillations may arise due to fluctuations in power generation. These fluctuations can adversely affect sensitive electronic systems. Supercapacitors provide an effective solution for stabilizing voltage fluctuations. They can also ensure smooth power transmission and store excess energy produced by solar panels or wind turbines. To maintain their longevity and efficiency, supercapacitors must be operated within their specific voltage parameters. Overcharging beyond their threshold can cause severe damage and reduce their lifespan. [76]

Supercapacitors can be used as standalone storage solutions or integrated into a hybrid energy storage system (HESS) that combines at least two storage technologies. In microgrids supercapacitors can work in conjunction with BESS to absorb inrush currents during equipment start-up and line faults. This functionality extends batteries lifespan by maintaining optimal operating temperatures and reducing the discharge rate of batteries. Optimal hybrid configurations leverage the strengths of one technology to compensate for the limitation of another. In industrial applications, supercapacitors can be integrated into energy storage system of equipment to provide assisting power during acceleration and store braking energy through regeneration. [75]

Skeleton Technologies offers different types of supercapacitor energy storage solutions for automotive, grid, marine and heavy transportation. The SkelGrid supercapacitor energy storage system is designed for short-term backup power and power quality enhancement in industrial and infrastructure applications. It is specifically engineered to support demanding operational requirements, including voltage and frequency regulations as well as peak shaving. It can provide up to 3 MW of power for a short time or lower power for a longer period. Skeleton markets that potential applications for the SkelGrid are virtual inertia with RES, helping in microgrid stability, peak shaving, DC bus

stability and generator ramp up support. For heavy transportation the onboard ESS can cut fuel consumption up to 15% and reduce CO_2 emissions. At the same time diesel engine size can be reduced as supercapacitors take over the peak power requirements. [77][78]

Despite their quite widespread use across various industries for over 50 years, supercapacitors remain underutilized in power systems. The primary barriers to broader adoption include low energy density, high costs, and limited awareness of their potential advantages. [75]

4.7 Automation

Container terminal automation refers to the application of advanced technologies such as robotics and AI to optimize operational efficiency while minimizing human intervention. Automation in container terminals includes both equipment automation as well as process and data automation through terminal operating systems and real-time monitoring systems. Typical automated CHE are ASCs, AGVs, automated STS cranes and straddle carriers [79]. The integration of these technologies enables more efficient handling, transportation, and storage of containers, reducing delays and enhancing overall logistics performance. Digitalization is the foundation of full automation.

In digitalized and automated container terminals, the terminal operating system functions as the central coordinating entity, integrating and managing all equipment and operational tasks across the terminal. The terminal operating system facilitates decision-making at three different levels. The levels are terminal operation, equipment control and individual equipment. At the terminal operation level, short-term planning decision are made, such as berth allocation, STS crane assignments and container storage strategies. This level also involves communication with external stakeholders, shipping lines for example. The equipment control level consists of multiple subsystems that manage terminal gates, CHE, and transport vehicles. Upon receiving directives from the terminal operation level, each subsystem issues precise instructions to the designated equipment. At the individual equipment level, specific equipment executes assigned tasks while simultaneously updating its operational status within upper levels. [57]

Automated container terminals enable operators to optimize space utilization and increase operational density. It is anticipated that automation may allow terminals to achieve a given design capacity within a smaller footprint compared to conventional terminal configurations. Fully automated terminals are generally about 30 % larger in area than semi-automated terminals according to comprehensive study made by Knatz et al.

Their dataset included 63 fully and semi-automated container terminals around the world that were in operation during 2022. They found out that majority of automated terminals developed by the six major global terminal operators are characterized by a relatively large capacity footprint. Approximately one third of existing automated terminals originated as conversions from conventional terminals. [80]

Terminal operators are continuously trying to minimize operating costs and that way increase profitability. Automation reduces labor dependency and associated costs. Automation plays an important role in delivering cost-effective cargo handling services. However, some stakeholders, including labor unions, have expressed concerns regarding the potential workforce impacts associated with the adoption of new technologies. Sometimes electrification of CHE is connected to automation, and it therefore impacts the terminal labor. [55]

Knatz et al. found in their study that certain port regions aren't more inclined to adopt terminal automation than others. Semi-automated and fully automated terminals are present across all continents except Africa and Antarctica. These terminals are distributed in 23 countries, with an even division between semi-automation and full automation. Another finding was that automation is implemented across terminals of varying capacities and is not exclusive to the largest facilities. Most fully automated terminals handle between 2 and 4 million TEU annually. [80][81]

Another critical consideration in terminal automation is the financial aspect, particularly the return on investment (ROI). The automation necessitates substantial upfront capital investment for equipment and necessary infra modifications. Knatz et al. found that 61% of terminals anticipate a payback period exceeding six years and 29% expect to achieve ROI within five to six years. [80] Therefore automation is not a short-term project to achieve savings. Testing periods of automated equipment up to 37 months were conducted before proper operations began [80].

5. ENERGY MANAGEMENT

Energy consumption in container terminals is a factor influencing operational efficiency and environmental sustainability. Terminals rely on various types of equipment that all contribute to significant energy demand. The increasing electrification and automation of terminal operations have further highlighted the need for effective energy management strategies to optimize energy use and reduce emissions. Subchapters 5.1-5.5 focus on understanding the different consumption sources and how to manage the consumption more efficiently. In subchapter 5.4 terms smart grid and microgrid are presented and discussed as a potential solution for energy management in container terminals.

5.1 Understanding energy consumption

In port operations, energy consumers can be categorized into two primary groups: direct and indirect users. Direct energy consumers encompass port facilities and infra that consistently require energy, including indoor and outdoor lighting, administrative buildings, and other operational facilities. In contrast, indirect energy consumers demonstrate variable energy consumption patterns that are closely linked to the volume and intensity of port activities. This category includes equipment such as cranes, straddle carriers and reefers. Equipment, meaning STS cranes and reefers, is the biggest energy consumer in terminals consuming up to 80 % of total energy usage. Lighting is said to consume 3-5 % of the total energy in ports. The rest is consumed between other equipment and buildings. [10][62]

An energy management system comprises energy demand planning, energy supply planning and an integrated smart energy management system that optimally balances supply and demand. Effective implementation of such systems in container terminals requires accurate measurement and estimation of energy consumption, supported by a well-defined management strategy. The application of energy efficiency measures becomes more challenging in the absence of detailed energy consumption data. Without precise information, it is difficult to identify which operations, equipment, or areas require intervention. Furthermore, the environmental and economic impacts of energy efficiency measures cannot be accurately assessed. Since GHG emissions from port activities are directly linked to energy consumption, a lack of accurate energy data leads to uncertainty in assessing carbon footprint of goods transported through the port. GHG emissions of the whole port operations are also hard to define accurately without data. [10]

When thinking about energy consumption and what affects it, a few things usually pop up. Energy consumption is influenced by variations in cargo handling volumes and vessel call patterns, seasonal fluctuations in the energy demand for reefers, and changes in port dwell times for import, export and transshipment. [10] By implementing process improvements and retrofitting or upgrading equipment, terminal operators and management can achieve significant benefits. Examples of the benefits are enhanced operational efficiency and reduced energy costs. These improvements result from optimized performance, increased fuel efficiency, and minimized energy losses. [62]

Terminal operators should consider real-time monitoring of energy consumption. It can enhance the flexibility and effectiveness of energy management. Nowadays when digitalization is a priority for most terminals, real-time monitoring can be implemented to TOS or other remote monitoring software. However, real-time measurement systems are often associated with higher cost as they need specialized equipment installment. These monitoring systems are technologically integrated with real-time operational monitoring. Smart meters and other smart energy management systems can be part of the real-time energy consumption monitoring system. [10] Understanding the energy consumption of the CHE is also vital when considering replacing or retrofitting the older machines with new electric CHE. More about smart energy management will be discussed in subchapter 5.4.

5.2 Equipment energy management

The operational efficiency of a container terminal is highly dependent on the effective management of available resources. Operational measures aimed at enhancing energy efficiency encompass procedures that emphasize energy-conscious operational design within container terminals. The primary objective of energy-aware planning is to minimize energy consumption and reduce the processing time of equipment. This is done by optimizing operations during off-peak hours and considering energy price fluctuations. [10]

By analyzing the energy consumption profiles of various equipment and other resources, port operators can develop targeted energy conservation strategies aimed at reducing overall energy use and emissions. The implementation of efficiency measures for specific energy-intensive consumers can further enhance sustainability efforts. [32] Analyzing performance data can help operators make data-driven decisions for energy saving. Implementing predictive maintenance using AI and IoT sensors can help reduce unnecessary energy consumption. For example, equipment that operates inefficiently due to wear and tear consumes more energy.

Container terminal has different functional areas as we know from subchapter 2.3. In the quayside, optimization and planning of STS cranes operation is the main problem. On the yard side, efficient container transportation and stacking are prioritized. Typical problems are yard allocation, in other words, how the containers should be stacked and scheduling of the yard equipment. [10][11] To optimize energy consumption and reduce harmful emissions, advanced container terminal operating systems, including crane optimizers, yard optimizers, and truck schedulers have been increasingly adopted. A crane optimizer enhances crane productivity and yard optimizer improves yard allocation and storage area efficiency. Truck scheduler minimizes truck idle time. [11][82] These different optimizers are often associated especially with the automated CHE.

Recently, the electrification of port equipment has gained prominence due to its potential to reduce emission compared to fossil fuel-based operations while simultaneously yielding cost efficiencies. Additionally, peak shaving has emerged as an important strategy for reducing a port's peak energy consumption. Various peak shaving techniques have been explored, as peak electricity usage has been observed to account for approximately 25-30 % of a port's monthly electricity expenses [83]. The overall energy bill consists of two components: a fixed cost for electricity usage, which remains constant, and a variable cost, which fluctuates based on energy consumption levels. Although ports cannot influence the fixed cost, efforts can be directed toward lowering the variable cost which is primarily determined by peak energy usage and electricity consumption. Simultaneous operation of all equipment leads to high peak energy consumption, and it leads to increased energy expenditures. [37][83] Peak shaving techniques are discussed in more detail in subchapter 5.5. Combining electrification with automation can also enhance energy efficiency. Autonomous CHE can operate with optimized acceleration and braking patterns and therefore reduce energy waste compared to manned CHE.

5.3 Energy supply

The ongoing transition towards automation and electrification has substantially altered the energy consumption and supply framework of container terminals. This transformation has also introduced complexities in balancing energy supply and demand, as well as in implementing integrated energy management strategies. [84] Many ports worldwide are adopting RES, and the proportion of energy derived from these sources is often understood as a key performance indicator (KPI) for evaluating the sustainability and smart capabilities of ports. [10]

The energy supply for terminal operations can be derived from multiple sources such as fossil fuels, clean fuels and renewable energy. Additionally, port may procure electricity

from the utility grid. Renewable energy is sourced from naturally replenishing resources such as solar radiation, wind, tidal forces and wave energy. [10] ESS can be used and is often used with RES. The energy sources can either directly supply terminal operations or be redirected by selling excess power back to the utility grid or stored in ESS. This diversification in energy sources and flows increases the complexity of energy management in container terminals. Discrepancies in electrification processes across terminals, coupled with variations in shore power configurations for vessels necessitate careful consideration of the alignment between energy consumers, energy types, and supply levels. [84] RES alone can't ensure a reliable supply to port operations, so ports need additional energy sources to complement the supply.

5.4 Smart grid and microgrid

IEA describes smart grid as an advanced electricity network that leverages digital technologies and automation to monitor and optimize the transmission and distribution of electricity from various generation sources to end users. Smart grids facilitate the coordination of power generators, grid operators, consumers, and electricity market stakeholders to enhance system efficiency, minimize costs and environmental impacts, ensure reliability, resilience, flexibility and stability in power supply. [85] Smart grid operates on a large scale covering cities or regions.

The rapid expansion of variable RES and the electrification of multiple sectors have introduced challenges for power systems. The integration of smart grid technologies enables real-time system monitoring that allows the optimal utilization of existing infrastructure. Another benefit is the operation of power networks closer to their true capacity without compromising reliability. Additionally, these technologies help contain system failures into smaller areas, reducing the risk of cascading power outages. [85]

Smart grid and microgrid are often related but have some differences. According to U.S. Department of Energy, a microgrid is a localized group of interconnected energy loads and distributed energy resources that functions as a single, controllable entity within a clearly defined electrical boundary. Microgrids can operate in grid-connected mode, interacting with the main power grid, or in island mode, where they function independently. [86] Microgrid operates on a small-scale near the consumer.

Microgrids vary in size and complexity, but they generally consist of three key components [86]:

1. Electricity generation resources (solar photovoltaic systems, wind turbines, diesel or natural gas generators, biogas plants)

2. BESS to store excess electricity and provide backup power
3. Microgrid control systems, often managed through a central controller that coordinates distributed energy resources, balances different loads and facilitates the seamless disconnection and reconnection of the microgrid to the main grid.

One of the primary advantages of microgrids is their ability to enhance energy resilience by operating autonomously during power outages. When a disruption occurs in the main grid, a microgrid can island itself and continue supplying electricity to critical facilities. [86] This kind of behavior would be beneficial for some container terminals.

The integration of microgrid systems into container terminal operations presents an opportunity to enhance energy resilience and improve efficiency. Microgrids improve the reliability of power supply by enabling terminals to operate independently of the main grid during disruptions or outages. Many terminals have robust grid and backup power available, but this is beneficial for terminals located in regions that are susceptible to extreme weather conditions or unstable grid infrastructure. The integration of RES reduces dependence on conventional fossil fuels. By incorporating BESS, terminals can optimize the utilization of renewable energy and ensure a stable power supply, even during periods of low generation.

Microgrid systems also enable real-time energy management, which can help with demand side optimization and peak load shaving strategies. Intelligent energy distribution allows terminals to schedule energy-intensive operations based on real-time demands and electricity prices. By utilizing stored energy during peak hours, terminals can reduce electricity cost associated with high grid tariffs. Also, the ability to trade surplus renewable energy with the main grid provides an economic incentive for ports to invest in on-site energy generation and storage. Another possibility is to participate in the ancillary service markets if the stringent requirements are met. A simplified version of container terminal smart energy management system is presented in figure 13.

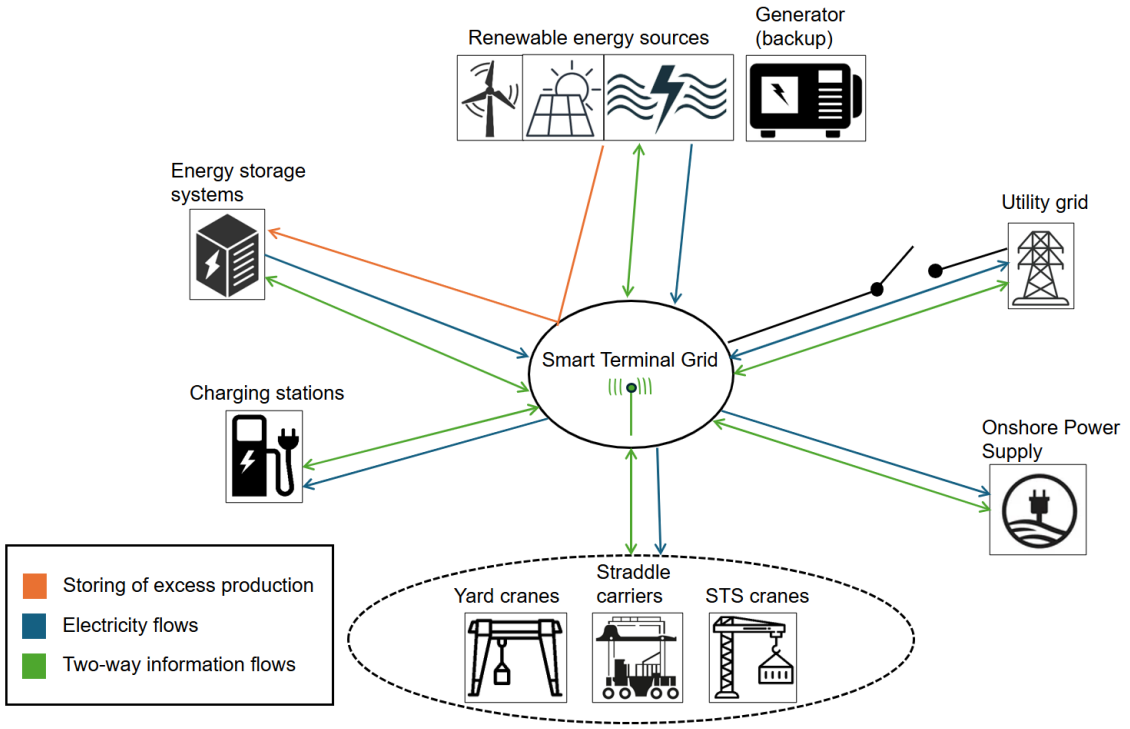

Figure 13: Smart energy management at the container terminal (adapted from [79])

Smart terminal grid is in the center of the energy management of the port. The blue arrows show the electricity flow between the electricity production and the smart grid and from the smart grid to the electricity consumers. Smart terminal grid can be described as the brains of the whole energy management system that manages the electricity flow from the grid to the consumers and back to the grid. It provides load shifting and peak shaving during daily operations. Suppliers are utility grid, RES and generator. Electricity consumers are OPS, electrified CHE, charging stations and storage systems. The green arrows show the two-way information flows between the smart grid and energy consumers and smart grid and supply. [79] Different kind of digital technologies such as smart communication devices, smart meters and sensors are used to provide the two-way information flow between each participant of the system. The orange arrow shows that excess electricity production can be stored. Excess electricity production from RES can be stored for later use into the ESS such as batteries or supercapacitors. Smart terminal grid can isolate itself from the utility grid if there is a loss of power from the utility grid.

Despite the several benefits, integrating microgrid into operations presents some challenges. Significant capital investment is renewable energy generation, ESS and control systems are needed. The ROI may take years to materialize, depending on energy price fluctuations and government incentives. The compatibility of microgrid technology with

terminal operating systems and automated CHE requires careful planning and integration. Also, safety and legal concerns are present, for example if the system fails during operation or operation stops due to cyber threats [79].

5.5 Peak shaving and load management

The increasing adoption of electrified CHE is driven by its economic and energy-efficient characteristics. This transition leads to elevated electricity consumption, especially during peak operational periods. To address this challenge smart load management and peak shaving technologies have emerged as an important strategy to mitigate power consumption within port facilities. Three different load management technologies are well known [11][79]:

1. Load shifting, redistributing energy demand from peak periods to off-peak hours.
2. Load shedding, also known as peak shaving, temporarily switching off non-essential loads during peak hours to reduce overall energy demand.
3. Peak sharing, also known as power sharing, utilizing stored energy during peak demand periods to offset excessive electricity consumption.

Figure 14 shows graphical representations of the three load management technologies.

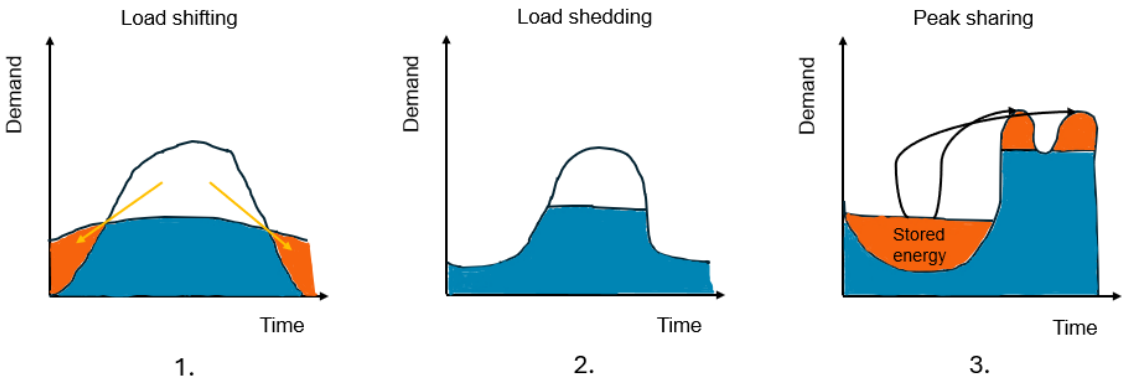

Figure 14: Different load management technologies (adapted from [11])

Load shifting is the first example in figure 14. Terminals can employ load shifting by scheduling energy-intensive activities such as charging electric CHE during off-peak hours. This minimizes peak-hour electricity consumption and reduces associated expensive tariffs. By effectively rescheduling energy use, terminals can achieve load stabilization and cost efficiency. Sometimes load shifting is understood as demand response. Basically it means the same thing but with an incentive for consumers to shift or reduce

electricity demand in wholesale and ancillary power markets. Demand response operates through two primary mechanisms. Implicit demand response means that consumers are incentivized to adjust their energy consumption patterns based on dynamic pricing structures and tariffs. Explicit demand response means that consumers receive direct compensation for adjusting their electricity demand as part of demand-side response programme. [87]

Load shedding is presented as second technology in figure 14. Load shedding is executed through smart energy management systems and by using intelligent sensors. These allow terminals to temporarily disconnect specific non-critical loads during peak periods. [79] Previously reefers, yard lighting and office heating have been identified as potential areas for load shedding. However, energy reductions in reefers must be carefully managed to prevent temperature fluctuations that could result in product spoilage. [70] In Port of Long Beach's energy initiative roadmap it was estimated that 1-day power outage of the port would result in 100 million dollars financial loss. In the same study it was said that the frequency and duration of grid outages is expected to increase in the future. Various factors affecting this were mentioned, such as equipment failures due to old infrastructure, cybersecurity attacks and rough weather events. [88]

The third technology in figure 14 is peak sharing. With peak sharing the main idea is to supplement power supply during peak periods by using ESS or generators that are installed in the terminal premises. STS cranes or yard cranes can make big spikes in electricity demand if they operate simultaneously. [79]

6. ACTIONS TOWARDS GREENER TERMINALS

The global maritime industry is undergoing a significant transformation, with port electrification emerging as a critical pathway towards enhanced sustainability and efficiency. Terminal operators stand at the forefront of this shift, facing a confluence of pressures and opportunities that necessitate a move away from traditional fossil fuel-powered equipment towards cleaner alternatives. Understanding the multifaceted drivers behind this transition is the first step in developing a robust preparation strategy.

One of the primary motivators is environmental stewardship. Port operations, particularly the use of diesel-powered CHE, emit a lot of air pollution locally. The emissions have detrimental effects on the health of port workers and nearby communities. Electrification offers a direct solution that reduces these harmful pollutants and improves air quality. Furthermore, electric CHE generates notably less noise compared to its diesel alternatives, mitigating noise pollution for surrounding areas and improving working conditions within the terminal. Beyond local impacts, electrification addresses climate change by reducing GHG emissions, primarily carbon dioxide. This aligns with global commitments like the Paris Agreement and specific industry targets set by the IMO, which aim for GHG reductions by 2030, 2040 and finally net-zero emission around 2050.

Closely linked to environmental concerns is the increasing weight of regulatory compliance. International bodies like the IMO, regional blocs such as the EU with its ‘FIT for 55’ package that includes FuelEU Maritime and AFIR, and state or local authorities like the California Air Resources Board (CARB) [89][90]. These mandates often target emission from ships at berth and landside equipment, guiding ports and terminals to lean towards cleaner technologies. Programs like the San Pedro Bay Ports’ Clean Air Action Plan (CAAP) exemplify this trend, setting ambitious goals for zero-emission terminal equipment [91].

While environmental and regulatory pressures are strong, the economic advantages of electrification provide a compelling business case. Although electric equipment often carries a higher initial purchase price (CapEx), it typically offers lower operational expenditures (OpEx) over its lifespan. This is driven by greater energy efficiency and notably reduced maintenance costs, as electric drivetrains have fewer moving parts compared to internal combustion engines. The TCO of certain electric equipment has already fallen below the TCO diesel-electric counterparts. Access to low-cost electricity and potentially

including generation through renewables like solar can further enhance savings. Compliance with environmental regulations can also lead to cost savings through avoided penalties and access to incentives.

Electrification also promises improvements in operational efficiency and resilience. Electric equipment can offer greater dependability and potentially reduced downtime due to lower maintenance needs. Integrating electrification with on-site generation and ESS within a microgrid framework can significantly enhance energy resilience. Critical operations can continue even during disruption to the main power grid. This reduces dependency on volatile global fossil fuel markets and improves energy security.

Finally, one of the most important motivators needs to be corporate commitment. Many large shipping lines, terminal operators and logistics companies have established internal sustainability goals and corporate social responsibility initiatives that drive investment in decarbonization. There needs to be internal motivation on the topic on top of the pressure coming from outside.

The transition to an electrified terminal is not a simple equipment swap; it represents a fundamental operational and infrastructural transformation. Furthermore, electrification necessitates adjustment to operational workflows, maintenance protocols and workforce skills. Coordinating these changes requires engagement with a wide array of stakeholders, including electric utilities, port authorities, other tenants, equipment manufacturers, regulators, labor unions and local communities. Each of these have distinct priorities and constraints that must be managed. The potential risks are considerable, ranging from technological underperformance and grid instability to cost overruns and operational disruptions.

Given this complexity, a structured, phased framework is indispensable for terminal operators. Such a framework provides a roadmap for navigating technical, operational, financial, and logistical challenges. Operators can make informed decisions, mitigate risks and manage investments effectively. The framework should help in ensuring a smooth transition towards zero-emission operations.

In subchapter 6.1 similar previously done frameworks are shortly presented. In subchapter 6.2 a four-phase framework designed to guide terminal operators through this critical preparatory process is outlined. The following subchapters 6.3-6.6 focus on explaining each phase of the framework in more detail.

6.1 Previously done frameworks

As electrification is a quickly growing trend, a few similar kind of frameworks have already been done. The first study conducted by Ismail AM. et al. focuses on integrating ports into Green Shipping Corridors (GSCs). GSCs are understood as collaborative actions for addressing environmental challenges. [92] GSCs take into account the kind of broader scope and electrification is one of the potential technological solutions. The study provides a short literature review on the GSC topic and identifies drivers and challenges for ports in joining GSCs. Finally, a practical framework is provided to address implementation of GSCs by ports. The framework has eight different stages as can be seen from figure 15.

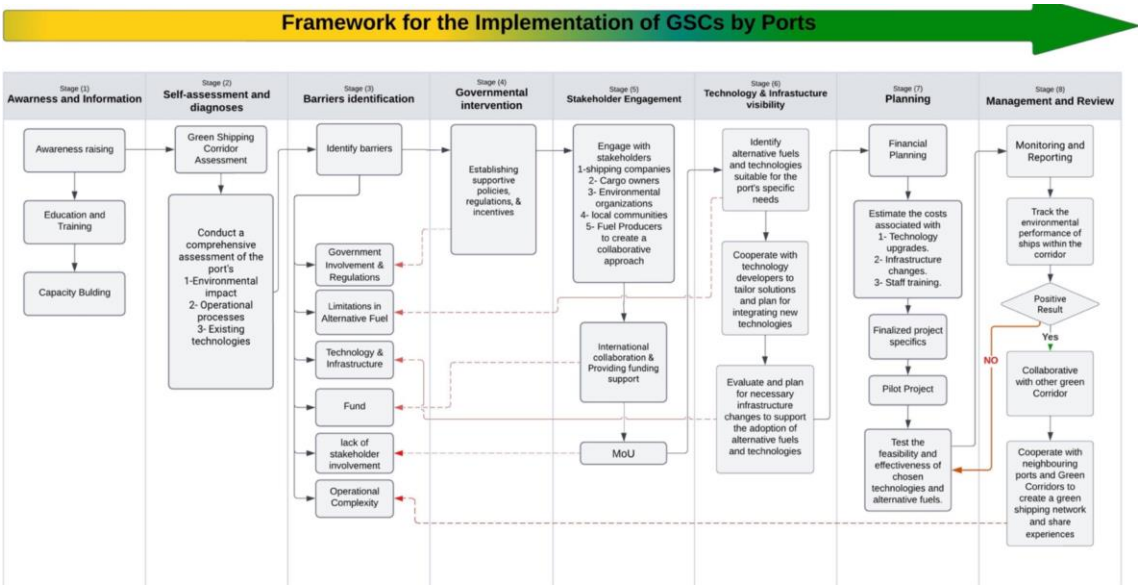

Figure 15: GSCs implementation framework [92]

Initially, the focus is on building awareness and capacity through education and training for port employees and tenants regarding environmental impacts and sustainable practices. The second stage involves a self-assessment of GHG emissions, operational processes and technology gaps, guiding priorities for upgrades, sustainable fuels and so on. Stage three identifies key challenges to GSC participation. Subsequent stages systematically address these barriers. Stage four highlights early engagement with government bodies to shape supportive regulations. Stage five concentrates on securing funding through various means and engaging stakeholders. Stage six involves selecting appropriate alternative fuels and planning the required infrastructure. The seventh stage focuses on financial planning and initiating a pilot project. The final stage emphasizes continuous monitoring and assessment of the corridor's environmental performance.

Another relevant study done by Pacific Northwest National Laboratory for U.S. Department of Energy was conducted to help evaluate different challenges of increased electrification. The Port Electrification Handbook serves three primary functions: assisting in evaluating electrification options, explaining the implications for ports and local communities, and offering a structured approach to electrification planning and implementation. The Port Electrification Program Management Framework provides a high-level guidance on port electrification phases and gives example tasks in each phase. [55] The framework and its steps can be seen in figure 16. This framework is in the core of electrification and more relevant to the topic the author of this study is investigating.

Figure 16: Port Electrification Program Management Framework [55]

The framework itself is divided into four different phases: pre-planning, planning, implementation and iteration. Ongoing tasks are important during all phases. Each phase is divided into subtasks. The initial pre-planning phase establishes the strategic foundation and direction for the port electrification program. Collection of baseline information, stakeholder input, and reviewing existing regulatory frameworks are part of this stage. Planning, implementation, and iteration encompass potential project-specific tasks that necessitate adaptation based on the nature of the project. The implementation phase focuses on the execution and completion of planned projects. Natural tasks related to this phase are project funding securing and coordinating across projects. The iteration phase is meant for evaluating project performance and systematically documenting outcomes to optimize future initiatives. [55]

6.2 Framework of the steps to prepare for electrification

Port electrification planning framework is presented in figure 17. The purpose of the framework is to act as a general guiding framework during the planning phase when preparing the electrification journey of the terminal. The framework is divided into four different phases and each phase has different subtasks which need to be taken into account.

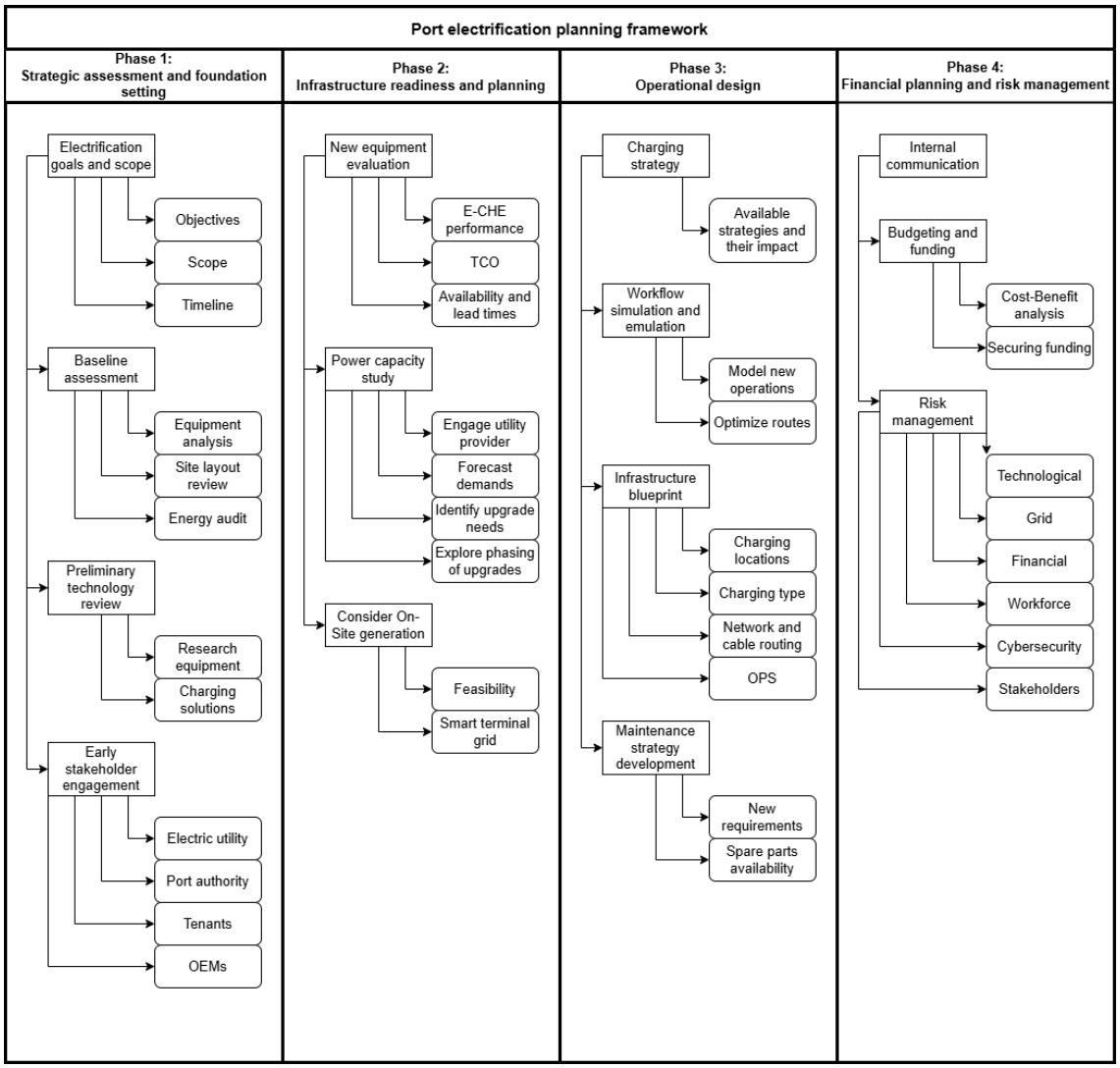

Figure 17: Port electrification planning framework

Phase 1 is strategic assessment and foundation setting. The purpose of the first phase is to understand the strategic direction of the terminal and its current state. Phase 2 is infrastructure readiness and planning. Its purpose is to evaluate E-CHE feasibility, electric network needs and other infrastructure related matters. Phase 3 is operational design. Phase 3 focuses on choosing charging strategy, simulating and emulating new operation and understanding how electric machines will affect day-to-day operation. Maintenance related things should also be considered during that phase. Phase 4 is financial planning and risk management. Cost estimates of equipment and infrastructure upgrades should be created during this phase. Potential funding options should be researched at local and national levels. Staff should be kept informed about upcoming changes. Risk management focuses on identifying and mitigating different risks related to projects.

6.3 Strategic assessment and foundation setting

The initial phase of the framework focuses on establishing the strategic direction, understanding the current state, identifying potential pathways, and initiating crucial relationships. These subtasks are presented in more detail in subchapters 6.3.1-6.3.4. This foundation work is essential for guiding all subsequent planning and implementation efforts.

6.3.1 Electrification goals and scope

Before embarking on detailed technical planning, terminal operators must define their electrification ambition. This involves setting clear, measurable, achievable, relevant and time-bound goals. These goals should directly address the drivers identified earlier – for example, achieving specific percentage reductions in NO_X and particulate matter (PM) emissions by 2030 [55].

The scope of the initial electrification effort must be defined. Which specific types of equipment will be targeted first? Common candidates are forklifts, straddle carriers, RTGs and terminal tractors. Another question to think is that will OPS for visiting vessels be included in the initial phase? Defining a realistic timeline is critical, considering factors like regulatory deadlines, technology maturity, funding availability, and grid upgrades.

Developing a long-term vision for zero-emission terminal provides an overarching direction. This vision, aligned with the port authority's broader strategic plan and the terminal's tolerance for risk associated with adopting new technologies, will inform decisions about technology choices and the phasing of the transition.

6.3.2 Baseline assessment

A foundational step is to conduct a comprehensive baseline assessment of the terminal's current energy consumption and associated emissions. This involves inventorying all energy sources used by equipment and operations within the defined scope and quantifying the resulting emissions. Typical usage patterns, operating hours, fuel consumption and maintenance schedules of the current equipment should be analyzed.

This baseline serves multiple important purposes. It provides the benchmark against which progress towards emissions reduction goals will be measured. It helps identify the largest sources of energy consumption and emissions, highlighting the equipment or operations where electrification will have the greatest impact. Furthermore, the baseline forms the basis for developing realistic forecasts of future electrical load requirements, which are essential for discussions with the utility provider.

Beyond simple accounting, the process of creating this baseline acts as a powerful diagnostic tool. It forces a detailed examination of current operational patterns and energy use, often revealing inefficiencies or identifying specific equipment types that are prime candidates for electrification due to their high emissions or operating costs. This detailed understanding allows for a more strategic prioritization of electrification efforts, focusing investments where they yield the fastest environmental and economic returns. Additionally, credible baseline data is often a prerequisite for securing grants and funding. It helps to demonstrate the quantifiable impact of the proposed project.

6.3.3 Preliminary technology review

With goals defined and a baseline established, the next step is an initial survey of available electric technologies relevant to the terminal's scope. This involves identifying potential battery-electric alternatives for targeted CHE from different manufacturers.

A key consideration is the Technology Readiness Level (TRL) of equipment. The original version was defined by NASA. The TRL scale is meant to measure the maturity level of a particular technology. TRL scale goes from 1 meaning the basic principles are documented to 9 meaning the technology is released, and industrial production is started. [93][94] For near-term planning within a 5-year horizon, focus should be on technologies that have reached at least TRL 6 (prototype demonstration in a relevant environment) or higher, as these are more likely to be commercially viable within the planning timeframe.

It's important to note that electrification can occur through purchasing new electric equipment or retrofitting existing diesel equipment. The feasibility and cost-effectiveness of retrofitting depend on the age and type of the existing equipment. The technology landscape is evolving rapidly, with continuous improvements in battery energy density, charging speeds, equipment performance, and cost reductions. Therefore, this initial scan should be viewed as a starting point that requires ongoing monitoring of technological advancements.

6.3.4 Early stakeholder engagement

Effective stakeholder engagement that is initiated early and maintained through the process, is fundamental to successful terminal electrification. Delays or conflicts arising from inadequate coordination can significantly impede progress. Key stakeholders include:

- Electric utility: Engagement with the utility provider is important and must begin at the earliest possible stage. Discussions should cover existing grid capacity serving the terminal, the process and potential costs for serving upgrades, real-

istic timelines for these upgrades, and the utility's requirements for interconnecting DERs and ESS. Initial load forecasts should be shared if possible. Challenge is that utilities often require precise future demand figures before committing to costly infrastructure upgrades, while terminals may still be finalizing their electrification plans and browsing equipment choices. Establishing formal relationships and clear communication channels can help navigate this dynamic. The utility's ability to deliver sufficient and reliable power is often the single most critical factor determining the feasibility and pace of large-scale electrification. The utility provider is a strategic partner whose timelines shape the project's path.

- Original equipment manufacturers: Early dialogue with equipment manufacturers helps clarify equipment availability, performance specifications, charging requirements, maintenance needs and lead times.
- Port Authority: The port authority plays an important role in setting the overall port decarbonization strategy and may offer support and incentives. They are often best positioned to facilitate discussions involving multiple tenants, particularly regarding shared infrastructure like grid connections. Collaborating with port authority and understanding their plans is essential because they usually understand the government side and bigger picture.
- Tenants/Terminal Operators: Multiple terminals can share the same utility feeders or substations. Coordination among tenants is vital to avoid collectively overwhelming the available grid capacity. A lack of collaboration can lead to situations where individual actions strain the grid and can hinder electrification efforts for all.
- Local Communities: Engagement with near-port communities helps address concerns about operational impacts during the transition and build support for the project's environmental benefits.

Also variety of other stakeholders need to be kept in the loop. For example government agencies and regulators and labor unions are important bodies in terms of potential funding opportunities, compliance deadlines and training needs.

6.4 Infrastructure readiness and planning

Following the strategic groundwork of phase 1, phase 2 delves into the specifics, involving detailed technical assessments of equipment and infrastructure. On-site electricity generation and ESS should be also considered in this phase. The specifics of phase 2 are explained in more detail in subchapters 6.4.1-6.4.3.

6.4.1 Equipment evaluation

This stage moves from the preliminary technology scan to a rigorous evaluation of specific electric equipment models suitable for the terminal's needs. Key assessment criteria include performance, TCO, availability and lead times and standardization. Table 2 presents comparison between diesel-electric and battery electric CHE, which can help during the evaluation process. Factors in comparison are initial cost, fuel/energy cost, maintenance cost, emissions, noise, performance, refuel/recharge time, infrastructure needs, expected lifespan and TCO. Information sources for the table 2 are discussions with case company experts and knowledge of the author.

Table 2: Comparison of diesel-electric vs battery electric CHE

Factor	Diesel-electric CHE	Battery electric CHE	TCO considerations & notes
Initial Cost (CapEx)	Lower	Higher	Significant upfront investment for electric, important factor in TCO. Gap expected to narrow with scale.
Fuel/Energy Cost (OpEx)	Higher, volatile	Lower, more stable	Major driver of long-term savings for electric.
Maintenance cost (OpEx)	Higher	Lower	Major OpEx savings for electric. Reduced downtime.
Emissions	Significant	Zero tailpipe emissions	Key environmental benefit, essential for compliance and community health.
Noise	High	Significantly lower	Improves working conditions and reduces community impact.
Performance	Established performance	Almost comparable performance achievable, rapid torque	Technology rapidly improving. Pilot testing crucial.
Refuel/Recharge time	Fast (minutes)	Depends on charging strategy, up to hours for full charge, minutes with opportunity	Major operational planning factor. Dictates charging strategy choice.
Infrastructure needs	Existing diesel tanks	Charging stations, grid upgrades, potential BESS and microgrid	Significant CapEx for charging infra and grid connection.
Expected lifespan	~10 years in port setting (mechanisms main bottleneck)	~10 years in port setting (mechanisms main bottleneck)	Battery degradation and replacement should be included in TCO.
TCO Parity	Baseline	Below baseline, highly dependent on local energy costs, incentives, and operational factors	TCO of electric CHE has already fallen below diesel alternative, depends on whether charging equipment is taken into calculations

Can the electric equipment meet the operational demands of the terminals? This involves evaluating power output, speed, lifting capacity, battery operating time, and overall reliability under demanding port conditions. Concerns about electric CHE potentially being less powerful or requiring frequent charging must be addressed through careful selection and operational planning.

An analysis comparing the lifetime costs of electric versus other alternatives such as diesel-electric or hybrid is essential. While electric equipment generally has a higher purchase price, this can be offset by notably lower operating costs due to cheaper energy and reduced maintenance requirements. TCO calculations should factor in energy consumption rates, local electricity tariffs, expected maintenance schedules and costs, battery replacement costs and lifespan, and potential government grants or incentives that can reduce the initial investment. Potentially, charging stations and infrastructure costs can be added into calculations.

Commercial availability of the desired electric equipment models and their manufacturing lead times should be confirmed. Supply chain constraints or high demand could impact delivery schedules. Value chains are not yet scaled for large roll-outs. Ensuring that equipment meets any specific grant requirements or necessary certifications such as UL listed should be done in this phase. [55]

Lack of standardization in the battery electric CHE market has been a barrier, leading to higher costs and limited interoperability. Zero Emission Port Alliance (ZEPA) has released 11 voluntary standards, which aim to harmonize aspects of batteries and charging interfaces for terminal tractors and straddle carriers. [95][96] Terminal operators could investigate equipment adherence to these standards, because they could simplify the integration of electric CHE and charging stations.

6.4.2 Power capacity study

This step involves detailed coordination with the electric utility provider, building upon the initial engagement in phase 1. Based on the refined load projections derived from the equipment selection and charging strategy, the terminal operator must confirm available capacity. This means working with the utility to determine the maximum power capacity available at the terminal’s existing point(s) of interconnection with the grid. The historical reliability of the grid should be also investigated. Frequent power outages or surges pose real operational risks for an electrified terminal and may necessitate investments in on-site backup power or microgrids.

If the projected load exceeds current capacity, the necessary upgrades to the utility's infrastructure should be defined. Realistic estimates should be obtained from the utility for the cost and the lead time required for the upgrades. Grid expansion projects are often complex so it can be a constraint on the terminal's electrification schedule. Possibilities for phasing the grid upgrades can be considered if the terminal plans to do phased equipment rollout.

If immediate upgrades are infeasible, terminal should consider demand response programs and on-site RES generation and storage. If the terminal plans to install its own generation such as solar panels or BESS, utility should be contacted to clarify technical requirements and other technical details with connecting the RES to the grid. Other possible solutions to balance the electrical load are lower power charging solutions, load management system or vehicle rotation charging strategy. Smart terminal grid solutions should also be investigated. They could enhance the energy efficiency of the whole terminal, giving room for electric CHE needs.

6.5 Operational design

After selecting the potential electric CHE and assessing the utility grid it is time to choose the fitting charging strategy. Selecting the right charging strategy is a critical operational design decision that impacts equipment availability, infrastructure upgrade costs and grid. New operations should be carefully simulated and emulated to make sure that the chosen solution fits the operational goals of the terminal. Subchapters 6.5.1-6.5.4 open the workflow simulation, charging strategy impacts and maintenance strategy in more detail.

6.5.1 Charging strategy selection

The choice of charging strategy depends on the terminal's specific operational characteristics such as shift lengths, fleet composition, labor availability, site layout and grid connection capacity. For some terminals a combination of more than one strategy might be the most optimal solution. The main charging strategy options are presented and compared in table 3. Five different charging strategies can be identified.

Table 3: Charging strategies

Strategy	Operational Pros	Operational Cons	Grid impact
Depot charging	Simple scheduling, driver keeps same vehicle	Requires downtime, can cause high peaks if unmanaged	High & peaky
Vehicle rotation	Continuous operation, flat demand profile	Requires extra vehicles	Low & flat
Opportunity charging	Minimal downtime, flat demand profile	Fast chargers required, precise planning needed	Low & flat
Battery swapping	Near-continuous operation, stable demand profile	High CapEx, labor for swapping	Low & stable
Smart charging	Reduces peak demand & energy costs, optimizes grid use	Smart chargers & management software required	Variable (managed to be low)

The charging strategies are depot charging, vehicle rotation, opportunity charging, battery swapping and smart charging. Smart charging is mainly meant to be connected or combined with the other archetypes. With depot charging, equipment is charged simultaneously during scheduled downtime, such as shift breaks or overnight. Chargers are usually at a central location and often there is a dedicated charger per vehicle. Operational pros are simple scheduling and the fact that drivers can use the same vehicle throughout their shift. However, high demand peaks can be expected with the simultaneous charging. Required downtime during charging is the negative impact. [95]

The second charging strategy is vehicle rotation. It means that when a vehicle's battery runs low during a shift, the operator swaps it for a fully charged vehicle standing by. Depleted vehicles are charged while others operate. Operational pros are that operations can continue with minimal downtime and the peak electricity demand is lower. This strategy needs additional CHE to cover those being charged which increases CapEx. [95]

The third charging strategy is fast opportunity charging. Opportunity charging means that CHE receive quick, high power charges during short operational pauses at strategically placed decentralized chargers. This kind of operation minimizes charging downtime and supports flat demand profile. Cons are typically required more expensive fast chargers

and the need for careful planning to align charging opportunities with operational patterns. [95]

The fourth charging strategy is battery swapping. The idea of batter swapping is that instead of charging the CHE, depleted batteries are physically removed and replaced with fully charged ones at dedicated swapping stations. Swapping stations charge the empty batteries. Near-continuous operation similar to refueling diesel is a benefit of this strategy. Another benefit is stable electricity demand profile from the swapping station. Negatives are the investments required in extra batteries and the swapping station infrastructure. [95] Additional labor for the swapping process might also be needed.

The final charging strategy is smart charging. It should be a complementing strategy to the four previously mentioned strategies. The idea of smart charging is that it utilizes software to control when and how fast vehicles charge. Charging can be shifted to off-peak hours, slowed down to stay within grid capacity limits or coordinated across the fleet to minimize overall demand. Pros are that it can reduce peak demand and energy costs and optimize the use of available grid capacity. Smart charging can also be connected to smart energy management systems of the terminal. Charging management software and communication infrastructure are needed. Charging times may also be extended if power output is limited. In that case smart charging might not work well with fast opportunity charging.

6.5.2 Infrastructure blueprint

Based on the selected equipment and the chosen charging strategy, a comprehensive plan for necessary on-terminal and charging infrastructure must be developed. The need for routing of new electrical cables and conduits is already good to keep in mind when doing the power capacity study. Final planning can be done after the charging strategy has been selected. Charging station locations should be identified based on operational workflows, equipment dwell times and in a way that they minimize interference with cargo movement. Space constraints are a common challenge in busy terminals.

Charger’s type and power level must be specified according to the charging strategy and operation. Slower DC charging might be suitable for overnight charging or charging during long breaks. Faster DC charging or even Megawatt Charging System (MCS) should be considered in case of fast opportunity charging. MCS is suitable for very high-power needs in the future. At the end the choice also depends on equipment’s battery capacity and its ability to receive power. With smaller capacity batteries it is more vital to fill up fast during operation. High capacity batteries can operate longer and may be charged during longer breaks in operation.

If OPS is part of the project scope, detailed engineering design is required according to international standard IEC/IEEE 80005. [63] Voltage and frequency compatibility, cable management systems, safety matters and connection points on the quay need to be specified.

Planning for the future is a really important step of infrastructure design. The electrical backbone installed today represents a long-term asset that will likely remain in place for decades. The network could outlast more than one generation of charging equipment or electric vehicles. Given the rapid evolution of charging and battery technologies, charging infrastructure should be designed with scalability and flexibility.

6.5.3 Workflow simulation and emulation

Electrification changes flow of operation. Physical space for charging stations, maybe for battery swapping areas or dedicated maintenance halls is required. Charger placement must consider accessibility for equipment without obstructing primary traffic lanes. How will equipment move to and from charging locations? Consider if specific charging lanes are needed. Queuing at chargers needs to be managed in some way. Poorly planned logistics can create new bottlenecks.

Dynamic simulation modeling provides a powerful tool to evaluate different infrastructure layouts, charging strategies, fleet sizes, and operational rules under variable conditions. Simulation allows operators to visualize potential bottlenecks such as charging queues. Different types of what-if scenarios can be tested. Common simulation scenarios include charger failures or different battery sizes. Real operational data from the terminal site can be used as an input for the simulation model. Simulation reduces implementation risks and in a way helps ensure that the fleet performs efficiently from day one.

6.5.4 Maintenance strategy development

Electric CHE differ quite a lot in terms of power unit and refueling compared to the diesel machine. Making a robust maintenance strategy helps in controlling long-term operational costs. Because of the differences, the new equipment also has different maintenance needs. Batteries are critical and expensive components. Maintenance will focus on battery health monitoring and other parameters in order to schedule preventative maintenance. Thermal management systems need regular inspections for leaks and proper coolant levels. Loose connections and damage to high-voltage cables should be inspected to ensure safety and performance. Charging stations also need to be kept up to date and inspected every now and then.

Electric motors and drivetrain generally require less frequent maintenance than internal combustion engines but still need attention. Manufacturer recommendations should be followed for lubrication of any mechanical components. Electric equipment relies heavily on software for control and diagnostics. Planning and implementing software upgrades regularly are necessary for performance.

The equipment and charger manufacturers will be primary sources for recommended maintenance schedules. These should be integrated into terminal operators overall maintenance plan. Shifting maintenance towards more data based preventative or predictive maintenance rather than time-based intervals should be discussed. Condition of critical components could be monitored in real time. This can reduce unexpected costs and maximize CHE uptime.

Spare parts needs and availability should be discovered. New parts are needed for batteries and charging components. Essential spare parts and lead times for those should be determined. Strong relationships with component suppliers help to ensure timely access to parts. New specialized tools might be needed for working on electric CHE. All maintenance personnel shall receive comprehensive training in high voltage safety procedures and the proper use of safety equipment.

6.6 Financial planning and risk management

A thorough financial analysis is essential to justify the investment in electrification and secure necessary funding. This can involve developing a detailed Cost-Benefit Analysis (CBA) or TCO model that compares the proposed electrification scenario against the baseline. The analysis must capture all relevant CapEx and OpEx costs. Using realistic assumptions for key variables like future energy prices, equipment lifespans, maintenance intervals and battery degradation rates is important for credible analysis.

External funding sources can be available for electrification and zero emission projects. Terminal operators should proactively research and pursue a diverse range of funding opportunities. Specific eligibility criteria, application deadlines and reporting obligations need to be understood before applying. Collaboration with port authorities or participating in regional initiatives can sometimes help in securing funding.

Risk assessment should be conducted before starting the project. Key risk categories include:

- Technological risks: Equipment may not perform as expected, especially common with newer technologies. Rapid technological evolution could lead to early obsolescence. Lack of standardization can create interoperability issues.

- Grid related risks: Insufficient grid capacity, delays in utility upgrades, grid instability or power outages can disrupt operations.
- Financial risks: Higher than expected CapEx or OpEx, failure to secure anticipated incentives, lower than expected operational savings, volatile electricity prices.
- Operational risks: Disruptions during transition phase, inadequate charging leading to CHE downtime, charging logistics causing bottlenecks.
- Workforce risks: Shortage of skillful personnel for maintaining high-voltage systems or electric drivetrains, resistance to change, safety incidents due to insufficient training.
- Cybersecurity risks: Connected charging infrastructure creates vulnerabilities to attacks that could disable chargers, steal data, or impact the grid.
- Stakeholder risks: Resistance from tenants, labor, community groups, lack of coordination among stakeholders.

Understanding the different risks and their connection is important. For example, a delay in grid upgrades directly impacts the project timeline and can jeopardize grant funding deadlines. In a similar manner, the lack of standardization can inflate costs and complicate maintenance. Recognizing these interdependencies allows for a more holistic approach to risk mitigation. At the same time terminal staff should be kept informed about the upcoming changes and how those will affect their roles. Concerns should be addressed and feedback gathered.

7. CONCLUSIONS

7.1 Key takeaways

The imperative for decarbonization within the maritime logistics sector has positioned port electrification as a critical pathway towards achieving environmental sustainability and operational efficiency. For terminal operators, the transition from conventional diesel-powered equipment to electrified alternatives is a big transformation with significant opportunities and considerable challenges.

Achieving long term sustainability and complying with regulatory compliance is a primary driver for port electrification. Electrification addresses increasing pressures from international bodies and national governments to mitigate GHG emissions and improve air quality. Furthermore, evolving environmental regulations and potential carbon pricing mechanisms are likely to make operations relying on diesel more expensive and less competitive. Proactive adoption of electrification can therefore be viewed as a strategic move to futureproof terminal operations and maintain competitive edge.

The complex interplay of infrastructure development and energy management emerges as a central challenge. The successful implementation of electric CHE might require substantial investment in new electrical infrastructure. Determining the optimal placement, capacity and type of charging infrastructure necessitates data driven decision making based on equipment duty cycles, operational workflows and anticipated future demand. Efficient energy management including peak shaving, load shifting and potentially the integration of RES should be one the key priorities in order to minimize energy costs and ensure grid stability.

The transformation of operational processes and workforce skills is a major undertaking. Electric equipment necessitates adjustments to operational schedules and equipment dispatching. Charging times need to be seamlessly integrated into workflows to minimize downtime. Workforce needs to be trained to operate and maintain the new electric equipment in safe way. Neglecting this aspect can lead to safety hazards and delays in the transition process.

The financial viability of port electrification is one the key considerations. The initial capital investment in electric CHE and charging infrastructure can be substantial, often exceeding the cost of their diesel counterparts. While long term operational costs are expected to be lower, securing financing and demonstrating a clear return on investment

are important for adoption. Cost-benefit analyses and researching funding opportunities are key steps during the project planning phase.

7.2 Evaluation of the research

This study offers relevant information for the case company and a framework to support terminal operator's electrification planning. Similar style frameworks have been conducted already but this study focuses more on the planning phase of the project. Utilizing literature sources and knowledge of case company experts, a thorough information package has been gathered that helps in understanding the big picture of green transition in a port environment. The main challenges of terminal operators related to port electrification and emission reduction have been examined. Potential technological solutions were presented after understanding the challenges. Terminal energy consumption and energy management were also discussed. A concept of smart terminal grid was introduced as a solution to balance terminal energy supply and demand.

The main limiting factors for this study were time and scope. Scope included only the imaginary marine terminal that could be generalized to other medium and large terminals. On top of that only the main challenges and proven technologies were researched. Researching also other smaller challenges and emerging technologies could have given a more holistic view of the whole green transition process. Including inland terminals in the research would have broadened the understanding of the whole freight distribution. Literature and informal discussion were used as a data source for this study. If the timeline of the study wouldn't had been so strict, proper interviews with company experts or terminal operators could have given even more viewpoints and up to date data.

7.3 Future research opportunities

Several possibilities for future research emerge from the complexities surrounding port electrification. In-depth studies on the long term economic impacts and TCO of different electrification strategies are needed. Research should incorporate real world operational data, take into account evolving energy prices and technology advancements and provide terminal operators with financial models for decision making. Research could focus also on the smaller terminals to find out if they have different challenges compared to larger terminals.

Optimization of charging infrastructure deployment and energy management systems could be researched. Dynamic charging scheduling algorithms and integration of RES

and ESS within smart terminal grids belong to this topic. Researching strategies for minimizing peak demands and maximizing energy efficiency should continue.

Studies exploring the impact of electrification on terminal operational efficiency and productivity are justified. This research could involve simulation modeling of electrified operations and analysis of the impact of charging times on equipment availability. Optimized operational workflows for electrified fleets could be created.

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