Electrification and Power Demand Management for Container Terminals

A Two-stage Stochastic Power Allocation Optimization for Electrifying Container Terminals Considering Electricity Costs and Uncertain Ship Arrival Time

MSc Mechanical Engineering, Multi-Machine Engineering

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A Two-stage Stochastic Power Allocation Optimization for Electrifying Container Terminals Considering Electricity Costs and Uncertain Ship Arrival Time

by

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Preface

After my bachelor in Mechanical Engineering at TU Delft, I was interested in pursuing logistics and modeling besides just engineering. So I turned to the Multi-Machine Engineering track from mechanical engineering to combine both engineering and modeling principles. My master has been filled with many captivating and interesting courses that the first year flew by quickly. Soon after, I would already be starting bigger projects the following year with a grown interest in logistic problems and courses about optimization, simulation and machine learning. With these interests in mind, I got into contact with the project idea that eventually shaped this thesis, thanks to discussions with Frederik Schulte, Arjan van Voorden, Michelle van Meijeren, and Sophie Ammerlaan. I am happy to announce that this work marks the conclusion of my academic journey at TU Delft.

First of all, I would like to thank the members of my graduation committee: Frederik Schulte, Arjan van Voorden, and Henk Polinder. I Would also like to thank my daily supervisor from TU Delft, Frederik Schulte, for his support, guidance and help with coming to my methodology. I am also grateful for my daily supervisors from Stedin, Arjan van Voorden and Michelle van Meijeren for helping me set up this project and creating a path towards this thesis.

Additionally, I would like to thank Michelle van Meijeren and Çagatay Iris for the many brainstorming sessions and valuable discussions, as well as Timothy Alders and colleagues at Stedin for their input. My gratitude also goes to the terminals in Rotterdam for taking the time to answer my questions and for providing data that formed the basis of my case study.

Finally, I wish to thank my parents for their continuous support and encouragement throughout my studies.

I hope you enjoy reading this thesis.

Ivo Schriemer
Delft, September 2025

Abstract

The transition to more sustainable operations is being widely adapted in order to reduce the green house gas emissions and meet future sustainability requirements. This transition most often utilizes electrification as a means to reduce emissions and utilize renewable energy sources. This transition comes with extra burden on container terminal authorities who have to manage their power demands and transmission and distribution system operators who have to keep up with providing this growing electricity demand.

This comes with extra costs as distribution system operators have to build and maintain a larger network and larger power capacities can not always be ensured for consumers such as container terminal authorities due to grid congestion. To achieve electrification for container terminals these distribution system operator costs as well as electricity costs and a congesting grid should be taken into account. To combat this, this thesis will analyze the electrification for a container terminal with a case study considering these factors.

However, scheduling power demands for container terminals is not trivial as they operate in a very dynamic and uncertain environment. This stochasticity is caused by uncertainty due to for example uncertain energy generation or uncertainty in operations, such as arrival time of ships. To ensure a container terminal has sufficient electric capacity and can manage its power demand for the day-ahead around this uncertain arrival time, a two-stage stochastic power optimization is modeled.

This optimization takes into account the flexible resources which a container terminal could benefit from, such as a battery energy storage system and flexible cooling of refrigerated containers. The charging decisions for the electric yard fleet as well as charging and discharging of battery energy storage system and cooling of reefers are scheduled for the next day. Power such as shore power and crane power for berthed ships which are loading or unloading are considered uncertain due to the uncertainty in arrival and its deviation from the estimated time of arrival will be taken into account.

In this two-stage optimization where the aforementioned uncertain loads are second stage decisions, while decision such as when to charge batteries or cool refrigerated containers are made beforehand and therefore belonging to the first stage decisions. This stochastic two-stage optimization with uncertain ship arrival time is then solved with the progressive hedging algorithm, which decomposes the possible ship arrival scenarios in to individual solvable problems. These solutions are then pushed towards a common decision value through a penalty term.

With this model it is found that with the current electric contracted capacity, full electrification of the port equipment will not be a viable option. The necessary capacity is then optimized considering the flexible resources and electricity pricing. Dynamic electricity pricing will utilize a higher capacity to benefit from the lower electricity prices by charging and cooling at these times, despite the cost for a higher capacity. Despite these higher distribution costs, the total costs for electricity for a dynamic electricity price contract is significantly lower, minimally 23.65 % lower for the same configuration. A Time Constraint Transport Right is also analyzed, which could work for container terminals with many flexible loads, but this does not provide more incentive compared to a regular contracted capacity.

AI Statement

For this Thesis for the course ME54035, I have used Generative AI to:

- Fill in many of my data points into a latex table such as Table A.1, only inserting my own data points from python into the proper layout for a latex table.
- Troubleshoot latex errors and formatting issues of pictures and tables to help achieve the layout I want.

In all cases I have reviewed and corrected the work and remain fully responsible for the content of the report.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AGV	Automated Guided Vehicle
ATA	Actual Time of Arrival
B-AGV	Battery Automated Guided Vehicle
BCHE	Battery Container Handling Equipment
BES	Battery Energy Storage
CHE	Container Handling Equipment
CI	Cold-Ironing
DSM	Demand Side Management
DSO	Distribution System Operator
EMS	Energy Management System
ESS	Energy Storage System
ETA	Estimated Time of Arrival
GHG	Green House Gasses
MPC	Model Predictive Control
PH	Progressive Hedging
PHA	Progressive Hedging Algorithm
QC	Quay Crane
RMG	Rail Mounted Gantry crane
RTG	Rubber Tired Gantry crane
SOC	State of Charge
STS	Ship-to-Shore Crane
TCTR	Time Constrained Transport Right
TSO	Transmission System Operator
VAT	Value Added Tax
YC	Yard Crane

1 Introduction

The objective of container terminals has always been to maximise container throughput as competitively as possible. However, there is a shift towards more sustainable operations as ports as an industry account for 3% of global greenhouse gas (GHG) emissions [72]. In light of these recent changes towards greater sustainability, port authorities will have to take on a new role to include more energy efficient measures and better management of their energy [3]. This can lead to energy savings, improve the green image of the port and provide a competitive advantage. The approach to a more sustainable port has two sides, the generation side and the consumption side.

In terms of energy generation, port authorities can continue to invest in renewable energy generation for their own use, such as wind power or solar energy and the possibility of storing excess energy generated in batteries for later use.

Container terminal can achieve more sustainable operations and reduce greenhouse gas (GHG) emissions by adapting their energy consumption through alternative energy sources, efficiency measures, and better energy management. This can be applied to port equipment by replacing typical diesel fuel powered equipment with electric, hydrogen, or other alternative/bio-fuels. It also involves assessing energy consumption within port operations and minimizing it while still maintaining the high operational throughput a container terminal requires. Additionally, managing available energy in an efficient manner, whether through self-generation, grid electricity, or other fuel sources, ensures more efficient and sustainable power use.

For this transition to more sustainable port operations, electrification is a promising solution [51]. All of the equipment used in container terminals can be or is electrified, from quay cranes, cold-ironing, gantry cranes and reefers to battery powered equipment such as automated guided vehicles. The electrification of cranes and transportation equipment allow for regenerative capabilities for example by lowering containers or regenerative braking, the power train of electric vehicles also has a higher efficiency when compared to the diesel ICE [14]. Furthermore, it also offers a universal solution to manage the energy usage in the port and is also able to use generated renewable energy. Going fully electric however has its caveats, it can introduce large peaks of electricity demand when equipment is simultaneously drawing power. Another problem that arises is the downtime of battery equipment due to charging, as this process still takes significantly longer than simply refueling and will have to be accounted for by either larger batteries or faster charging speeds.

With many businesses opting for electrification this also places a burden on the grid as electricity demand is rapidly increasing and grid operators having to keep up with this rising demand. This thesis proposes scheduling of the flexible loads: reefers, battery energy storage system and charging of battery powered equipment within a container terminal to assess the required demand for a fully electrified container terminal with uncertain ship arrival times. It will also compare fixed and dynamic electricity pricing and distribution system operator fees which are applicable for large electricity consumers in the Netherlands. Additionally, different distribution system operator contracts which are available in the Netherlands will be discussed and implemented.

1.1. Problem description

As electrification is one of the main adapters for ports to switch to more sustainable energy usage, partly due to the increasing implementation of renewable energy and electric alternatives to the original fossil fueled equipment. This transition does require significant investments for businesses and grid operators to make this switch. It also proposes new challenges for port authorities to manage their power demand more accurately, compared to previously diesel based operations. This makes the logistic operation more complex due to the additional energy-logistic coupling, especially when accounting for uncertainty in operations or uncertain renewable energy generation.

The electrification is currently happening at such a fast pace that the grid is becoming congested and demand for larger stations and capacities keep rising. For ports that have little electric infrastructure this is also a big problem, as requests for expansion can be put on hold, while they do not want to stay behind in this transition. So optimizing the existing electrical infrastructure and their own power usage becomes even more important. It is also important to not overestimate the needed capacity as this would give extra costs as well as take up more space in congested grid. Furthermore, DSOs have contracts in place to help mitigate and alleviate peak burdens on the grid by adjusting the capacities on a fixed or dynamic.

While many studies have considered electrification or renewable integration in container terminals, fewer have accounted for the uncertainty of ship arrivals and its impact on flexible loads. This Thesis will schedule the charging and discharging of battery energy storage, cooling of reefers and charging of equipment before the exact arrival time is known. Furthermore, often only the electricity price is being minimized not taking into account the necessary contracted capacity, as an already existing one is assumed, and other fees for distribution and transmission towards grid system operators are often not taken into account. Additionally, these papers use a greater time step for modeling the power demands, but with a smaller time step berth arrival times and stay times can more accurately be modeled, which is especially useful for smaller terminals due to their shorter stay times. It also allows 15-minute fees and day-ahead pricing to be modeled and give a more accurate depiction of the costs. This thesis contributes to filling these gaps by proposing a two-stage stochastic optimization framework to schedule flexible loads, such as: reefers, battery energy storage, and charging of mobile equipment under uncertain ship arrival times. The study also evaluates different electricity pricing schemes and takes into account distribution system operator (DSO) costs and contracts relevant to Dutch container terminals.

1.2. Research

Main question: *How can power scheduling scheduling of flexible loads for container terminal equipment be optimized to minimize electricity and distribution system operator cost and what are the resulting operational and economic impacts for an electrified terminal?*

Sub questions:

1. What is the literature on power demand and management for container terminal equipment?

   To this end the power demand and management of electric tethered and untetherd port equipment are analysed such as cranes, refrigerated containers and battery container handling equipment

2. What are the relevant system operator contracts and costs for electricity consumers such as container terminals?

   An overview has been made of all the relevant fees that container terminals have to take into account as well as listing the potential flexible DSO contracts that container terminals could work with.

3. How can the operations and power demand be modeled, considering all equipment's energy consumption and ship arrival uncertainty?

   Based on the literature and interviews with local container terminals a two-stage optimization approach is formalized accounting for uncertain arrival times of ships. The model considers typical container terminal equipment such as cranes reefers and battery container handling equipment and their energy demands. A battery energy storage device is added to be used to provide additional flexibility of power demand.

4. Can full electrification of container terminal be achieved with limited grid capacity and current working scheme? – Case study

   The full electrification of an examined port will be realized on existing electric contracted capacity and examined whether it would be feasible for such a container terminal to make this transition without needing any extra contracted capacity.

5. How much capacity would be necessary for a port considering full electrification and different operational levels, electricity pricing contracts and dso fees

   The necessary contracted capacity will be optimized along with the optimized two-stage power management, to determine the ideal contracted capacity based on electricity costs and DSO fees.

6. What energy contracts and contracted capacity contracts would be most beneficial for the studied port and could other contract options offered by DSO work for studied port.

   Other relevant capacity contracts found will be examined and compared considering electricity prices and feasibility of operations

1.3. Layout paper

Starting with background information in chapter 2 on literature for electric load management for ports and the electric grid in the Netherlands. Then the gap found in the literature and the proposed model to tackle this problem will be discussed in chapter 3. This model will then be implemented on a case study and an approach to implement this model will be provided in chapter 4. The results for this case study will be provided in chapter 5 along with a discussion about these results. Ending with a conclusion in chapter 6, which gives answers to the proposed research questions.

2
Background

This chapter will provide the background information obtained and used for this thesis. Firstly, background information about the electric loads of ports and current energy management systems in place to deal with these electric loads, both for tethered and untethered equipment will be analyzed. Secondly, the grid in the Netherlands will be discussed and its congested state, resulting from the significant growth in electricity demand over the last few years. The electricity costs and transmission and distribution costs, along with flexible contracts that are being offered will be discussed.

2.1. Port loads

In this section the literature on electrified port equipment and their energy management will be discussed for both tethered equipment, i.e. equipment which is directly connected to the grid, and untethered equipment which are capable of operation without direct electricity supply because of the battery inside this equipment. Firstly, a short introduction will be given on the literature on what has been investigated for the individual equipment relating to the management of electricity loads and then how these loads combine into larger energy management system.

2.1.1. Tethered equipment

This subsection will discuss the container terminal equipment which is directly supplied with electricity such as Refrigerated containers which have to be cooled; Cranes for the lifting and lowering of containers and cold-ironing for ships to replace the power of their generators. These types of equipment have direct impact on power usage as these are connected directly to the grid.

Reefer

Starting with refrigerated containers, also known as reefers, which are use world wide for the transportation of frozen or chilled goods. These containers require a constant power supply to manage the internal temperature and humidity. They typically operate at a set point temperature and have a lower and upper threshold for allowed temperatures to ensure the quality of the product.

Peak power consumption of a typical integral refrigerated container is approximately 10kW, while its average hourly energy consumption is 3-4 kWh [23]. Taking into account the typical maximum reefer power demand and assuming that a port hosts 1000 reefers operating in freezing mode, the peak power demand of the reefers could rise up to 10MW, approximately. Moreover, measurements have shown that under typical weather conditions the internal temperature in a well-insulated reefer increases approximately by 1°C per 9 hours, when it is switched off (ISO 668, [30], [31]). This makes clear that reefers with less stringent temperature ranges can act as flexible loads that can easily shift their power demand in time [28]. Most common method to simulate temperature and power for reefers can also be found in the container handbook [23] and by Kanellos, Volanis, and Hatziargyriou [51], which specify the temperature increase due to the difference between the internal temperature of a reefer and the ambient temperature

$$T(t + \Delta T) = T(t) + (T(t) - T_{amb}) * (1 - e^{-\frac{A*k*\Delta t}{m*C_P}}) \tag{2.1}$$

As can been seen in the equation 2.1, the main influence of the power of the reefers are the set point cooling temperature, the ambient temperature and the mass and the specific heat of what is cooled inside the reefers. The sun intensity could also be taken into account as reefers on the edges of reefer stacks are also effected by this, but for simplicity reasons and to not over complicate this, its often not taken into account. The difference in power demand according to the outside temperature can be seen in Figure 2.1 and the effect of solar intensity in Fig. 2.2.

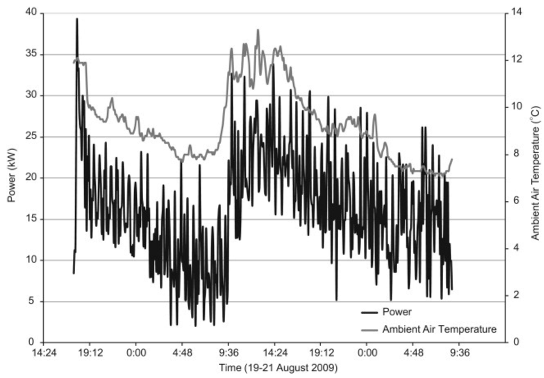

Figure 2.1: Power consumption of ten reefers and ambient temperature [32]

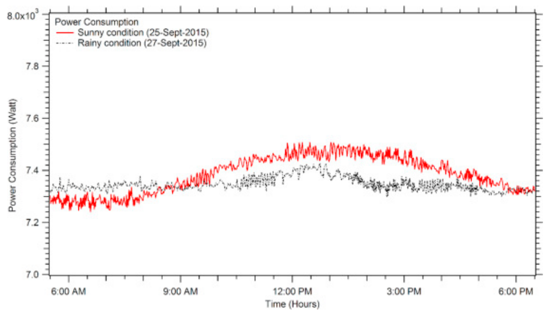

Figure 2.2: Power consumption reefer and solar intensity [15]

Reefers can account for a large sum of the ports energy demand, for some ports around 30-35 % [28]. They could also lead to large peaks in the power profile due to simultaneous cooling at maximum cooling power and should therefore be properly managed to deal with this power allocation.

Cranes

Cranes are essential for port operations as they fulfill one of the main purposes of container terminals, the loading and unloading of ships. There are many types of cranes used in container terminals such as Quay cranes (QC), rubber tired gantry cranes (RTG) or yard cranes (YC) and have unique load patterns, with high peak power during lifting and smaller for gantry/trolley and idle/auxiliary power. In the literature there are multiple ways of dealing with the power associated to lifting containers, as can be seen in Figure 2.3. One approach is by changing the behavior in which the QCs operate by for example avoiding simultaneous lifting with multiple cranes at a time. Results by Geerlings, Heij, and Duin [34] show that the peak demand (and peak-related costs) can be reduced by 50%, with an increase in the handling time of containerships of less than half a minute per hour handling time, which was achieved by reducing the maximum energy demand of all operating STS cranes or by limiting the maximum number of simultaneously lifting STS cranes.

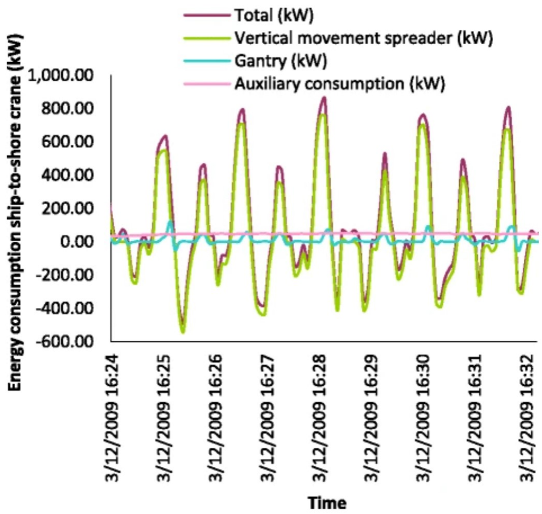

Figure 2.3: Power curve STS crane [34]

Another way of dealing with these high peak loads from cranes is to outfit them with some form of Energy Storage System (ESS). The main energy storage used for these are Battery Energy Storage (BES), Super Capacitors (SC) and Flywheel Energy Storage (FES). These can be implemented both on cranes working with a diesel generator or powered directly by the grid. To give an overview of all the combinations that are made with these energy storage Table 2.1, shows what has been implemented and the resulting energy saving gains or peak shaving achieved by the adaptation of these ESS.

Table 2.1: Overview of ESS applied in cranes.

Source	Equipment, E-Source	BES	SC	FES	GES	Method	Energy/fuel saving	PS
Ovrum and Bergh [81]	Port crane, Diesel GenSet	✓	✗	✗	✗	PID control	30%	-
Niu et al. [78]	RTG, Diesel GenSet	✓	✗	✗	✗	SOC control	57%	-
Hong-lei, Wei, and Jian-Xin [43]	RTG, Diesel GenSet	✓	✗	✗	✗	SOC control	73.9%	-
Kusakaka, Phiri, and Numbi [61]	RTG, Diesel GenSet	✓	✗	✗	✗	Deterministic non-linear optimization	76.04% (cost)	-
Parise and Honorati [83]	STS, Grid	✗	✓	✗	✗	Logic control	57 %	90 %
Kermani et al. [55]	STS, Grid	✗	✓	✗	✗	PSO	-	62 %
Corral-Vega, Fernández-Ramírez, and García-Triviño [25]	RTG, Diesel GenSet	✗	✓	✗	✗	DC/SOC control	21%	-
Antonelli et al. [8]	RTG, Diesel GenSet	-	✓	✗	✗	SOC control, internal algorithm	30-60%	-
Zhao, Schofield, and Niu [121]	RTG, Battery	✓	✓	✗	✗	Double closed-loop PI control	71.5%	-

Continued on next page

Table 2.1 – continued from previous page

Source	Equipment, E-Source	BES	SC	FES	GES	Method	Energy/fuel saving	PS
Bolonne and Chandima [13]	RTG, Diesel GenSet	✓	✓	✗	✗	State machine controller	27% (to other hybrid)	-
Chen et al. [20]	RTG, Diesel GenSet	✓	✓	✗	✗	Game-based	72.8%	88%
Parise et al. [84]	STS, Grid	✗	✓	✓	✗	POT	-	85%
Kermani et al. [52]	STS, Grid	✗	✓	✓	✗	PSO	-	-
Pietrosanti, Holder-baum, and Becerra [87]	RTG, Diesel or Grid	✗	✗	✓	✗	Optimal control	38.47%	-
Kermani et al. [53]	STS, Grid	✗	✗	✓	✗	PSO	-	82.3 %
Pietrosanti, Alasali, and Holderbaum [86]	ERTG, Grid	✗	✗	✓	✗	Fuzzy logic	32%	-
Alasali et al. [6]	ERTG, Grid	✗	✗	✗	✓	MPC	-	28.9%
Alasali, Haben, and Holderbaum [4]	ERTG, Grid	✗	✗	✗	✓	SMPC	-	32.8%
Alasali, Haben, and Holderbaum [5]	ERTG, Grid	✗	✗	✗	✓	Genetic Algorithm	-	28.7%

E-Source: Main Energy Source, BES: Battery energy storage, SC: Supercapacitor, FES: Flywheel Energy Storage, GES: General Energy Storage (Energy storage not specified, general approach), PS: Peak Shaving

Because it is difficult to compare the possible energy savings from all of the implemented hybrid systems, due to the different crane models, different controllers and various sizing of e.g. diesel GenSets before and after hybrid transformation and ESSs equiped. Vlahopoulos and Bouhouras [110] compares the solutions for the RTG diesel and ESS hybrids in a case study and determines an average liter diesel used by the diesel generator per move as the performance indicator.

Papaioannou et al. [82] analysed the energy usage per motor for a RTG and found that during average operations the following energy distribution holds: hoist energy share was 62 %;+ gantry energy share 31 % and 7 % for trolley, idle and losses. The potential energy recovery ability for hoisting in normal operations was 84 % to 89 % and for gantry 4 % to 5 %. For a Ship to Shore crane this absorb potential is up to 90 % [54] with similar characteristics of peak loads from hoisting and lowering as that of the RTG. It is assumed that the energy share for hoisting with STS crane is larger than that of the RTG crane, as the horizontal travel distances are shorter and only the trolley moves over the crane, instead of the total weight of the RTG. From graph in [34] it is assumed that the vertical movement of the spreader accounts for approximately 75 % of the total energy.

To approximate the energy saving from the potential energy recovery of adding a properly sized ESS (capable of peak load), equation (2.2) is used considering the Round Trip Efficiency (RTE). Which is an indicator of how much of the mechanical energy from for example lowering the container and then storing it into the ESS, which can be used again to power the motors. The RTE includes the converter efficiency to transmit the electricity to and from the ESS, including the RTE of the ESS itself. For batteries, SCs and flywheels it is usually transmitted to a DC bus which would require a AC/DC and DC/DC converter steps, however there also exists AC flywheels.

$$Energy\ saving\ RTG = 0.62 * 0.85 * RTE\ +\ 0.31 * 0.04 * RTE \tag{2.2}$$

$$Energy\ saving\ STS = 0.75 * 0.90 * RTE \tag{2.3}$$

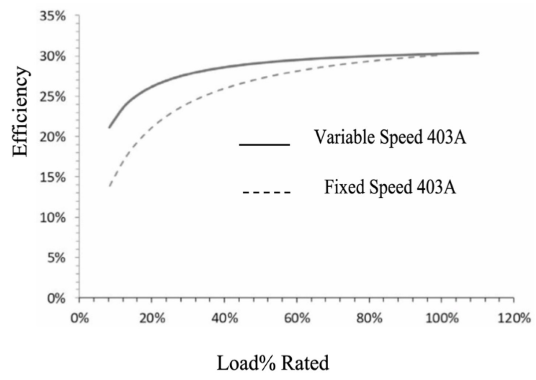

Figure 2.4: Diesel generator efficiency curve [73]

Efficiency	Value
$\eta_{DC/AC}$	0.97-0.98
$\eta_{AC/AC}$	0.95-0.98
$\eta_{AC/DC}$	0.95
$\eta_{DC/DC}$	0.98
η_{BES}	0.60-0.90
η_{SC}	0.90-0.95
η_{FES}	0.85-0.95

Table 2.2: Power converter efficiency [74] and ESS efficiency [76], [18], [75]

Furthermore the extra efficiency from changing the diesel GenSet can also be considered, see Figure 2.1.1, as an addition to equation (2.2) and (2.3). When the total investment cost for the properly sized ESS and the RTE is known, a total cost of ownership can be made to see the benefits of using such a hybrid system.

Crane type	**Li-Ion BES**	**SC**	**FES**
Energy saving RTG, regen	$\sim$ 41 %	$\sim$ 46 %	$\sim$ 44 %
Energy saving STS, regen	$\sim$ 52 %	$\sim$ 58 %	$\sim$ 55 %

Table 2.3: Energy saving from regeneration

To summarize the cranes can adjust their power demands by changing their operational pattern such as avoiding simultaneous loading or limiting the amount of lifting. Or by adapting a form of Energy Storage System which can provide additional power for the lifting of containers, reducing their peaks and storing the energy again during lowering of the containers.

Shore power

Ships arriving at container terminals will also make use of shore power, also known as cold-ironing (CI). This CI is used to supply the ships energy system when its berthed, so the ships generators can be switched off which can reduce the environmental impacts by avoiding the emissions these auxiliary engines create during berth. A typical connection with shore power for ships from the quay side can be seen in Figure 2.5.

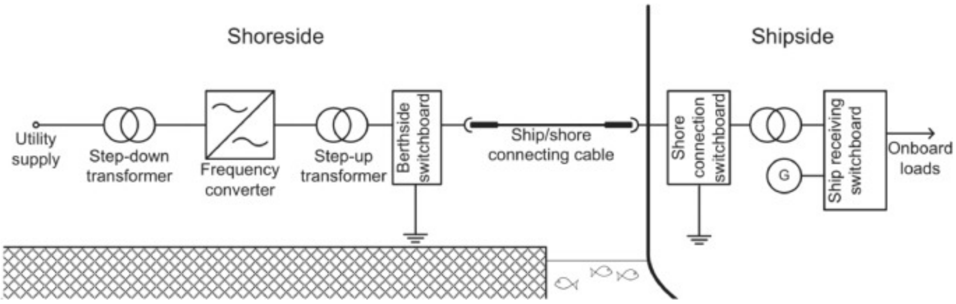

Figure 2.5: Typical connection of shore power [88]

Zero-emission requirements for passenger ships and container ships at berth are also included. The Regulation mandates the use of on-shore power supply (OPS) or alternative zero-emission technologies, from 1 January 2030 in EU ports covered by the Alternative Fuels Infrastructure Regulation (AFIR), and, from 1 January 2035 in all EU ports equipped with OPS facilities [77]. These steps to more sustainable ports as well as the requirements listed by AFIR has set for growth of CI utilization.

The power demand for shore power supply depends on the size and type of ship. For instance cruise ships require more power for the necessities on board, while for example container ships need power to cool the reefers, an overview can be seen in Figure 2.6 of the average power demand some ship types would require. All these ships would need to turn off their auxiliary engines at berth and the power should be substituted by shore power.

Ship Type	GT	Voltage (kV)	Power Demand Average (Peak), MW	IEC/IEEE Standards (Operability); Connectivity		Power Demand drivers/ Operating Profile/ Safety
				LVSC	HVSC	
Oil tankers	<5,000	0.4/0.44/0.69	4 (6)	(80005-3 - annex-D) IEC 60309-5	(80005-1 - annex-F) 62613-2 - annex I	Power demand driven by cargo pumps and auxiliary systems. (majority of oil tankers use steam driven pumps/systems) Hazardous Areas in the ship-shore interface challenge the use of SSE. Critical safety and reliability of SSE during cargo operations.
	<10,000	0.69/6.6/11	6 (8)			
	>10,000	0.69/6.6/11	8 (10)			
Chemical/product tankers	<5,000	0.4/0.44/0.69	6 (9)	(80005-3 - annex-D) IEC 60309-5	(80005-1 - annex-F) 62613-2 - annex I	
	<10,000	6.6/11	9 (12)			
	>10,000	6.6/11	10 (20)			
Gas tankers	<5,000	0.4/0.44/0.69	5 (8)	(not defined) IEC 60309-5	(80005-1 - annex-E) 62613-2 - annex I	Cargo pumps and auxiliary systems drive the load. Critical system reliability during cargo pumping operations.
	>5,000	6.6/11	9 (12)			
Bulk carriers	<50,000	0.4/0.44/0.69	0.5 (0.7)	(not defined) IEC 60309-5	(80005-1 - annex-E) 62613-2 - annex I	Cranes, where fitted, hydraulic systems and hatches operation.
	>50,000	0.69/6.6/11	2 (2.8)			
General cargo	<25,000	0.4/0.44/0.69	1.5 (3)	(not defined) IEC 60309-5	(not defined) 62613-2 – as appropriate	Cranes, where fitted, hydraulic systems and hatches operation.
	>25,000	0.69/6.6/11	3 (5)			
Container vessels	<10,000	0.4/0.44/0.69	1.5 (2)	(80005-3 - annex-C) IEC 60309-5	(80005-1 - annex-D) 62613-2 - annex I	Cranes, where fitted, hydraulic systems, hatches operation, refrigerated containers. Reduced space at quay due to cargo terminal cranes pedestals.
	<50,000	0.69/6.6/11	2 (5)			
	>50,000	6.6/11	4 (6)			
Ro-Pax vessels	<20,000	0.4/0.44/0.69	2 (4)	(not defined) IEC 60309-5	(80005-1 - annex-B) 62613-2 - annex J	Predominant Hotels loads and displacement of vehicle ramps. Short turn-around times at berth.
	>20,000	0.69/6.6/11	5 (6.5)			
Cruise ships	<50,000	0.4/0.44/0.69	4 (4.5)	(not defined) IEC 60309-5	(80005-1 - annex-B) 62613-2 - annex H	Large Hotel load driving the power requirements . Safety and Reliability of SSE is critical for operation
	<100,000	0.69/6.6/11	9 (12)			
	>150,000	6.6/11	18 (20)			
Offshore supply vessel	<5,000	0.4/0.44/0.69	1 (1.5)	(80005/3 - annex-B) [IEC 60309-5]	(not defined) 62613-2 – as appropriate	Load from hydraulic systems, possible refrigerated module connections. modest hotel load.
	>5,000	6.6/11	2 (3)			
Fishing vessels	<5,000	0.4/0.44/0.69	0.5 (0.7)	(not defined) IEC 60309-5	(not defined) 62613-2 – as appropriate	Refrigerated systems and possible hydraulic/cranes operation
	>5,000	6.6/11	2 (3)			

Figure 2.6: Overview of shore power demands per ship from EMSA [source]

2.1.2. Untethered equipment

In the container transportation on the yard side, besides the gantry cranes mentioned in the previous subchapter, there are many pieces of equipment which can be used for horizontal transport of containers. Some of these options are automated guided vehicles (AGV), straddle carriers, reach stackers, empty container handlers, yard trucks and forklifts. These pieces of equipment can not be directly charged through a direct grid connection, as they move freely through the yard area. This means that for electrification these pieces of equipment will have to switch to a battery alternative, which will be referred to as Battery Container Handling Equipment (BCHE). Converting to a battery powered alternative, however comes with the downside that they will have to recharge, which increases there downtime. Battery size and charging speeds are also limited, which poses a challenge for heavy industrial vehicles which have large power demands. For example the straddle carrier and the reach stacker both have the possibility to lift full containers, which increases their power demands significantly.

In the literature the problem of charging and logistic coupling is being tackled for the AGVs. For the horizontal transport between the quayside and yard side in large container terminals the Automated Guided Vehicle (AGV) is mostly used. Similar to the batteries and ESSs discussed in the previous section the AGV when shifted to a Battery-AGV (B-AGV) could also benefit from regenerative energy by reclaiming the kinetic energy through braking ([39]). However, as these batteries are not connected to a power supply during operations, the B-AGVs must also be able to operate for long periods of time and/or have short recharge times so that the B-AGV can be operational again. For a long time, this was not feasible or economically viable due to insufficient battery performance. Bian et al. [11] noted that the new upcoming battery technology could enable the use of electric AGVs in automated container terminals in the future.

The potential for the B-AGV was assesed and the economic viability was optimized. It was found that electric mobility is economically beneficial in container terminals because the charging and maintenance costs of a B-AGV fleet are significantly lower than their diesel counterpart, which can compensate for the higher investment costs of charging infrastructure and spare batteries ([93]). Furthermore it was found that using their controlled charging strategy which used a BSS (battery swapping station) the economic efficiency could be increased even further, as can be seen in Figure 2.7.

With this possibility to transition to B-AGVs, many papers have researched this topic to come up with viable charging strategies and scheduling methods within container terminals to minimize B-AGV downtime. In these papers, two main strategies for implementing and charging the B-AGVs emerge: Charging stations for fixed batteries and battery swapping stations for removable batteries.

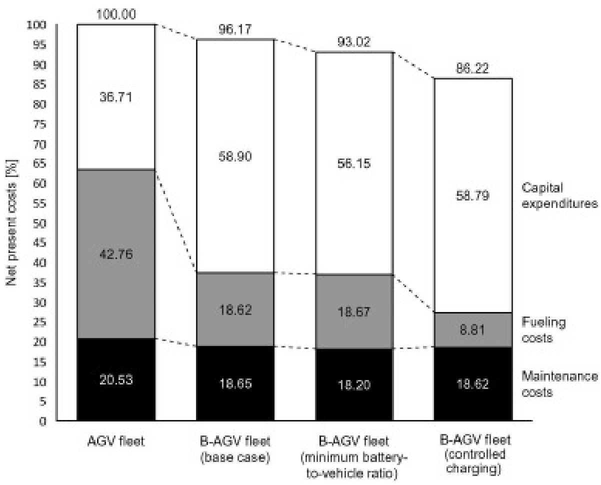

Figure 2.7: Economic viability AGV ([93])

To determine the optimal configuration of the charging stations and B-AGVs, Ma, Zhou, and Stephen [67] made a discrete event simulation model to compare the performance of a decentralized or centalized scheme and a conservative or progressive charging policy. From the results it was determined that the decentralized layout, which are spread out charging locations, and a progressive charging policy performed best.

Due to the dynamically changing environment in which the B-AGVs have to operate, which has a negative on the performance of the B-AGV scheduling problem, Gao et al. [33] proposed a digital-twin based decision support to improve the scheduling efficiency in these complex scenarios. With recent technology allowing for faster charging, Li et al. [64] investigated CS with fast charging capabilities while aiming to reduce the total charging cost and penalty costs such as tardiness.

To improve the efficiency of the ACT, Sun et al. [103] implement a multi-resource collaborative scheduling of quay crane, B-AGV and yard crane to realize the integration of the scheduling plan along with the charging effects for the B-AGV. It then aims to achieve energy saving of the terminal by quantifying the used energy.

Zhou et al. [122] address challenges due to limited charging station capacity and tight vehicle schedules, using a Multiagent Q-Learning approach to optimize recharging decisions. Which showed to perform better than rule-based heuristics and benefits from the consideration of both assignment and scheduling at charging stations.

The disparity in energy consumption between B-AGVs in unloaded and loaded states is adressed by Zhou et al. [123] and allows for more resilient B-AGV scheduling. A mixed-integer programming model is developed with the objective of minimizing energy consumption costs while satisfying AGV battery constraints and is solved with A Large Neighbourhood Search based algorithm. Similarly Song et al. [100] considers more detail of the B-AGV operation with power under loaded and empty conditions as well as the non linearity of battery charging.

Che, Wang, and Zhou [19] approached the B-AGV charging problem as the recharging-considered vehicle scheduling problem (R-VSP) for B-AGVs and aims to minimize the makespan. Limited number of charging stations and tight schedules were considered with scheduling based on the actor-critic multi-agent deep reinforcement learning framework, outperforming distributed-agent deep reinforcement learning and several benchmark heuristics.

Battery swapping:

Battery swapping involves replacing the entire battery from the particular equipment and replacing it with a charged battery inside a BSS. This approach has the benefit that it decouples the energy-logistic relation more. As mentioned previously, Schmidt et al. [93] implemented the BSS to asses the total cost of ownership for implementing an ACT and B-AGVs with this approach. It also implements a controlled charging strategy with the goal of minimizing the charging costs by charging the batteries in the BSS at moments with low electricity prices, which proved to be a more cost efficient method.

Xiang and Liu [113] implemented both the CS and Battery Swapping Station approach for battery recovery of the AGV into a Semi-Open Queuing Network (SOQN). The different strategies were investigated by comparing annual cost and results show that the BSS performs better than the CS strategy unless the price of the spare battery is very high.

A speed control strategy was developed by Yang et al. [116] that considers the traffic environment of the terminal with the aim of energy conservation and emission reduction and the BSS's limited handling capacity is modeled to avoid congestion. Yang, Hu, and Jin [115] also considers the limited handling capacity at the BSS. Zhou et al. [124] expanded on the integration of a BSS with the aim for co-optimization of both operation and energy for B-AGV. Minimizing both the makespan of B-AGVs and the maintenance cost of the implemented energy system, using a multi-objective mathematical, which reduced the terminal operation cost significantly.

Due to the heavy logistic environment of ACT, a two-stage stochastic programming model for B-AGV task allocation and battery swapping joint scheduling problem with random tasks in an uncertain environment with double-threshold battery constraint for B-AGVs is investigated by [63].

An integrated scheduling model is created by Li et al. [66] that takes into account different battery degradation for task assignment and battery swap time for B-AGVs, with the aim of minimizing task completion time.

Xiao et al. [114] introduces battery swapping and opportunity charging modes into the B-AGV system and proposes a new B-AGV scheduling problem considering the hybrid mode. This reduced the average number of battery swapping times by 43.48%, and the total costby 7.2%.

Charging constraints:

The papers mentioned in the sections over the charging stations and battery swapping stations implement different constraints for the B-AGVs and the decision whether they should charge or not. To make an overview of the implemented battery constraints and when the B-AGVs are scheduled for charging the papers' strategies will be categorized.

- Charged if depleted: The most common method is to check whether the battery is depleted or has sufficient energy left. So the first category will be charging when the B-AGV can no longer perform another task, so the B-AGV is scheduled to recharge.
- Charged lower threshold reached: The second common option is setting a lower threshold for the SOC or used energy, instead of driving till the battery is depleted, avoiding a high DOD.
- Dual threshold charging: Similarly a dual threshold charging strategy works with an opportunity interval from a higher SOC to a mandatory charging SOC for the B-AGV to be scheduled. This is for example implemented by Gao et al. [33] where the opportunity interval starts when the SOC is below the high threshold of 80% SOC and ends at 20%, after which the mandatory interval starts and charging will be enforced.
- Triple threshold charging: Ma, Zhou, and Stephen [67] proposed a triple interval charging strategy. If the SOC drops below 50% the opportunity interval (checks if CS is idle) starts for the nearest CS, when dropped below 30% the oppertunity interval extends to the nearest 3 CS, followed by mandatory charging when SOC reaches 15%.
- Charging is allowed at all times, but is mandatory when the battery reaches a lower SOC threshold

To give an overview of the papers a Table 2.4 is made with the Author and year; the battery recovery method; their optimization goal; Constraints as listed above and additional battery constraints; the method which was used for the implemented model.

Table 2.4: Overview of battery charging strategies for AGVs

Source	Battery recovery	Objective function	Charging constraints	Method
Schmidt et al. [93]	BSS	Total cost of ownership of B-AGV with BSS	Charged lower threshold reached. Batteries charged at hours with lowest electricity prices, if possible	Simulation
Xiang and Liu [113]	BSS, CS	Optimize the number of AGVs R to match the capacity of QC and YC. Optimal layout design of the yard with the objective of minimizing system throughput time. Optimize task assignment strategy to minimize system throughput time. Which charging strategy is more effective from an economic perspective, with a throughput time constraint.	Charged if depleted. Battery checked after completing task, traveling distance and time taking into account.	Semi-open queueing network model
Ma, Zhou, and Stephen [67]	CS	Minimum number of B-AGVs required for an acceptable waiting time when visiting a CS. Best configuration of CS, how they are distributed. Best recharging policy for charging B-AGVs. Minimum ratio of B-AGVs to Diesel AGVs that achieves similar performance	Triple threshold charging strategy, with upper threshold of 50 % SOC, below this the opportunity charging starts for nearest CS, below 30 % for the nearest 3 CS and mandatory charging below 15 %	Discrete event simulation
Yang et al. [116]	BSS	Speed control strategy that considers traffic and energy conservation/emission reduction. Minimize the CO2 emission cost and penalty costs caused by operational delays	Constraints to ensure B-AGV has sufficient power to travel to battery-swapping station or taks	Mixed integer programming, genetic algorithm
Li et al. [63]	BSS	Minimize the total cost of the B-AGV no-load cost, waiting time cost, task waiting time cost, and tardiness cost	A double-threshold constraint for battery swapping decision-making is adopted	Simulation-based ant colony optimization
Yang, Hu, and Jin [115]	BSS	Minimize the no-load energy consumption of the B-AGVs	Charging when lower threshold is reached	Mixed integer programming, set partitioning

Continued on next page

Table 2.4 – continued from previous page

Source	Battery recovery	Objective function	Charging constraints	Method
Li et al. [64]	CS	Minimize the charging cost of B-AGVs and penalty cost related to makespan for finishing a set of assigned container jobs	Charging when lower threshold is reached. During charging SOC is bounded between maximum and minimum thresholds to avoid overcharging and DOD.	Mixed integer programming, A decomposition-iteration algorithm
Zhou et al. [124]	BSS	Minimize operation and maintenance cost of the implemented energy system and the makespan of B-AGV.	Dual threshold charging. If remaining energy of an B-AGV is less than upper threshold then checks if swapping can be performed before next earliest operation. Else continues normal operation until reaching lower threshold when swapping must be performed	Multi-objective mathematical model, (DMWOA)
Li et al. [66]	BSS	Minimize task completion time	SOC must remain above safety/lower threshold, based on state of battery degradation	Hybrid genetic algorithm, neighborhood search
Xiao et al. [114]	BSS	Minimize the sum of the energy consumption cost and delay cost of the B-AGVs	Opportunity charging with a lower threshold, battery must have sufficient energy left after task to drive to BSS	Mathematical model, adaptive large-neighborhood search
Gao et al. [33]	CS	Minimize the completion time of tasks	Charging when lower threshold is reached when it is depleted. Check If remaining capacity is sufficient for completing current task.	Digital twin
Che, Wang, and Zhou [19]	CS	Minimize the makespan of the transport jobs	Allowed to charge even at high SOC, not allowed to drop below a threshold, batteries are fully charged after charging	Multi-Agent DRL
Zhou et al. [123]	CS	Minimize travel distance of B-AGVs within the planning horizon	Charging when lower threshold is reached. Ensure that B-AGVs travel to the charging area for recharging after completing a task once SOC is below a lower threshold	Mathematical model, Large neighborhood search
Song et al. [100]	CS	Largest AGV spent the shortest time completing all the tasks	Dual charging strategy. Nonlinear characteristics of lithium battery charging is considered. Partial charging for the B-AGVs is allowed	Metaheuristic algorithm
Zhou et al. [122]	CS	Minimize the total job delay in the planning period	Operates between minimum and maximum SOC, not allowed to drop below minimum SOC. When charged the battery is assumed full	Markov decision process model, Multiagent Q-learning

2.1.3. Energy management systems in electrified ports

Ports with electrified infrastructure can manage their loads through energy management systems where Batteries/ESSs powering the equipment, reefers or large stand alone batteries/ESSs offer opportunities in the incentivized management of electricity demand, also known as Demard Response (DR). This can be through the optimization or change of the port's own electrical load, but ports could also play a role for the grid through the energy market. Demand response is the overarching topic that consists of multiple strategies for balancing the power demands on the grid. To achieve this balance there are three different categories for implementing DR [7]:

- DR Incentive Based Program, classical: Direct Load Control programs, see Figure 2.8, and Interruptible/Curtailable Load programs.
- DR Incentive Based Program, market based: Demand Bidding, Emergency DR Programs, Capacity Market, and the Ancillary services market
- DR Price Based Programs: Different pricing schemes

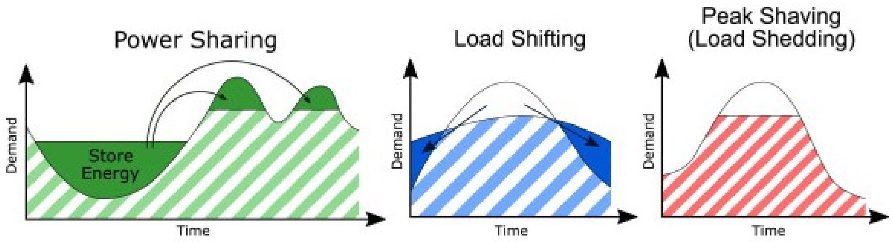

Figure 2.8: Peak shaving methods ([47])

To achieve the balancing of the different loads within a container terminal and deal with their dynamic and stochastic nature many models, simulations and optimizations, are created to recreate the demand. One of the first steps to making a complete model of the container terminal is knowing all the loads and characteristic profiles of the different equipment used and modeling the operations, these can be based off of calculations or measured with smart meters [97], [46]. With this approach the energy demand can be forecasted and different energy management strategies can be implemented by modeling these demands around the operations.

According to Lee Lam et al. [62] their one of the first in the literature to investigate the costs and benefits of employing energy management system in ports. Unloading and loading process of a ship is simulated along with the respective equipments power usage and solar energy. It is found that the implementation of an energy management system is financially beneficial for terminal operators, giving port authorities and researchers incentive to investigate this area further.

To forecast the short-term energy load and their profiles in a CT, Grundmeier et al. [36] used a simulation based approach of the CT including BSS, which has the benefit of decoupling energy use and logistic operation. The benefit of using the BSS in this manner is that it allows for load shifting and peak clipping, see Figure 2.8. A software architecture for demand-side energy integration CTs, leveraging the flexibility provided by the BSS was also developed by Ihle et al. [46]. The simulation of logistics which forecasts the exchange times of batteries and logistic operation, followed by energy demand optimization which determines the optimal battery charging strategy from the forecasted loads. These flexible loads can reduce battery charging energy costs by up to 10%, using day-ahead EPEX-Spot prices and minute reserve auction data. Schmidt et al. [92] and Schmidt, Eisel, and Kolbe [91] examines both the technical feasibility and the commercial viability of several demand-side integration (DSI) programs to utilize the charging flexibility of electric transport vehicles in a logistic facility (BESIC project Altenwerder) to optimize load profiles, control charging based on variable prices or possibly provide minute reserve.

By introducing batteries inside equipment and utilizing ESSs and the flexible cooling of reefers, ports are now able to manage their energy profile even with their operational constraints. This is especially due to the fact that there is a growing amount of predictable load shifting potential due to manipulating the battery charging and discharging cycle [36]. Reefers also have the capability of flexible loads, their frozen goods can for example be cooled ahead if the electricity price is low and delay cooling when the price is high, or when there is limited electricity capacity during heavy operations. This could be counteracted by cooling during off peak hours so that less cooling will have to be done during hours with higher demand.

A larger BES can also be placed in systems storing the renewable energy, which allows for better utilization of renewable energy. These systems, also known as Hybrid Renewable Energy System (HRES), smart-grids or micro-grids for ports usually consist of renewables, shore power and a BESS. There are many more variations possible some including container terminal operations [48] others incorporating Combined Cooling Heat and power [70], or the use of hydrogen [24]. The optimal management, design and sizing of such energy systems can be very challenging due to the uncertainties of renewable resources and operations, system constraints, and multiple design objectives. To this end many studies have investigated the optimal design or management of these systems for a wide variety of ports. Table 2.5 and Table 2.6 aim to give an overview of the literature of what aspects of the port has been investigated, their energy providers and consumers, what has been implemented and which method they used to achieve this. The most commonly modeled aspect for all ports is shore power, as no matter what ship type, ferries, cruises, tankers or container ships are all aiming to diminish their emissions by turning off their auxiliary engines while berthed and are instead supplied with power from cold-ironing, as mentioned in previous section 2.1.1. Starting with an overview of the studies focusing on CI implementation with a BES and possibly renewables in seaports. These studies often focus on the sizing of renewables and BES to be optimally used for the seaport. They will also account for ship arrival times and the CI power demands for the respective ships. BES could also play a role here by providing the peak power necessary for these ships, to reduce the burden on the grid and/or to avoid going over the capacity of the ports electric substation.

Table 2.5: Overview of load management studies in ports

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Wang et al. [111]	Grid, Wind, ESS	CI, ESS	To overcome the dynamic and uncertain nature of seaports and often lack of real energy data, a two-stage optimal framework is proposed. The first stage determines the optimal installed capacity of the sub systems and the second stage models the stochastic characteristics of wind energy and port energy demands to minimize operational costs	Discrete Event Simulation
Hein et al. [41]	Distributed generators, PV, Wind, ESS	CI, ESS	Addresses the uncertainty in the renewable energy sources by modeling the day-ahead operation as a two-stage robust optimization model. The results are used as input parameters for the hour-ahead generation scheduling in the following day.	Two-stage optimization, column and constraint generation algorithm
Sifakis, Konidakis, and Tsoutsos [96]	Grid, PV, Wind, ESS	Port load, ESS	Cycle charging and PS strategies for three different ESSs have been studied, as well as two billing tariffs with PS providing better results and improved energy management and the vandaium redox flow battery being the preferred choice of ESS	Optimization analysis
Bakar et al. [9]	Grid, PV, Wind, ESS	CI, ESS	Design of a hybrid system for a seaport microgrid with optimally sized components. The selected case study is the Port of Aalborg, Denmark.	Hybrid Optimization Model for Electric Renewables (HOMER)
Conte et al. [24]	Grid, PV, Hydrogen, ESS	CI, Electrolyzer, ESS	A model predictive controller is designed to define the best economic strategy to be followed during operations. The control algorithm takes into account the uncertainties of renewable energy generation using stochastic optimization. Components were sized using HOMER	HOMER, Model predictive control
Caprara et al. [17]	Grid, ESS	CI, ESS	Providing CI for cruise ships will require significant power draw from the grid. To avoid installing an extra substation, the possibility of installing a high power and high energy ESS is researched.	Energy Management Simulation Software
Colarossi and Principi [21]	Grid, PV, ESS	CI, ESS	The optimization model proposed aims to provide the best power plant, consisting of PV and ESS, size to support a cold ironing system. The model is based on a life cycle cost approach	Optimization
Darwish [26]	Grid, PV, ESS	CI, ESS	Modular power electronic converter, with an isolated cuk converter as the sub module, for power flow of PV, ESS and shore power	Mathematical analyses, Simulation, Prototype
Vakili and Ölçer [107]	Grid	Ferries, CI, ESS	The Philippines is aiming to significantly reduce its carbon footprint by 75% by 2030 as part of its Nationally Determined Contribution. One step in this process is making its domestic ferries emit zero emissions. To this end, the use of electrified and battery powered vessels is being explored with a life cycle analysis	Life Cycle Analysis
Tao et al. [104]	Grid, Renewables	AES, CI, ESS	This paper discusses flexible scheduling of All Electric Ship (AES), their ESS and CI to satisfy both the transportation demands and mitigate the burden of charging AES on the grid	Temporal Spatial Dynamics

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Table 2.5 – Continued from previous page

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Buonomano et al. [16]	Grid, PV, CCHP, Biogas production, Ocean energy, ESS	CI, CCHP, ESS	ESS and renewable sources can be designed to be connected to national electricity and natural gas grids and can also include alternative fuels, thermal energy networks and different biomass fluxes. Energy demands of nearby towns and port infrastructure, as well as CI power supply are also included in the dynamic assessments	Constrained optimization
Vakili and Ölçer [108]	Diesel generator, PV, Wind, ESS	ESS	In this study, the potential use of solar and wind energy and diesel generators in different stand alone and grid connected systems for a port in the Philippines were assessed	HOMER
Abu Bakar et al. [2]	Grid, PV, ESS	Ferries, CI, ESS	Two-stage energy management for CI of short berthing ferries with BES and solar energy. Where the first stage sizes the PV, BES and CI installation and the second stage optimizes the operations	Two-stage optimization
Binot et al. [12]	Grid, PV, ESS	CI, ESS	Proposes a methodology for optimizing both sizing of PV and storage as well as use of an energy management for a seaport microgrid to minimize costs and CO2 emissions	Bi-objective, Mixed integer Linear programming

Besides modeling the renewables and shore power demand, ports or container terminals can model more of their electric loads to further optimize or forecast their demands. In Figure 2.9 a typical layout for a smart electrical grid is displayed for a container terminal, making use of BES and renewables to power an electrified terminal. Modeling these can be very complex due to the coupling between energy and logistics, size of the terminals and the uncertainties of ports such as uncertain arrival time of ships and uncertain renewable energy supply which can not be perfectly forecasted. With this extra coupling between more modeled resources different studies investigate this electrified port with different aims.

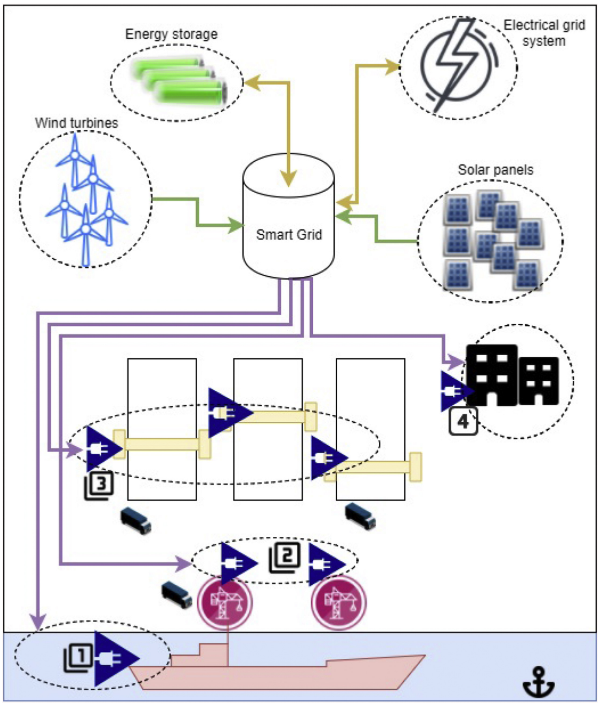

Figure 2.9: A smart grid incorporating renewables, energy storage, reefers, container terminal equipment and shore power [48]

To get better oversight of energy management in more container terminal oriented energy systems another Table is provided. Similar to the layout in Table 2.5, Table 2.6 depicts what the paper's energy generators and consumers were, what they investigated and which methods they used. Battery energy storage in these container terminals can not only be used for optimizing the renewable energy usage, but could also function as peak power control and can also be used for energy arbitrage which is for example done by Iris and Lam [48]. These flexible loads could also be effective under different pricing strategies which could reduce the electricity bill. Again it can be seen that most studies include the CI demand for ships replacing their auxiliary engine usage, however these are mostly container ships which have different demands as depicted in Figure 2.6. Also a wide variety of energy resources and renewables are implemented. However these studies include more loads which are typically present in container terminals such as the cooling of reefers and crane power loads from hoisting containers. These loads account for a large part of the container terminal's total energy consumption and are also responsible for peak power present in ports. Therefore modeling these demands is significant to forecasting energy demands for container terminals. Modeling and managing energy distribution like this also gives port authorities insight how much they can diminish in terms of costs and emissions, but could also relieve the burden on the grid by some extent.

It is also important to account for uncertainties of renewable energy generation and ship arrivals as these influence the energy management of the port drastically. Uncertain ship arrival will not only account for when CI is provided but the cranes assigned to empty or load the ship will also be affected and this way it propagates through the energy-logistic management. The uncertainty for renewable energy generation affect the power available throughout the day even if the BES is able to partially offset this. Therefore these subjects are also addressed in some of these studies.

As previously mentioned it can also be seen that reefers and BES provide flexibility in the container terminals power supply, while CI and QC operations are more or less tied to ship arrival. Unless the berth allocation problem is solved to account both for the uncertainty of arrival and energy-logistic scheduling, which would allow the power demands to be shifted by adjusting the arrival schedule of ships. However if studies would be solving for all these uncertainties and dispatching decisions the complexity of these models would become very large. As well as the fact that every port is different and researchers are interested in different aspects of the port's energy-logistic operation, it results in a wide variety of studies each contributing their own part for an energy aware port.

Table 2.6: Overview of load management studies in container terminals

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Lee Lam et al. [62]	Grid, PV	QC, AGV, RMG	According to paper the first in the literature to investigate the costs and benefits of employing energy management system in ports. Unloading and loading process of a ship is simulated along with the respective equipments power usage and solar energy	Discrete Event Simulation
Manolis et al. [69]	Grid, PV, Wind	Reefers	Distributed demand response application using Multi-Agent System of reefers for improving the voltage in distribution network. Co simulation framework, power system simulator and agent environment	Multi agent system
Kanellos [50]	Grid, Wind	Reefer, PEV	A hierarchical multi-agent system is implemented for the demand response of flexible loads. The port management agent is at the head of operations connected with a wind park agent and followed by a cluster of reefer and PEV agents. Each of these clusters subsequently have agents for each reefer and PEV	Multi-Agent System
Li et al. [65]	Wind, ESS	QC, YC, CI, ESS	Optimizes installation capacity and operation strategy for a container terminal with offshore wind energy using a hybrid renewable energy system	Simulation-based optimization algorithm
Kanellos, Volanis, and Hatziargyriou [51]	Grid	Reefer, PEVs, CI	To combat the large number of decision variables and constraints in large ports, this paper proposes a power management method based on multi-agent systems to maximize the flexibility of power demand. A hierarchical structure is implemented, where each equipment is an individual agent with a cluster agent for the group of equipment and a central port agent	Multi-Agent System

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Table 2.6 – Continued from previous page

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Gennitsaris and Kanellos [35]	Grid, Wind	Reefer, CI	A hierarchical multi-agent system is implemented for the real-time control of flexible port loads. This real-time distributed demand response controls the electric demands with a fuzzy-logic-based system for reefers	Multi-Agent System, Fuzzy Logic
Iris and Lam [48]	Grid, PV, ESS	QC, YC, CI, Reefer, ESS	Port operations and energy management with ESS and renewables with their uncertainties, using a mixed integer linear programming model. Bidirectional energy trading is used between energy sources and ESS allowing for the possibility of energy arbitrage, furthermore different pricing schemes are examined: single price, peak/off-peak price and market price	Mixed Integer Linear Programming
Shi et al. [94]	Grid, Hydrogen storage, Thermal storage, ESS, Wind, PV	QC, YC, CI, Reefer	This paper proposes an optimal operation strategy for the integrated energy-logistics system to minimize the operation cost of a green-port considering a multitude of energy generation options	Mixed Integer Linear Programming
Mao et al. [70]	Grid, PV, Wind, Thermal energy storage, ESS	CI, Thermal energy storage, ESS	An optimization for the multi-energy coordination and berth allocation with the objective of reducing the energy and electricity costs, the dispatch and mooring decision of reefer vessels and cruise ships are established	Mixed Integer Linear Programming
Fang et al. [30]	Grid, Thermal Network	QC, YC, CI, Reefers	An optimization is formulated for the seaport power scheduling, which integrates various logistic demand response methods for cranes' operating speed and ESS as well as reefer areas into an unbalanced multi-phase power network model coupled with a thermal network	Non-Linear, Non-Convex Optimization
Yu, Voß, and Song [119]	Grid	QC, CI	This paper proposes a multi-objective model to optimize the problem of berth allocation and quay crane assignment. The proposed optimization model integrates the decisions on each vessel's berthing position, berthing start and departure time. In this time the duration of using CI and duration of using auxiliary engines is also optimized to minimize the costs of using CI, departure delay and emissions	Multi-objective optimization, Partial optimization Metaheuristic (POPMUSIC)
Yin et al. [118]	Grid, PV, Wind, Fuel cell, ESS	CI, QC, Electrolyzer, ESS	An energy management and scheduling method for the day-ahead planning with intraday adjustments is proposed to reduce the impact of random power during the day using a scenario tree prediction model and stochastic model predictive control	Stochastic Model Predictive Control
Yin et al. [117]	Grid, PV, Wind, Hydrogen, ESS	CI, QC, RTG, Container truck, BES	A day-ahead energy logistic scheduling model considering carbon emission costs is implemented to improve the economic performance and reduce emissions of port operations. A nested bi-layer energy management and capacity allocation method is made to coordinate the imbalance between hydrogen and electricity supply and demand	Model pursuing sampling algorithm
Sarantakos et al. [90]	Grid, ESS	Cranes, CI, Cargo handling equipment, Reefer, ESS	A robust micro grid for multipurpose ports considering uncertainty of arrival time is developed. An optimal power flow method is made for multiple port logistic assets such as cargo handling equipment, reefers, and renewable energy sources. The aim is to minimize the total operation costs while ensuring that grid limits are not violated due to the uncertainty of ship arrivals	Two-stage adaptive robust optimization
Shi et al. [95]	Grid, PV, Wind, Hydrogen, Thermal Storage, ESS	Reefer,ESS	Establishes an optimal strategy for flexible operations of ESSs and reefers with a multistage stochastic optimization model to minimize costs. It takes into account uncertainties of renewables, load demands, electricity prices and ambient temperatures. The first stage is for the day ahead and power is adjusted intraday with BESS, reefers and thermal storage	Multi Stage Stochastic Optimization

Continued on next page

Table 2.6 – Continued from previous page

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Song et al. [99]	Grid, BSS	CI, BSS	To deal with the uncertainty of renewable energy generation, vessel arrival times and lack of real-time adjustability, a two-layer deep reinforcement learning based energy management strategy is proposed, considering berth allocation, energy management and BSS scheduling	Deep Reinforcement Learning

Energy markets

Beside the possibility for load management of the Port, the BES/ESS and reefers can also be used for actively participating in energy markets, such as ancillary services for Transmission System Operators (TSO). Flexibility of port resources can not only be used for its own energy demand but could also alleviate grid burdens with these types of services. With all these flexibility options from the ESS, Battery equipment, Reefers, SMGs and other energy resources there are many opportunities to partake in these services

Virtual power plant (VPP) is a network that manages decentralized energy resources (DER) which include power generation and storage on the consumer side, its implementation could lower emissions and the electricity bill. Kolenc et al. [59] explore the use of a VPP to operate DERs over public internet infrastructure. The study focuses on utilizing the battery stacks of B-AGVs within a container terminal to provide ancillary services to the TSO

One of these ancillary services is frequency containment reserve (FCR), which is a mechanism used by TSOs to keep the electricity grid stable. The main objective of the FCR is to restore grid frequency back to its nominal value following disturbances, which can for example happen when there is a sudden increase in demand or when a provider stops generating energy, which can for example be caused by cloudier weather than expected. When such a disturbance occurs, the FCR comes into action and the reserve power is immediately injected or withdrawn from the grid to balance the mismatch between supply and demand to stabilize the frequency. In the case of ports, BES and battery-charging processes can be initiated earlier or accelerated to withdraw more from the grid, also known as negative reserve, or can be postponed or injected, decelerated or discharged to offer positive reserve.

Holly et al. [42] discuss how the potential of a fleet of battery vehicles can be used to provide FCR in a logistical context, such as a port. For this an artificial neural networks is used to predict the availability of B-AGVs day-ahead, the marketable flexibility is computed with a heuristic approach and checked if plausible in schedule with a simulation. The B-AGVs are continuously supervised and controlled with a multi-agent system and the electric fleet's flexibility is integrated into a larger pool of DER within a VPP.

Kanellos [50] proposes a decentralized demand response method for a port comprising of flexible loads and power generation from a wind park, using a multi-agent system. This proposed method also proved to be efficient in providing ancillary services. Later Kanellos, Volanis, and Hatziargyriou [51] expanded the research further with the previous multi-agent system for reefer and plug in electric vehicles, with the aspect of cold-ironing instead of a wind park. Gennitsaris and Kanellos [35] then combines the previous two without PEVs for a more complete agent based model of a container terminals flexible load which could be used.

The FCR with batteries has the issue that it could lead to faster degradation of vehicles' batteries due to the additional charging cycles. How much this affects the battery life and what degradation costs are incurred depends on its implementation and is evaluated by Harnischmacher et al. [40]. For their setup Cycle-Count Models best represent battery degradation, showing an increase in battery degradation of just 1.36% through the use for FCR. Improving the business case for its implementation.

2.2. The grid in the Netherlands

This chapter will discuss the grid in the Netherlands from its structure depicting the role of transmission and distribution system operators. The current difficulties with the electric infrastructure in the Netherlands. Electricity prices and Stedin DSO fees and flexible contracts.

2.2.1. Structure

The Dutch electricity grid is an interconnected system that transports electricity from power plants, renewable energy sources, and foreign imports to end users. It consists of different voltage levels that together form one national electric network, ensuring that households, businesse, and industries can access electricity reliably. At the highest voltage level, the transmission grid (220–380 kV) is managed by the Treansmission System Operator (TSO) TenneT. Tennet connects the large power plants and stations and neighboruing countries their TSO's on this high voltage grid. One level below this, the distribution grids (110–150 kV down to 0.4 kV) are managed by Distribution System Operators (DSO) such as Stedin, Liander and Enexis as seen in Figure 2.11. These grid system operators are tasked with keeping the grid in balance by matching supply and demand, maintaining and expanding the existing infrastructure and prevent and solve disturbances or outages. The Dutch electricity grid is designed with high reliability in mind. To reduce the impact of failures parts of the network, especially at the high-voltage level, are built with extra redundancy measures by installing double parallel cables, reducing and limiting outages [10].

The ongoing energy transition has significant consequences for the Dutch electricity grid. The increase of renewable energy resources comes with extra uncertainty as predictions for its generation would have to made according to weather forecasts. Furthermore, with the increase in electric demand from electric mobility, electric heating and many businesses transitioning towards full electrification. The grid has to account for all these peak demands. Currently in the Netherlands the increasing demand for additional transmission capacity and distribution is outpacing the speed at which grid operators can expand the power grid. This leads to grid congestion and businesses and consumers are restricted in the expanding of their power usage until the particular grid area is expanded. Figure 2.10 depicts the state of grid congestion within the Netherlands, with red signifying that their is a shortage of transport capacity and orange noting the area is under investigation. Due to restricted pace the transport capacity is able to expand, it is important to optimize the own power usage as much as possible to still continue the path of electrification.

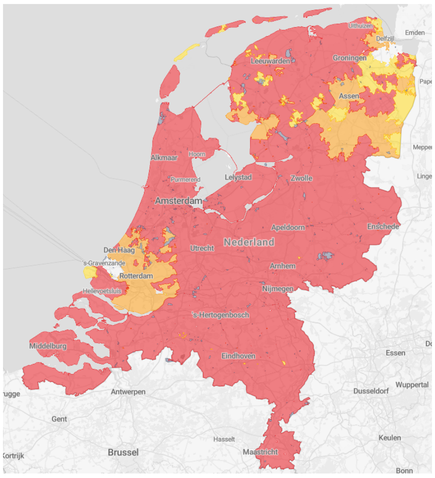

Figure 2.10: Net congestion map of the Netherlands

Figure 2.11: DSOs Netherlands

These challenges require both short-term and long-term solutions. In the short-term, TSOs and DSOs are optimizing the use of existing networks, while in the long term, large-scale investments for the high- and medium-voltage grids are required. However, expansions can take a long time to finalize, thereby the need for optimizing within the current limits of this grid. For the short-term contracts and management of power demands ensure for greater utilization of the grid and reduction in peak demands for stations.

This relates back to container terminals who are currently for a large part adopting electrification as a means to more sustainable operations. A container terminal typically has power demands for cranes, reefers, charging of battery equipment and also shore power or cold-ironing when the ship is berthed. These container terminals can be connected to a DSO at medium voltage level or directly on the high voltage level at the TSO, depending on the power needs for the specific port.

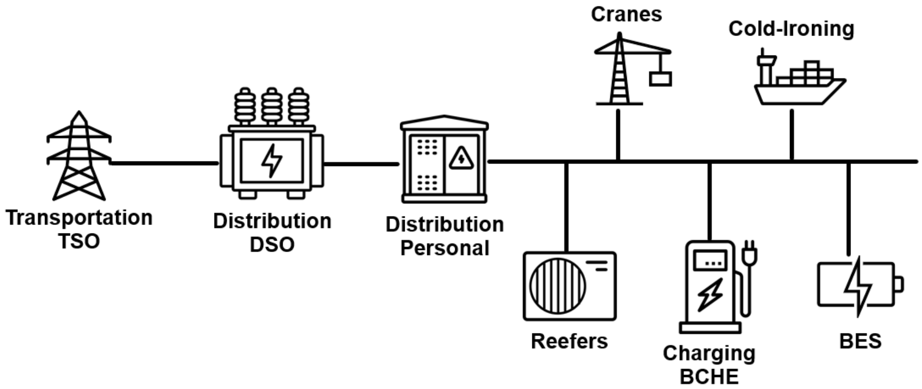

Figure 2.12: Port connected to grid

Large power consumers have multiple options of contracts for their electricity needs. There are options for the purchased electricity, for example fixed pricing or dynamic pricing. Also contracts with the DSO /TSO which give incentive to change your power use to avoid peaks/congestion.

2.2.2. Electricity pricing

The most common form of energy or electricity pricing is a contract with a constant rate per kWh for the entire year. This rate is set in a contract which lasts for around 1-3 years. This has the benefit that customers and businesses have certainty of what their costs will be and do not have to worry about adjusting their power usage behavior through out the day or during energy crisis's with suddenly greater energy prices.

Another form of electricity pricing contracts is dynamic pricing. These prices fluctuate hourly during the day based on supply and demand and are determined on the day ahead market. These prices fluctuate not only hourly but also seasonal effects have large influence, as can be seen in Figure 2.13. In this Figure the average hourly electricity price can be seen per month for the year 2024, with green associating to relatively low electricity prices and red to relatively high prices.

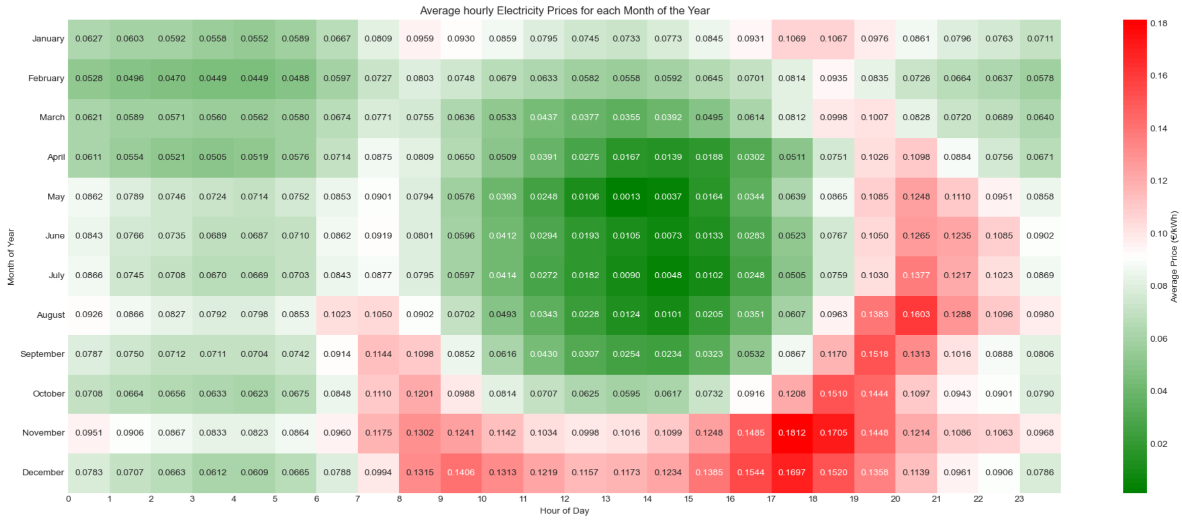

Figure 2.13: Varying hourly prices for 2024 (buy cost without taxes and fees), data from ENTSOE

The seasonal effect seen in Figure 2.13 is for example caused by less solar energy during the winter and heating for households and businesses. There is also significant difference between electricity prices during weekdays and during the weekend which can be viewed in the appendix in Figure A.1 and A.2. Efforts are also being made to decrease the sampling interval from one hour intervals to 15 minute intervals to improve the coordination of electricity throughout Europe. The participating countries can be seen in Figure 2.14 and Figure 2.15. This would mean that instead of having hourly electricity prices, these prices would fluctuate in 15 minute intervals based on supply and demand.

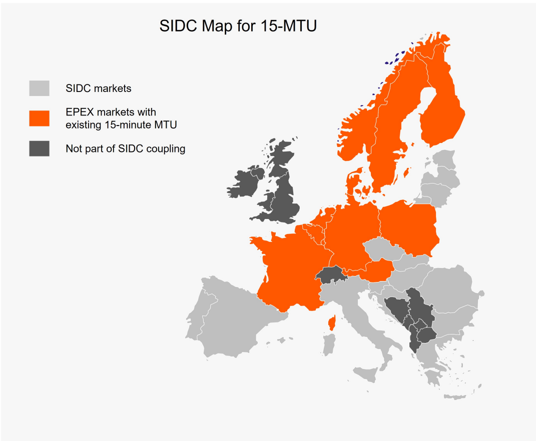

Figure 2.14: Single Intraday Coupling (SIDC)

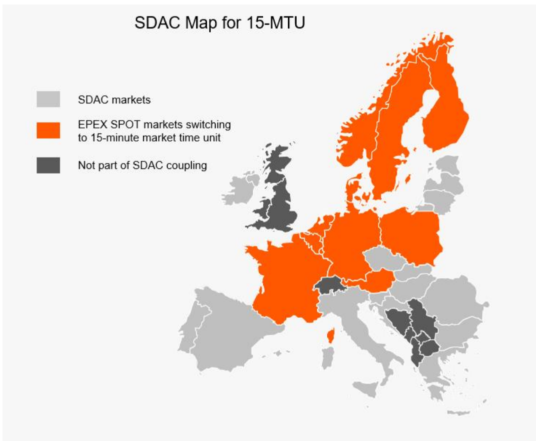

Figure 2.15: Single Day-ahead Coupling (SDAC)

The price consumers pay for electricity with an electricity contract is not just the buy price of electricity at each hour or fixed rate but consists also of other fees and taxes, based on the type of contract and how much energy is consumed. In Table 2.7 the energy tax per kWh can be seen based on the customers total yearly consumption. This

Table 2.7: Electricity tariffs in the Netherlands per consumption range [source belastingsdienst]

Jaar	0–2.900 kWh	2.901–10.000 kWh	10.001–50.000 kWh	50.001–10 mln kWh	>10 mln kWh particulier	>10 mln kWh zakelijk
2024	€ 0,10880	€ 0,10880	€ 0,09037	€ 0,03943	€ 0,00254	€ 0,00188
2025	€ 0,10154	€ 0,10154	€ 0,06937	€ 0,03868	€ 0,00388	€ 0,00321

Furthermore the VAT rate of 21 % is applicable on top of all the associated costs of electricity. To demonstrate the actual price the customers or businesses have to pay the following steps can be used to calculate the total amount per kWh.

1. Buying price of electricity on the day-ahead market.
2. Energy tax per kWh, divided into brackets of the total yearly consumption in kWh.
3. Small free from the energy provider, covering for storage/balancing costs, when buying is done through an energy provider who has to account for fluctuations in energy demand.
4. Tax rate (BTW) of 21% over the sum of the aforementioned costs.

2.2.3. DSO tariffs and contracts

Large electricity consumers with a connection greater than 3x80A have to pay transmission and distribution fees on top of the electricity price. These fees consist of annual fixed charges for infrastructure, as well as variable charges for transmission services. Additionally, different contract options available to large electricity consumers from DSO Stedin will be discussed. This will give more insight to what the total cost will be related to electricity consumption for these larger electricity consumers.

Tariffs Stedin

Starting with the tariffs that all large energy consumers have to pay. As well as paying for electricity, large energy consumers also have to pay grid operators for the infrastructure that provides them with electricity. These fees consist of the following parts:

1. A one time payment for installing the connection.
2. A periodic fee for the connection to the grid that is installed.
3. Variable fees based on the transported power.

Each of these fees can be retrieved from their respective tables which are listed in this section and are Tariffs from Stedin for the year 2025 [105]. An overview of the costs needed for installing the required connection that would be necessary for a Business can be seen in Figure 2.16. This cost is based on the size of the connection required and the required cable length to the needed station per meter. Once this installation is in place these fees are no longer relevant, unlike the fees to maintain this connection.

Aansluitcapaciteit	Aansluitvergoeding in € excl. BTW per aansluiting[1]	Tarief meerlengte in € excl. BTW per meter[2]
> 3 x 80A t/m 3 x 125A	7.100,05	110,00
> 3 x 125A t/m 175 kVA	8.750,00	115,00
> 175 kVA t/m 630 kVA MS met LS-meting	34.002,10	205,00
> 630 kVA t/m 1.000 kVA MS met LS-meting	36.000,00	210,00
> 1.000 kVA t/m 1.750 kVA MS met MS-meting	58.000,00	403,50
> 1.750 kVA t/m 5.000 kVA	330.000,00	519,95
> 5.000 kVA t/m 10.000 kVA	445.000,00	585,10
> 10.000 kVA	aansluittarief o.b.v. voorcalculatorische projectkosten	

[1] *Exclusief de kosten voor een vereiste meetinrichting*
[2] *Als er een verbinding tussen knip en beveiliging van meer dan 25 meter nodig is*

Figure 2.16: One time installation fee for required grid connection (excluding BTW)

The periodic fee for the grid connection is similar to the one time installation fee mentioned before. Figure 2.17 shows the yearly or monthly fee for using the installed connection divided into similar but fewer categories. These fees are associated with the maintenance and upkeep cost for this connection. Lastly there are fees for the transportation services for the installed capacity, consisting of fixed and variable costs.

Aansluitcapaciteit	Aansluitcategorie[3]	In € excl. BTW per jaar	In € excl. BTW per maand
	LS[5]	74,4400	6,2033
> 3 x 80A t/m 175 kVA	Trafo MS/LS	164,3000	13,6917
> 175 kVA t/m 1.750 kVA	MS-distributie	1.455,5000	121,2917
> 1.750 kVA t/m 5.000 kVA	Trafo HS+TS/MS	3.642,0000	303,5000[4]
> 5.000 kVA t/m 10.000 kVA	Trafo HS+TS/MS	16.950,0000	1.412,5000[4]
> 10.000 kVA	TS	Maatwerk	Maatwerk

Figure 2.17: Periodic fee for grid connection (excluding BTW)

As shown in Figure 2.18, the fees based on transported power are divided into multiple components. There is a fixed monthly rate for the contracted capacity category and size (kW), multiplied by the kW size. Another fee is charged for the maximum power used in a 15-minute interval during the month, multiplied by the power used in kW. There are also fees for power used from Monday to Friday, 07:00–23:00, for the 'Dubbel tarief normaal' period, and for the night hours, weekends, and holidays, for the 'Dubbel tarief laag' period. These fees apply to contracted capacities above 51 kW and are not applicable to those above 1500 kW. Lastly, there is a fee for exceeding the power factor to ensure that the reactive power stays within limits.

Transportcategorie	Grens gecontracteerd transport-vermogen[6]	Transportdiensten					
		Vastrecht	Variabele tarieven[11]				
		Transport in € per maand	kW contract in € per maand per kW	kW max in € per maand per kW[7]	Dubbel tarief normaal in € per kWh[9]	Dubbel tarief laag in € per kWh[10]	Blind verbruik in € per kVARh
LS	t/m 50 kW	1,50	1,5500	-	0,0750	0,0460	0,0170
Trafo MS/LS	51 t/m 150 kW	36,75	3,9350	3,1000	0,0198	0,0198	0,0170
MS	151 t/m 1.500 kW	36,75	2,0250	3,1000	0,0198	0,0198	0,0170
Trafo HS+TS/MS reserve	> 1.500 kW	230,00	1,8958	1,8346[8]	-	-	0,0170
Trafo HS+TS/MS	> 1.500 kW	230,00	3,7917	5,3000	-	-	0,0170
TS reserve	> 1.500 kW	230,00	1,5642	1,4365[8]	-	-	0,0170
TS	> 1.500 kW	230,00	3,1283	4,1500	-	-	0,0170

Figure 2.18: Transport fee of power (excluding BTW)

For long term use these variable transport fees are the most relevant when assumed the contracted capacity remains in the same capacity category, as they give the monthly costs for the contracted capacity and the maximum power used in a 15 minute interval based on the transport category, besides the fixed fees based on transportation type. For determining optimal contracted capacity these fees should be taken into account. However, these values are monthly fees so they will be normalized to daily values, to be used in the model later.

Flex contracts at Stedin

Beside the standard transport fee costs there are also flex contracts options available at Stedin which would give incentive for parties to adjust their power by increasing or decreasing their demand or supply [79]. These contracts are different in that they are not continuously fixed power contracts but alter their capacity throughout time or are combined into groups. These contracts aim to reduce grid congestion and resolve disturbance and maintenance, which allows for better utilization of the grid. An overview of the current flexible electricity contracts at Stedin can be seen in Figure 2.19.

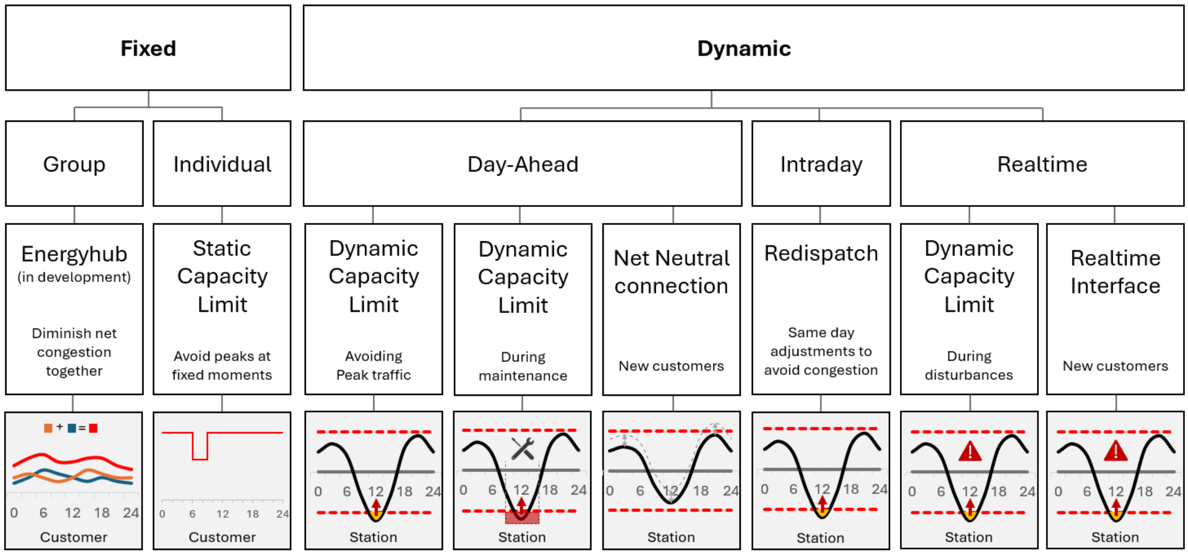

Figure 2.19: Flex contract options at Stedin [79]

Energy hub

Starting from the left of Figure 2.19, we see the fixed contracts. In this context, 'fixed' means that the contract remains the same each day, week, month or year. The Energyhub is a group contract in which neighboring companies or businesses can match their power profiles based on demand and supply, for example to flatten each other's peaks. A requirement for this is that they must be part of the same local grid infrastructure, by for example being on the same medium-voltage circuit. They will have a combined total transport capacity, which will be monitored, while the individual contracted power capacities will not. This allows more flexibility for individuals within this hub and their electricity usage. There is also a cost benefit to this approach, as electricity or other energy sources can be bought collectively, and combined investments can be made. They can for example invest in renewables and energy storage, which can be used within this group. Another benefit of this approach is that Stedin can offer this possibility despite congestion, which can also help to reduce it. This contract option allows for better utilization of the local grid and creates room for businesses and sustainability goals.

Static Capacity Limit

Another fixed contract format is a static capacity limit. This involves reducing a company's contracted capacity at set times during the day. For example, this could be a fixed reduction in contracted capacity during peak hours, such as a 40% reduction from 16:00 to 21:00. A company with flexible power could adjust to help alleviate these peak hours, for which it would be reimbursed.

This could also enable growth outside local peak hours, with an increase in contracted capacity, except during the aforementioned peak hours. However, as more businesses want this opportunity, the electricity available outside peak hours is shrinking. Peak demand differs by region and station, so each business would need to be assessed to determine how much its contracted capacity could be reduced on a fixed basis and at what times. This contract type is suitable for battery, cooling & heating, and charging infrastructure, which can adjust their power. For example, freezers could cool more before the reduction in power, and cool less during it. These characteristics would also make it suitable for the power flexibility of ports. However, it is not possible for the container terminal itself to determine how much and when it should decrease power. The container terminal can only give bounds at what times and the size of the reduction, after which it will be determined wether this is suitable for the station which its connected to. So in this sense, the container terminal cannot opt for such a contract at its own accord, but this should be discussed with the DSO at a regional and station level.

Dynamic Capacity contracts

Similar to the static capacity limit, the dynamic capacity limit reduces capacity at a given block of time. However, unlike the static capacity limit contract, the dynamic capacity limit does not adhere to fixed, predictable time slots. Instead, the dynamic capacity limit time slots will only be known until 08:00 for the following day. This contract helps to avoid peaks for the day-ahead; enables the system to react to possible maintenance at the same station level and can also be implemented in real time to react to and solve disturbances. Day-ahead options for this dynamic contract type could also be suitable for container terminals, provided their power demands are optimized for the day-ahead and flexible port resources can accommodate this reduced contracted capacity. However, managing power in real time would be complex in the energy-logistic context of ports and is usually not implemented for these types of businesses. As with the static capacity limit, the dynamic capacity limit cannot be determined by the container terminal itself, an agreement could only be made with mutual benefit between Stedin and the container terminal.

Other contracted capacity contracts, Alternative transport rights

There are also two additional contract capacities that are not listed in Figure 2.19 and are referred to as alternative transport rights. These two are the Time Constrained Transport Right (TCTR) and the Fully Variable Transport Right (FVTR). The Time Constrained Transport Right is being introduced in the Netherlands and enables businesses to increase their contracted capacity, typically between 00:00 and 06:00. This can supplement the existing contracted capacity. This is especially useful for parties who need to charge their equipment in the morning but do not require extra capacity throughout the day. Container terminals that do not operate on a 24/7 basis could also use this time slot in the morning to charge their battery container handling equipment. However, not every region allows this type of contract due to congestion and is not always available at the same time slots mentioned previously. The amount of additional power is determined by the container terminal, but, as previously mentioned, depends on whether this contract will be made available in this region.

A Fully Variable Transport Right (FVTR) is a type of contract where electricity is only provided when it is available. This creates a large amount of uncertainty and would only be useful for a very small number of businesses. It is usually only offered when there is no more room available on the grid, but the DSO has to provide an option to provide power. This would then have to be supplemented with a different energy source. This would only be a temporary solution, and other contract types should be considered. Therefore, this would not be a suitable contract option for the electrification of a container terminal.

Contracted capacity limitation

What is stopping businesses from spending just a little more to claim more capacity than they require? In the Netherlands, this is called GOTORK ("Gebruik op Tijd of Raak Het Kwijt"), and it is also used in different countries under the name "Use It Or Lose It" (UIOLI). These rules state that, if parties are not using most of their capacity, grid operators are permitted to reduce the contracted capacity [71]. This allows for other parties to use this unused capacity and ensures that parties look more critically at how much contracted capacity they would need.

It also gives grid operators more certainty regarding evaluating expected growth, enabling them to take smaller safety margins and freeing up more space on the grid for all consumers. However, UIOLI cannot be invoked suddenly and requires a strong basis. It only applies to contracts for medium, high or extra-high voltage connections. It can also only be applied in regions with congestion and substantial unnecessary contracted capacity. First, there will be discussions about the reason for the high contracted capacity. If no proper reason is provided for the current or near-future power demand, the contracted capacity will be limited.

This ruling means that businesses will not be able to claim unnecessarily high contracted capacities and will have to investigate how much capacity they really need. This is partly enforced by fees based on contracted capacity as shown in section 2.2.3, which could increase in the future due to growth in electricity infrastructure.

3 Problem formulation

This chapter will highlight the key differences between the implemented model and models used in literature. The mathematical model will then be formalized with an explanation for all the parameters and constraints. Afterwards will be discussed how to solve the formalized two-stage optimization, by utilizing the progressive hedging decomposition method. The first stage decisions and second stage decisions will be specified and explained how the progressive hedging algorithm will find a solution to this problem. Finally, all the assumptions and limitations of the model will be listed which are made.

3.1. Literature gap

To highlight the key differences between the work in this thesis and literature mentioned in chapter 2 about port energy management, Table 3.1 is made. It depicts what is currently lacking or missing in the literature and how this thesis aims to bridge this gap.

What is missing/lacking in literature	This thesis
A significant amount of papers study the energy and logistics coupling for large/automated ports, with little attention going to smaller terminals	In this thesis the model can also be applied for the energy-logistic planning of smaller terminals, with shorter berthing times, for which the time step is appropriately sized
Most papers assume an existing electric infrastructure from the grid with an already properly sized contracted power capacity	The optimal sizing of the electric contracted capacity considering different weather, electricity pricing and operational loads
Many papers use a timestep of an hour or half an hour for the logistic and energy planning. This only allows for example the arrival of ships to be rounded to the nearest hour and only allows for hourly electricity prices. Furthermore it also does not account for the future possibility of 15-minute electricity pricing of day-ahead and intraday electricity costs	This Thesis uses a 15 minute interval in the optimization model, which allows for shorter stay times which are more relevant for smaller ports. And also the opportunity of modeling the electricity costs on a 15 minute bases as well as the DSO costs which are based on 15 minute averages
Most papers only consider fixed, time of use or real time pricing options for their optimization. Not accounting for fees from DSO such as fees for maximum power used, monthly contracted capacity costs etc. Also all studies consider a continuous fixed contracted capacpity without considering contract options where the capacity is limited during certain time blocks	This thesis also considers the fees from DSO and capacity constraint contracts. It considers fees for maximum power used, fees for the contracted capacity, penalty for exceeding the contracted capacity, flat energy tax fees, costs for unbalance and VAT. Also discusses additonial contracted capacity options offered by DSO in the Netherlands.
Most papers assume more real-time knowledge for scheduling of power resources or only have few decision beforehand, for example Sarantakos et al. [90] only considers reefer cooling ahead of uncertain arrival	This thesis uses two-stage optimization for the power scheduling using progressive hedging. BCHE, BES and reefer power scheduled are decided before ship arrival to give a more robust approach to power management

Table 3.1: Literature Gaps and Thesis Contributions

3.2. Mathematical model:

To achieve the goals of this thesis the mathematical model formulation will be provided. In the mathematical model the parameters will be denoted with a small letter and the decision variables will be denoted by a capital letter.

Table 3.2: Name, Description, and Variables

Indices	Parameters	Variables
Sets and indices		
I	Set of BCHE types at the port	$i \in I$
J	Set of Reefer clusters at the port	$j \in J$
V	Set of vessels arriving at the port	$v \in V$
T	Set of time periods in the day	$t \in T$
S	Set of possible scenarios for ship arrivals	$s \in S$
Parameters		
dt	Size of timestep	[h]

Table 3.2 – continued from previous page: Sets, Parameters and variables

t_{max}	Total number of time steps in the model	[int]
$soc^{\min}, soc^{\max}$	Minimum and maximum SOC	[%]
w_i^{lim}	Maximum work rate per BCHE type i	[TEU/h]
$p^{bche,ch}$	Maximum charging speed for BCHE	[kW]
j_i^{bche}	Average power usage of BCHE i per job	[kWh]
b_i^{bche}	Battery size of BCHE i	[kWh]
η^{bche}	Charging efficiency BCHE i	[%]
cs	Number of available charging stations	[int]
m	Number of available employees	[int]
b^{BES}	Capacity of Battery Energy Storage	[kWh]
$p^{bes,max}$	Max charge/discharge power of Battery Energy Storage	[kW]
η^{BES}	Efficiency of BES	[%]
p^{lim}	Power limit from the station	[kW]
n_j^{reefer}	Number of reefers per cluster	[int]
T_j^{des}	Desired temperature of reefer j	[°C]
$T_j^{tolerance}$	Temperature tolerance of reefer j	[°C]
$w_j^{loss}, sur_j, cp_j, m_j$	Thermal parameters for reefer j	
T_t^{amb}	Ambient temperature at time t	[°C]
$T_j^{initial}$	Initial temperature for reefers	[°C]
$p^{reefer,max}$	Maximum cooling power of reefer	[kW]
ep_t	Electricity price at time t	[€/kWh]
ec	Monthly cost of contracted electricity capacity of the DSO	[€/kW]
em	Monthly cost of peak electricity used in a 15 minute interval	[€/kW]
eo	Penalty cost for going over contracted electric capacaity	[€/kW]
cr	Maximum container handling per crane per time period	[Teu]
q	Total number of cranes available	[int]
z_i	Number of battery equipment per type	[int]
$a_{v,s}$	Arrival time of vessel v for scenario s	[t]
k_t	Truck arrivals per time step t	[int]
l_v	Total containers to handle for vessel v	[Teu]
p^{crane}	Maximum power consumption per crane per time unit	[kW]
p_v^{shore}	Shore power usage when vessel v is berthed	[kW]
P^{con}	Positive contracted power capacity	[kW]
$P^{undercon}$	Negative contracted power capacity	[kW]
Variables		
$X_{i,t}$	Amount of BCHE type i charging at time t	[int]

Table 3.2 – continued from previous page: Sets, Parameters and variables

$Y_{i,t}$	Amount of BCHE type i working at time t	[int]
$SOC_{i,t,s}^{bche}$	SOC of BCHE type i at time t in scenario s	[%]
$SOC_{i}^{init,bche}$	Initial SOC of BCHE type i	[%]
$W_{i,t,s}$	Working rate of BCHE type i at time step t in scenario s	[TEU/h]
$P_{i,t}^{charge}$	Charging speed of BCHE type i at time step t	[kW]
$P_{j,t,s}^{reefer}$	Power used by reefer j at time t	[kW]
$P_{t}^{bes,ch}$	Charging power for BES	[kW]
$P_{t}^{bes,dch}$	Discharging power for BES	[kW]
SOC_{t}^{bes}	SOC of BES at time t	[%]
$SOC^{init,bes}$	Initial BES capacity	[%]
$T_{j,t}^{reefer}$	Temperature of reefer cluster j at time t	[°C]
$P_{t,s}^{total}$	Total power used at time t in scenario s	[kW]
P_{s}^{max}	Maximum power used in a 15 minute interval during the day in scenario s	[kW]
$D_{v,s}$	Departure time of vessel v in scenario s	[int]
$H_{v,t,s}$	Containers handled for vessel v at time t in scenario s	[Teu]
$C_{v,t,s}$	Cranes assigned to vessel v at time t in scenarios s	[int]
$B_{v,t,s}$	Whether vessel v is berthed at time t in scenario s	[0,1]
$P_{t,s}^{crane}$	Total crane power usage at time t in scenario s	[kW]
$P_{t,s}^{shore}$	Total shore power usage at time t in scenario s	[kW]

Objective function

The objective minimizes the electricity costs and the fees from the DSO, which are a monthly fee for the contracted capacity and the maximum average power used measured in a 15 minute interval. There is also a penalty for exceeding the contracted capacity.

$$\min \quad \pi_s \sum_{s\in S}(\sum_{t\in T}(P_{t,s}^{total} \cdot ep_t \cdot dt) + (P_s^{over} + P_s^{under}) \cdot eo + P_s^{max} \cdot em + P^{con} \cdot ec) \tag{3.1}$$

Global power constraints

The global power constraint of the port considers the power of cooling the reefers; power of charging the battery energy storage; the discharged power from the battery energy storage; the power of charging the batteries of the battery electric container handling equipment; The shore power of berthed ships and the cranes working on these berthed ships. The electric contracted capacity is enforced by penalizing the power over and under their respective capacities. This is done so the contracted power can also be optimized as well as operating as a more feasible constraint, because stringent constraints might be violated with the chosen decomposition method by a tiny margin.

$$P^{total}_{t,s} = \sum_{j\in J} P^{reefer}_{j,t} + P^{bes,ch}_{t} + P^{bes,dch}_{t} + \sum_{i\in I} P^{charge}_{i,t} + P^{shore}_{t,s} + P^{crane}_{t,s}, \quad \forall t \in T,\ s \in S \tag{3.2}$$

$$P^{total}_{t,s} \leq P^{max}_{s}, \quad \forall t \in T,\ s \in S \tag{3.3}$$

$$P^{total}_{t,s} - P^{con} \leq P^{over}_{s}, \quad \forall t \in T,\ s \in S \tag{3.4}$$

$$P^{under}_{s} \leq P^{undercon} - P^{total}_{t,s}, \quad \forall t \in T,\ s \in S \tag{3.5}$$

The limits for the power usage of these are described in constraint 3.6 for reefer cooling power; 3.7 for BCHE charging power; 3.8 and 3.9 for charging and discharging of BES respectively.

$$0 \leq P^{reefer}_{j,t,s} \leq p^{reefer,max}, \quad \forall j \in J,\ t \in T\ s \in S \tag{3.6}$$

$$0 \leq P^{charge}_{i,t} \leq p^{charge,max}, \quad \forall i \in I,\ t \in T \tag{3.7}$$

$$0 \leq P^{bes,ch}_{t} \leq p^{bes,max}, \quad \forall t \in T \tag{3.8}$$

$$-p^{bes,max} \leq P^{bes,dch}_{t} \leq 0, \quad \forall t \in T \tag{3.9}$$

$$\tag{3.10}$$

Constraints of Ships and cranes

For the ship arrivals and the cranes loading or unloading the ship the following constraints are created. The ships are planned according to a typical working rate at the terminal to determine the length of stay at the port. Ships however can deviate from their estimated time of arrival due to delays or they could be ahead of schedule. Furthermore ports typically have multiple cranes on the quay which could work simultaneously on one ship or could spread over multiple ships.

$$H_{v,t,s} \leq C_{v,t,s} \cdot cr, \quad \forall v \in V,\ t \in T,\ s \in S \tag{3.11}$$

$$C_{v,t,s} \leq q \cdot B_{v,t,s}, \quad \forall v \in V,\ t \in T,\ s \in S \tag{3.12}$$

$$\sum_{t\in T} B_{v,t,s} = D_{v,s} - a_{v,s}, \quad \forall v \in V,\ s \in S \tag{3.13}$$

$$B_{v,t,s} \cdot (t+1) \leq D_{v,s}, \quad \forall v \in V,\ t \in T,\ s \in S \tag{3.14}$$

$$t \cdot B_{v,t,s} + (1 - B_{v,t,s}) \cdot t_{max} \geq a_{v,s}, \quad \forall v \in V,\ t \in T,\ s \in S \tag{3.15}$$

$$D_{v,s} \leq a_{v,s} + \frac{l_v}{cr}, \quad \forall v \in V, s \in S \tag{3.16}$$

$$\sum_{t\in T} H_{v,t,s} = l_v, \quad \forall v \in V,\ s \in S \tag{3.17}$$

$$\sum_{v\in V} C_{v,t,s} \leq q, \quad \forall t \in T,\ s \in S \tag{3.18}$$

$$P^{crane}_{t,s} = \sum_{v\in V} \left(\frac{H_{v,t,s}}{cr} \cdot p^{crane} \right), \quad \forall t \in T,\ s \in S \tag{3.19}$$

$$P^{shore}_{t,s} = \sum_{v\in V} p^{shore}_{v} \cdot B_{v,t,s}, \quad \forall t \in T,\ s \in S \tag{3.20}$$

Constraint 3.11 specifies the handling rate for a ship must be smaller or equal to the assigned cranes and their maximum working rate. Constraints 3.13, 3.14, 3.15 specify that the ship is berthed during its arrival up untill its departure, and can not be berthed before its arrival or after its departure. Constraint 3.16 sets an upper limit on the departure time with the maximum allowed stay time, which is based on the handling rate used for scheduling purposes. Constraint 3.17 denotes that the amount of containers handled by the cranes for each ship must be equal to the amount of containers to be loaded and/or unloaded from each ship. Constraint 3.18 sets the limit for the sum of the assigned crane for each ship to not be larger than the total amount of cranes available. Constraint 3.19 specifies the power used by each crane by dividing it by its max work rate and multiplying by its power when working at its maximum rate. Constraint 3.20 sets the total shore power to be equal to shore power of each ship multiplied by whether they are berthed or not at every time step.

Constraints of battery handling equipment

To model the State Of Charge (SOC) of the batteries equations 3.21 and 3.22 are composed, which take into account at every time step whether they are charging or performing jobs at a certain rate and the resulting gain or loss in SOC. This SOC must stay between the minimum and maximum threshold according to 3.23 to prolong battery life. Furthermore it is assumed that the SOC of the BCHEs start with some capacity, this capacity needs to be the same as which it started with, as can be seen in constraint 3.24.

$$SOC_{i,0}^{bche} = SOC_i^{init,bche} + \frac{P_{i,0}^{charge} \cdot dt \cdot \eta^{bche}}{n^{bche} \cdot b^{bche}} \cdot 100 - \frac{W_{i,0,s} \cdot j_i^{bche} \cdot dt}{n^{bche} \cdot b_i^{bche}} \cdot 100, \quad \forall i \in I, \; t = 0 \tag{3.21}$$

$$SOC_{i,t}^{bche} = SOC_{i,t-1}^{bche} + \frac{P_{i,t}^{charge} \cdot dt \cdot \eta^{bche}}{n^{bche} \cdot b_i^{bche}} \cdot 100 - \frac{W_{i,t,s} \cdot j_i^{bche} \cdot dt}{n^{bche} \cdot b_i^{bche}} \cdot 100, \quad \forall i \in I, \; t > 0 \tag{3.22}$$

$$SOC^{min} \leq SOC_{t,s}^{bche} \leq SOC^{max}, \quad \forall i \in I, t \in T \tag{3.23}$$

$$SOC_{i,|T|-1}^{bche} = SOC_i^{init,bche}, \quad \forall i \in I \tag{3.24}$$

Constraint 3.25 sets the maximum arrival rate of jobs must never be larger than the combined work rate of the BCHEs at every time step. This constraint can be redefined more specifically to specify which BCHE type does what, but for ports with only the same equipment type this constraint holds. Constraint 3.30 ensures that the BCHE can not simultaneously charge and perform jobs at the same time with the integer decision variables. Constraints 3.26 and 3.27 set the limits for the continuous decision variables, by multiplying the integer variables with the maximum charge/work rate. The total amount of BCHEs that can charge simultaneously is limited by the amount of charging stations that are available at that time step, denoted by constraint 3.28. And the amount that can work at the same time is also limited for non-automated ports by constraint 3.29.

$$k_t + \sum_{v \in V} H_{v,t,s} - \sum_{i \in I} W_{i,t,s} = 0, \quad \forall t \in T, \; s \in S \tag{3.25}$$

$$W_{i,t,s} \leq Y_{i,t,s} \cdot w_i^{lim}, \quad \forall t \in T, \; s \in S \tag{3.26}$$

$$P_{i,t}^{charge} \leq X_{i,t} \cdot p^{bche,ch}, \quad \forall i \in I, \; t \in T \tag{3.27}$$

$$\sum_{i \in I} X_{i,t} \leq cs, \quad \forall t \in T \tag{3.28}$$

$$\sum_{i \in I} Y_{i,t} \leq m, \quad \forall t \in T \tag{3.29}$$

$$X_{i,t} + Y_{i,t,s} \leq z_i \quad \forall i \in I \tag{3.30}$$

$$\tag{3.31}$$

Reefer constraints

The Reefers need to maintain a set temperature and are allowed minor fluctuation, but product health is crucial. Constraint 3.32 sets the relation of the internal temperature of the reefer to the loss with the outside temperature and the cooling power. Constraint 3.33 sets the bounds for the allowed temperature fluctuation of the content inside the refrigerated container. Furthermore it is assumed that the starting temperature and end temperature must be at the desired temperature, denoted in constraint 3.34.

$$T_{j,t}^{reefer} = T_{j,t-1}^{reefer} + \left(T_t^{amb} - T_{j,t-1}^{reefer}\right)\left(1 - e^{-\frac{w_j^{loss} \cdot dt \cdot sur_j}{m_j \cdot cp_j}}\right) - \frac{P_{j,t}^{reefer} \cdot dt}{m_j \cdot cp_j \cdot n_j^{reefer}}, \quad \forall j \in J,\ t > 0 \tag{3.32}$$

$$T_j^{des} - T_j^{tolerance} \leq T_{j,t}^{reefer} \leq T_j^{des} + T_j^{tolerance}, \quad \forall j \in J,\ t \in T \tag{3.33}$$

$$T_{j,0}^{reefer} = T_{j,|T|-1}^{reefer} = T_j^{des}, \quad \forall j \in J \tag{3.34}$$

Battery Energy Storage constraints

Similar to the constraints for the batteries of the battery handling equipment, the battery energy storage system has constraints describing the SOC transition in equation 3.35 and 3.36. Charging and discharging the battery has some efficiency loss accounted for both in the charging power increasing the SOC less and discharging decreasing the SOC more than the discharging power. The battery energy storage also starts with some initial stored capacity which needs to be the same at the end, according to constraint 3.37.

$$SOC_0^{bes} = SOC^{init,bes} + \frac{\eta^{bes} \cdot P_0^{bes,ch} \cdot dt}{b^{BES}} + \frac{P_0^{bes,dch} \cdot dt}{\eta^{bes} \cdot b^{BES}}, \quad t = 0 \tag{3.35}$$

$$SOC_t^{bes} = SOC_{t-1}^{bes} + \frac{\eta^{bes} \cdot P_t^{bes,ch} \cdot dt}{b^{BES}} + \frac{P_t^{bes,dch} \cdot dt}{\eta^{bes} \cdot b^{BES}}, \quad t > 0 \tag{3.36}$$

$$SOC_{|T|-1}^{bes} = SOC^{init,bes} \tag{3.37}$$

First and second stage variables

Similar to real life decision making, not every decision can be made real-time. For example it is not certain when exactly the ship will arrive. To account for this uncertainty it is preferred to make decisions that would hold up for all possible scenarios that could come along. The decisions that can be made for the next day can be: when to charge the container handling equipment; when to charge or discharge the battery; when to cool the reefers. To give a better overview of the chosen first and second stage variables that have been chosen Table 3.3 is made. The second stage variables can also be interpreted by the index s under the variables, denoting a changing variable for every scenario.

Decision variable	First stage	Second stage
$X_{i,t}$, Decision whether to charge at t	✓*	✗
SOC_0^{bche}, Battery state of charge of bche at t	✓	✗
$SOC_{t,s}^{bche}$, Battery state of charge of bche at t	✗	✓
$SOC_i^{init,bche}$, Initial Battery charge of bche	✓	✗
$W_{i,t}$, Working rate of bche at t	✗	✓
P_t^{charge}, Charging speed of BCHEs at t	✓	✗
$P_{j,t}^{reefer}$, Cooling power of reefer cluster j at t	✓	✗
$P_t^{bes,ch}$, Charging speed of BES at t	✓	✗
$P_t^{bes,dch}$, Discharging speed of BES at t	✓	✗
SOC_t^{bes}, State of charge BES at t	✓*	✗
$SOC^{init,bes}$, Initial state of charge BES at t	✓	✗
$T_{j,t}^{reefer}$, Temperature of reefer cluster j at time t	✓*	✗
P_t^{total}, Total power used at t in scenario s	✗	✓
P_s^{max}, Max power used in the day in scenario s	✗	✓
$D_{v,s}$, Departure time of vessel v in scenario s	✗	✓
$H_{v,t,s}$, Containers handled from ship v at time t in scenario s	✗	✓
$C_{v,t,s}$, Cranes assigned for ship v at time t in scenario s	✗	✓
$B_{v,t,s}$, Whether ship v is berthed at quay at time t in scenario s	✗	✓
$P_{t,s}^{crane}$, Power used by cranes at time t in scenario s	✗	✓
$P_{t,s}^{shore}$, Shore power used by ships at time t in scenario s	✗	✓

Table 3.3: First stage and Second stage variables

Variables denoted with an asterisk are in reality first stage variables as they are fully defined by other first stage variables, however they are not penalized. For example the temperature of reefers is fully defined by the power allocated to these reefers. Furthermore, if uncertainty in weather prediction were to be added it would also not make sense to set the reefer temperature as a first stage decision.

3.2.1. Decomposition method

Even with relatively few scenarios, solving the extensive form of such an optimization problem is not trivial [89], therefore a decomposition algorithm will be utilized to obtain a solution which will split the extensive form into smaller subproblems by scenario which can be solved significantly faster. Each scenario used will have equal probability of occurring and the expected value will be minimized, as opposed to risk averse or robust calculations of the second stage cost. The first-stage objective cost is known while the second stage cost is an expected value. The reason why this is called a risk-neutral approach is because costs below and above are treated equally, unlike risk averse which minimizes the edge/critical cases and robust which minimizes the worst-case cost, as can be seen in Figure 3.1. There are multiple decomposition methods that can be used to solve the extensive form of the optimization problem. Four common decomposition methods being [89]:

- **Benders Decomposition:** Solves the first-stage problem by iteratively refining the second-stage cost until an optimal first-stage solution is obtained. Splits the problem into a main problem (first stage) and a subproblem (second stage). The main problem is solved step by step, while information from the subproblem is added through cuts until an optimal solution is reached.

- **Stochastic Dual Dynamic Programming (SDDP):** Is used for solving linear multi-stage problems, which breaks the problem into smaller stages and solves them efficiently over time.
- **Dual Decomposition:** Also Utilizes cutting planes and separates the problem into smaller parts that can be solved independently, then coordinates these independent solutions to obtain a final solution
- **Progressive Hedging:** Uses Augmented Lagrangian, proximal method, quadratic penalty. With a penalty approach to push the scenario-based solutions towards each other, iteratively adjusting this penalty until consistency is achieved.

To solve this Two-stage stochastic optimization model the progressive hedging technique will be used, because of the complexity of the model and as the library mpi-sppy [58] has a implementation for this approach. It should be noted that this library also has an approach similar to benders decomposition, however this breaks discrete variables such as binary and integer variables by relaxing them in the second stage. This is not desired as this will result in constraints relating to ship arrival to no longer be valid.

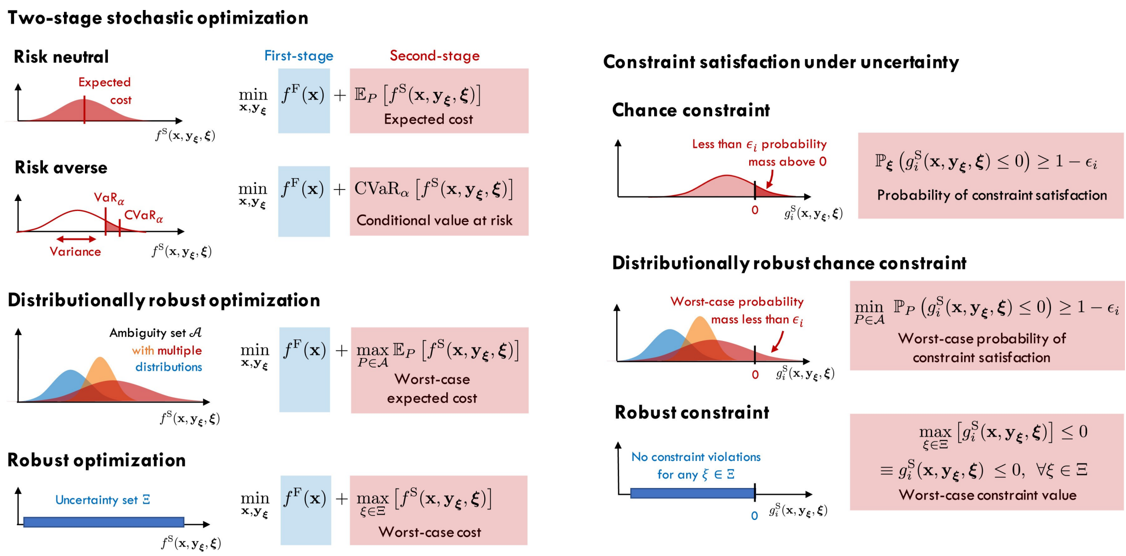

Figure 3.1: Ways of implementing uncertainty modeling [89]

This model implements the risk neutral approach as this gives a realistic expected cost and still enforces the constraints of the contracted capacity on the grid with a high penalty for exceeding this value. This way it minimizes for the average outcome, or expected value, while still maintaining the power constraints.

The progressive hedging algorithm decomposes the problem by scenario and uses a quadratic term to penalize a lack of consensus among the first-stage variables which all should be the same value across all the individual scenarios, i.e. subproblems. Firstly all the individual scenarios are solved, then the average $\bar{x}$ will be calculated of each first stage variable based on the probability of each scenario and then the difference between this average $\bar{x}$ and the first stage variable values x_s across the scenarios will be penalized with a quadratic term, as can be seen in Figure 3.2.

$$\min_{\boldsymbol{x}_s, \boldsymbol{y}_s} \quad \pi_s^F f^F(\boldsymbol{x}_s) + \pi_s^S f^S(\boldsymbol{y}_s) + \boldsymbol{\lambda}_s^\top (\boldsymbol{x}_s - \bar{\boldsymbol{x}}) + \frac{\rho}{2} \|\boldsymbol{x}_s - \bar{\boldsymbol{x}}\|^2 \tag{3.38}$$

$$h^F(\boldsymbol{x}_s) = 0, \quad g^F(\boldsymbol{x}_s) \leq 0 \tag{3.39}$$

$$h^S(\boldsymbol{x}_s, \boldsymbol{y}_s, \boldsymbol{\xi}_s) = 0, \quad \forall s \in \mathcal{S} \tag{3.40}$$

$$g^S(\boldsymbol{x}_s, \boldsymbol{y}_s, \boldsymbol{\xi}_s) \leq 0, \quad \forall s \in \mathcal{S} \tag{3.41}$$

Algorithm 1 The Progressive Hedging Algorithm for Two-Stage SMIPs

1: **Initialization**: Let $\nu \leftarrow 0$ and $w^{\nu}(\xi) \leftarrow 0, \forall \xi \in \Xi$. For each $\xi \in \Xi$, compute:

$$(x^{\nu+1}(\xi), y^{\nu+1}(\xi)) \in \underset{(x,y)\in X(\xi)}{\arg\min}\ c^{\top}x + g(\xi)^{\top}y$$

2: **Iteration Update**: $\nu \leftarrow \nu + 1$

3: **Aggregation**: $\hat{x}^{\nu} \leftarrow \sum_{\xi\in\Xi} p_{\xi} x^{\nu}(\xi)$

4: **Price Update**: $w^{\nu}(\xi) \leftarrow w^{\nu-1}(\xi) + \rho(x^{\nu}(\xi) - \hat{x}^{\nu})$

5: **Decomposition** : For each $\xi \in \Xi$, compute:

$$(x^{\nu+1}(\xi), y^{\nu+1}(\xi)) \in \arg\min_{(x,y)\in X(\xi)} \left\{c^{\top}x + g(\xi)^{\top}y + w^{\nu}(\xi)^{\top}x + \frac{\rho}{2}||x - \hat{x}^{\nu}||^2\right\}$$

6: If all scenario solutions $x(\xi)$ are equal, stop. Else, go to step 2.

Figure 3.2: Ph algorithm

Figure 3.2 gives the steps the progressive hedging algorithm takes until a stopping criterion is met. In this case it stops until all scenario solutions are equal, however this stopping criteria can be user defined as convergence is not always guaranteed for mixed-integer problems [37]. For this model a different stopping criteria is chosen which will be discussed more in depth in the results chapter. It stops when the first stage variables are considered close enough to obtain quality solutions.

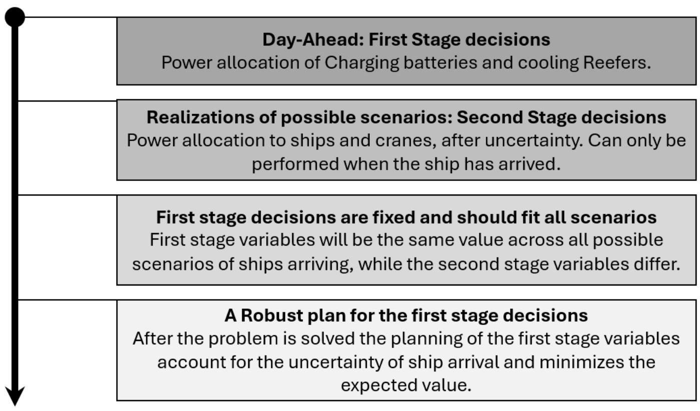

Figure 3.3: Timeline of two stage optimization

The allocation of power during the first stage is further described in Figure 3.3 and Figure 3.4. For the day ahead, considering the electricity price and temperature, the power supplied to the batteries from the equipment and the stand-alone BES, as well as the cooling of reefers, is determined. This accounts for the unrealised power required by ships that need shore power and crane power for unloading or loading of these ships.

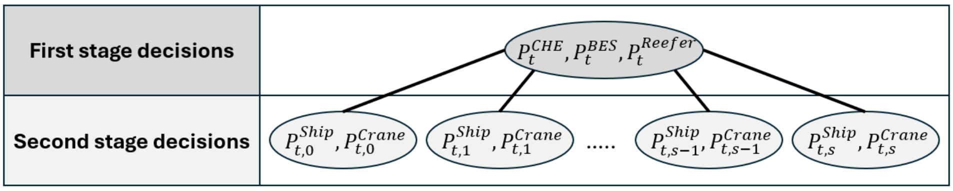

Figure 3.4: First stage and second stage decisions for each scenario s

3.3. limitations

In this optimization approach multiple assumptions have been made considering energy consumption, logistics and power demands. The following list aims to provide all the resulting limitations by making these assumptions

- Shore-power not widely implemented yet, limited information available about the required demand for shore power for large inland container vessels
- Assumptions energy use of crane are based on the handling rate, height, weight of the containers and efficiency and accounting for non vertical lift power. However, this is only an estimation based on its maximum working capabilities. This value can differ for example when lifting empty containers.
- Additionally, peak power effects from the container terminal are not taken into account such as simultaneous lifting of containers. Only the average power demand over 15 minute intervals are considered.
- It is also assumed that when a ship arrives multiple cranes could work on it at the same time and the unloading time decreases linearly. However for example in the port studied it is not always the case that this relation holds.
- Assumption are made for the energy consumption of container handling equipment, as there is limited data available. The optimization does not account for factors such as travel distance, how many containers have to be shuffled per move and how heavy the containers are, again an average is taken to account for these factors.
- Berthing and scheduling assumptions are also made, as every day for these terminals differ. Data is collected for two months to get insight of how these schedules would look like. Based on this data, a few scenarios are created to show what a day might look like when the port is fully electrified.
- Arrival times of ships, because these ports have short stay times sometimes even only unloading or loading a few containers, assumptions will be made that the minimum stay time is equal to the smallest timestep of the model, in this case 15 minutes.
- The reefers are also assumed stationary and effects such as arriving of undercooled reefers or extra cooling before transit are not taken into account. It is also assumed the reefer clusters have to start and end with the same temperature.
- The Reefers temperature constraint and power is aggregated, while in reality each reefer also has to control its temperature individually. However, the power allocated to these reefer clusters does give a depiction of how much power it would require for all these reefers with similar contents in the same cluster.
- Similar to the temperature constraint for the reefers, the SOC for the BCHE is also aggregated for this two stage optimization approach. In reality they all have individual SOCs which they have to stay in bounds for and could no longer work when it drops below a threshold. This would however be too computational and complex to track in this two stage approach as each handling equipment would have to handle the same amount of containers in each scenario. While having a combined SOC is more traceable.
- To reduce the solve time the reefer's temperature constraint and the state of charge constraint for the battery container handling equipment are aggregated. It is an approximation, in reality they

are all individually bounded.

- Temperature and charging speeds effects and degredation of the battery are not taking into account. For example less battery capacity when it is cold. Or Nonlinear charging when reaching the 80 % mark, upon which the charging will be slower.
- Electric loads such as lighting, PEV charging in the parking lot and others are not taken into account. However lighting could easily be added as a base load through an additional parameter. Only the power demands associated to the container terminal are modeled.
- Simultaneous charging and discharging of the battery is not strictly disallowed with for example a binary indicator. When solving single arrival instances this is not such a big problem as a solver can quite easily find the optimal values and determine charging and discharging at the same time is not optimal due to round trip efficiency loss. However, with multiple scenarios and progressive hedging this might lead to undesired behavior of the battery, as will be shown in the results. Adding this indicator would make the model significantly slower and would take too long to obtain results for this thesis. Therefore it is chosen to leave these constraints as is.

4
Implementation

In this chapter the model designed in chapter 3 will be implemented in a case study for a specific port in Rotterdam. It will provide the parameter values used for this case study. How the uncertain arrivals will be generated along with scenario generation for electricity pricing and temperatures

4.1. Information about case

For the implementation of the model, container terminals/depots for the inland waterway transport will be examined. Beside the transport over sea or inland over rail and by truck there is also inland transport utilizing the waterways. The Netherlands and Germany have some of the highest transport in inland waterways in Europe as can be seen in Figure 4.3 and Figure 4.4. The connections that can be reached with these inland container vessels from Rotterdam can be seen in Figure 4.1, extending to Belgium, Germany. Beside the Netherlands and Germany there are also other EU countries, as seen in Figure 4.2, and many other countries using their rivers for the transport of goods also having similar ports. Inland container vessels also require similar ports for unloading as the larger sea going vessels, however on a much smaller scale. For this case study these ports will be studied as they will also make a transition to more sustainable operations in the future, with electrification being one of the main contenders.

Figure 4.1: Inland waterway connections Netherlands from route scanner

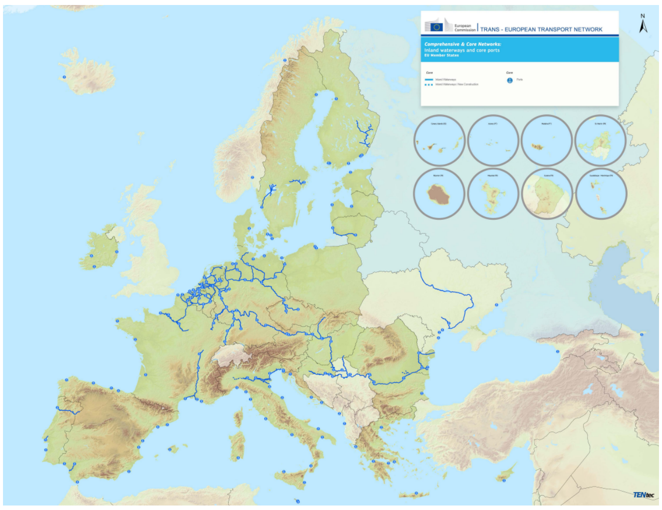

Figure 4.2: Inland waterway connections in Europe [106]

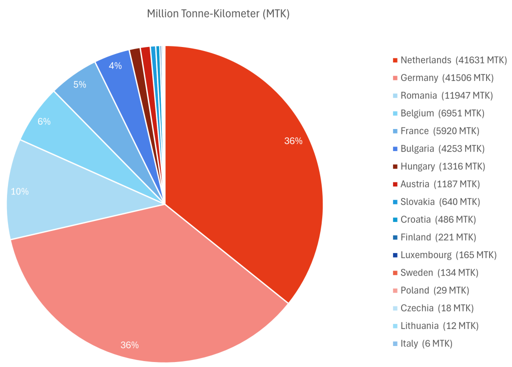

Figure 4.3: Million Tonne-Kilometer (MTK) transported via inland waterways in the EU (Eurostat [1])

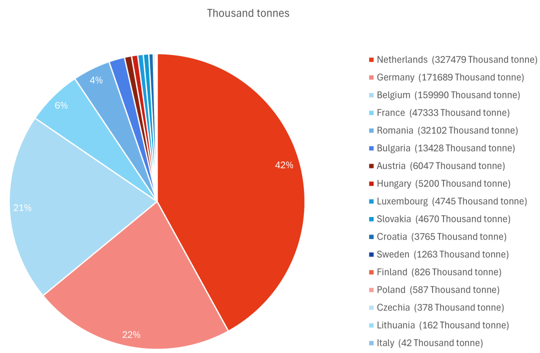

Figure 4.4: Thousand Tonnes transported transported via inland waterways in the EU (Eurostat [1])

4.2. Case study values

To get realistic values for this model interviews have been done with inland shipping ports in the Port of Rotterdam. The values for the case are therefore based on these small container terminals that serve inland container vessels, also known as barges. These terminals have fewer cranes when compared to large terminals in the Port of Rotterdam, they usually have container handling equipment such as reachstackers and empty container handlers. They will also often store refrigerated containers, mostly containing frozen goods. These inland container vessels also do not require a lot of shore power compared to typical container ships. Truck transport is also a significant part of the container logistics for these container terminals, compared to larger terminals which container flow is mostly through shore side.

4.2.1. Ships and shore power

Unlike the power demand for large cruises, container ships or RORO vessels, the demand for shore power of inland shipping vessels is much lower. The most common inland shipping vessels visiting these ports are inland container ships with a lenght of 110 to 135 meter, also known as larger Rhine vessels or inland container vessels. These types of ships are given the CEMT class V or Va for reference, further details of the ship size and classes can be seen in A.

Figure 4.5: Typical inland container ship

The reason these inland container vessels also do not require a lot of shore power compared to typical larger container ships is because they usually only require a little more than a typical household, having the same loads plus power for heating, ac, navigation, lighting, pumps, etc. They travel short distances and hop over the river with short stay times, they do not carry a lot of reefers if at all and they are often pre-cooled for transport so these ships do not have a large quantity of reefer plugs which would increase the shore power requirement significantly. Furthermore, it is rare for inland shipping vessels to connect with shore power during loading and unloading operations due to their often short stay times [102], but it is often used for overnight stays. This is done to reduce emissions and reduce the noise during their stay by turning off their diesel generators. In this study it will be assumed that all ships will make use of the shore power however short the stay time will be, similar to how larger terminals will have to provide shore power for larger container vessels. To give a range of the estimated shore power demand of these inland shipping vessels a Table is made of the values found in literature investigating the shore power and emissions for inland shipping.

Will probably be reinforced more heavily in the feature to reduce emissions further in this sector

Report	**Shore power demand**
CE Delft Verkeersmaatregelen ter vermindering van de NEC-emissies [27]	3.5 kW
CE Delft Stimulering van walstroom [102]	< 3 kW
CE Delft Maatregelen verschoning binnenvaart Rotterdam [68]	5-15 kW Hotel load, 23 kW Other
Elaad quickscan walstroom [60]	5 kW
Clinsh Onshore power supply [22]	6.33 kW, 2 kW
TNO-Rapport, Millieueffecten van de invoering van walstroom voor zeecruiseschepen, riviercruisescehepen en binnenvaartschepen in de haven van Amsterdam [45]	5 kW, 10.5 kW
Future Proof Shipping, Interreg North Sea (2021) [80]	Average 8.5 kW, Max 28.6 kW
Sustainable ships [44]	40 kW

Table 4.1: Reports on shore power for inland container vessels

There is a lack of information about the actual demand of shore power per ship class and cargo for the inland water transport ships. Many studies only estimate an average for the entirety of inland shipping or make basic assumptions, instead of measured values from for example the diesel usage of the auxiliary engines, which is often hard to track. The average inland shipping vessel has a diesel generator onboard with a power rating typically between 50-60 kW [68]. They will not be used at full capacity when moored, resulting in the large variety of assumptions of how much shore power these inland shipping vessels will require. Some assume only the loads necessary for an overnight stay with the bare minimum of shore power demand of around 2 kW, which could also differ for power when loading and unloading. However values for normal operations are harder to get by, so to this end assumptions will also be made. From the values of TNO report, measured values of future proof shipping for a 110m inland container ship and CE Delft's interview with an expert, a value of 10 kW can be assumed as an average continuous load for these larger inland vessels to be on the safe side.

Ship detail overview	
Type of ship	Inland container ship
CEMT Class	Va , VIa
Max containers per ship	Max 450 TEU
Required shore power	10 kW

Table 4.2: Case study: Ship specifications

4.2.2. Reefers

These inland terminals or river terminals also often store reefers. The most common type of reefers here is the 40 foot refrigerated containers storing frozen goods between -18 and -20 degrees. Reefers with a frozen load will require less cooling power compared to cooled or chilled products, at 45 °C a 40 foot refrigerated container will require 4 kW for low temperatures and 7-8 kW for chilled temperatures [23]. These reefers have the following common characteristics for frozen goods/meats.

Refrigerated Containers (Reefers)	
Usual amount of Reefers	50, 40 foot containers
Usual temperature setting	-18/-20 ≈ -19 °C
Temperature tolerance	± 1°C
Outer surface area of container	135.26 m^2 [51]
Mass in reefer	22,300 kg - 26,240 kg ≈ 25,000 kg [51]
Specific heat	2.1 - 3.2 KJ/(Kg °C) ≈ 2.6 KJ/(Kg °C) [57]
Thermal insulation reefer	0.4-0.9 W/m^2 °C ≈ 0.5 W/m^2 °C [28][51]
Maximum cooling power (frozen)	6.0 kW [23] [51]
Ambient temperature	Based on 2024 data

Table 4.3: Case study: Reefer specifications

To account for the variety of goods and their thermal properties and that of the reefers thermal insulation of the reefer which depends on the age of the reefer, average values will be taken between the specified intervals. The specific heat is based on the specific heat values for different meats [57] and is also inside the range used by Kanellos, Volanis, and Hatziargyriou [51]. As mentioned before the thermal insulation of the reefer worsens with age, this value will range for 0.4 for new reefers and 0.9 for old reefers (older than 12 years) [28]. It is assumed that this value will be around 0.5 for slightly used refrigerated containers. Scenarios for weather will be created in chapter 4.2.5 to not assume just a fixed temperature. Finaly, as a last sanity check the power demand will be compared to what is mentioned in the container handbook [23], which specify an average of 4.2 kW for a 40 foot container operating at -21 degrees with an ambient temperature of 45 degrees. Rewriting the reefer constraint in chapter 3 for a single reefer and filling the values from the table and operating temperatures of the container handbook gives equation 4.1 and is fairly similar to the value specified by the container handbook only on a slightly higher end.

$$P_{j,t}^{reefer} = \frac{m_j \cdot cp_j \cdot n_j^{reefer}}{dt} \left(T_t^{amb} - T_{j,t-1}^{reefer}\right) \left(1 - e^{-\frac{w_j^{loss} \cdot dt \cdot sur_j}{m_j \cdot cp_j}}\right) = 4.46\ kW \tag{4.1}$$

4.2.3. Port equipment

To convert the current diesel based equipment to an electric counterpart the following values will be used based on the ports operations and its energy usage. To model the estimated maximum average power for the cranes when working at its maximum rate can unfortunately not be determined by its diesel usage. Instead a simple calculation will be made to estimate its maximum average power usage. For power the maximum container weight will be multiplied by the height of the crane, gravity and the amount of lifts per hour, then divided by time to convert it to kW and also divided by 0.7 (roughly 70% of energy share is from lifting vertically, refer to chapter in the beginning). This results in a rough estimate of 42 kW per hour at its maximum handling rate.

$$E_{avg,max} = \frac{m_{container,max} \cdot h_{crane} \cdot g \cdot lifts}{3600 \cdot 0.7 \cdot \eta_{efficiency}} = 42\ kW \quad (4.2)$$

Furthermore for the particular port which schedules were used, the cranes make use of a stack underneath the crane as a well beside the more common stack in the yard. It can be assumed that about half of the containers handled by the crane will be passed along to a reach stacker as well. This will change the constraint mentioned in the previous chapter only slightly.

Cranes	
Amount of cranes on the quay	2 identical cranes
Safe working load of the cranes	40 tons
Handling rate per crane	18 Containers/h
Estimated max power consumption per crane	42 kW
Energy Storage System for energy capture	None installed

Table 4.4: Case study: Crane values

The container handling equipment in the port will be replaced by battery electric alternatives, for this study a large commercially available battery size of 600 kWh [49] will be chosen because of the extended working hours. The charging speed will have an upper limit, which is the lowest charging speed that is offered for this model with a maximum charging rate of 175 kW. It is assumed that these batteries can charge at any rate, which will alcharging speed. Furthermore, it is assumed that the amount of charging stations will be equal to the amount of battery container handling equipment. This assumption is made because most of these terminal do not operate on a 24 hour basis and the charging will have to be performed manually. Assuming limited amount of charging stations will not allow all container handlers to be charged overnight or over the weekend. Additionally, the SOC will be limited to a lower threshold of 20 % to avoid a too high depth of discharge, similar to what is done in literature in section 2.1.2.

Battery Container Handling Equipment	
Amount of container handling equipment	4 reachstackers
Amount of charging stations	4 stations
Maximum amount of reachstackers working at a time	3 reachstackers
Estimated power consumption for electric variant	60 kW
Battery size available on the market	600 kWh [49]
Maximum charging speed	175 kW [49]
Charging efficiency	95 % [49]
Maximum and Minimum SOC	100 %, 20%
Handling rate of reachstacker	20 Containers/h
Average power used per move	3 kWh

Table 4.5: Case study: Battery container handling equipment parameters

4.2.4. Battery Energy Storage

As there currently is no battery energy storage system installed at these ports, again values will be determined based on literature and what currently is available. The BES is sized at 200 kW / 400 kWh to match the port's current contracted capacity while enabling load shifting and peak shaving for anticipated future electrification. The 2-hour discharge duration provides operational flexibility without exceeding the existing grid connection, this is also to set the bounds for the battery energy storage system constraints. The model can choose any charging and discharging value between zero and the maximum charging and discharging rate, similar to the battery container handling equipment. This also holds for the SOC range used throughout the day.

Battery Energy Storage	
Capacity of BES	400 kWh
Charge & Discharge rate	200 kW
Round trip efficiency	90 % [98]
Efficiency charging/ discharging η^{bes}	$\sqrt{0.9} \simeq 0.95$

Table 4.6: Case study: Battery Energy Storage parameters

4.2.5. Electricity pricing and weather

In addition to the ship arrival scenarios that can occur within a day and within the optimization, different electricity prices and temperature conditions will also be considered. To generate unique weather and day-ahead electricity pricing scenarios, k-means clustering will be performed using the scikit-learn library [85]. The K-means algorithm from scikit-learn aims to select centroids that minimize the inertia, or within-cluster sum-of-squares criterion according to equation 4.3.

$$\arg\min_{C} \sum_{i=1}^{n} \min_{\mu_j \in C} \|x_i - \mu_j\|^2 \tag{4.3}$$

To achieve this, the hourly historical temperature data for Rotterdam in 2024 from the Royal Netherlands Meteorological Institute (KNMI) [56] is used alongside the day-ahead prices of 2024 from ENTSO-E [29]. Only the weekdays will be selected as the specific port usually does not operate during the weekend. The electricity price and temperature are then jointly clustered according to their hourly profile 24-hour arrays, rather than just their average values. Both the temperature and the electricity price are scaled using the robust scalar from sklearn beforehand due to some outliers, especially in the electricity price.

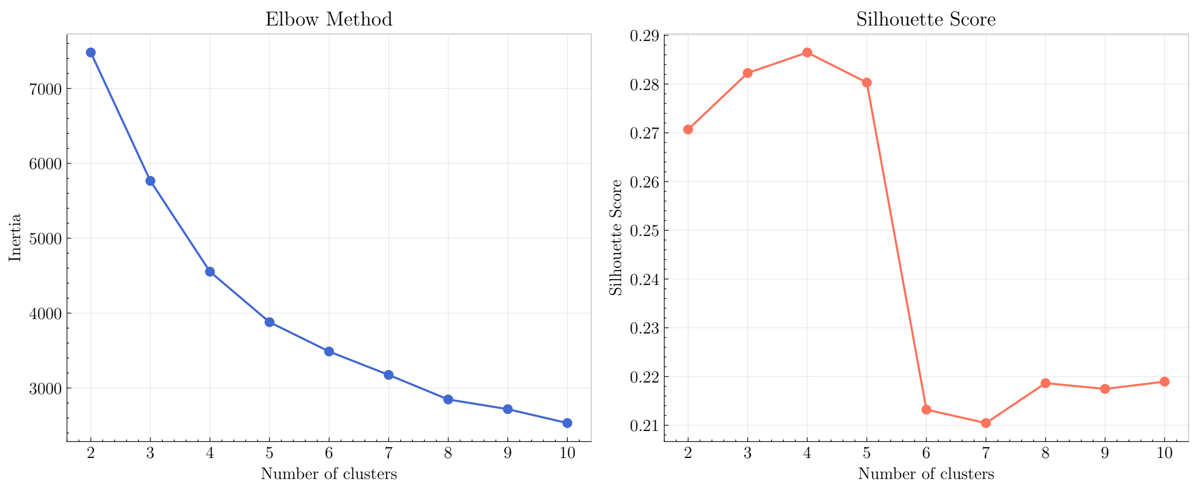

Figure 4.6: Elbow and Silhouette of kmeans clustering temperature and electricity price

A direct relationship is not realistic as the correlation coefficient is -0.234, which indicates a weak correlation relationship as can also be seen in Figure 4.7. These parameters will be used to create different and unique weather and electricity price scenarios beside the usual operations. The amount of clusters is based on the elbow method and the silhouette score as can be seen in 4.6. The chosen amount of clusters is 3 due to the higher silhouette score and the diminishing return of adding more clusters, adding an additional cluster would single out the day with the highest electricity price, which is just one extreme case. In Figure 4.8 the grouped electricity prices and temperatures can be seen, with Figure 4.9 and 4.10 showing which hourly profiles fit into the respective clusters.

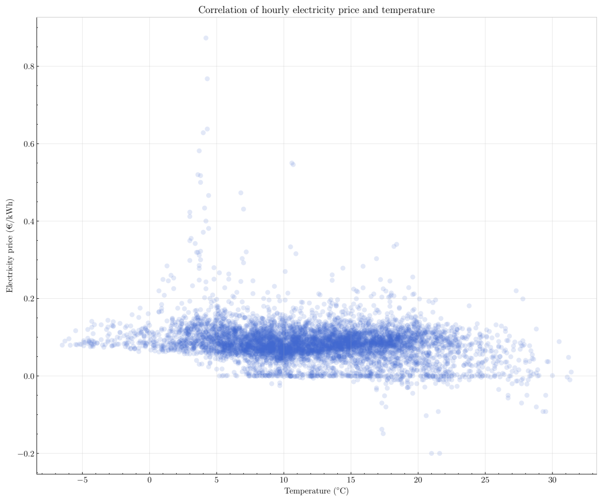

Figure 4.7: Correlation between hourly electricity price and temperature

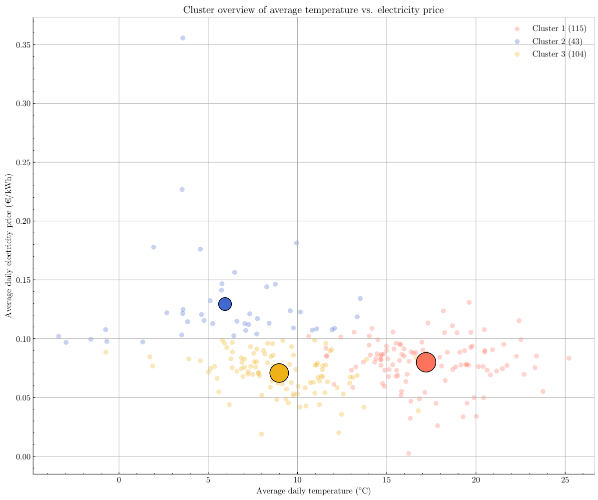

Figure 4.8: Overview of selected electricity and temperature profiles by their average

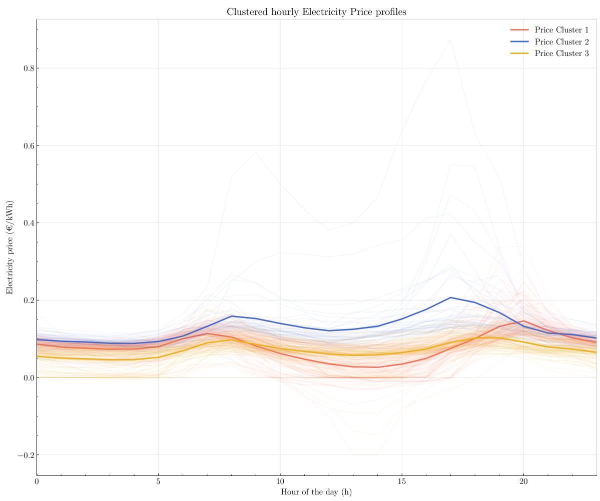

Figure 4.9: Overview of selected hourly electricity profiles

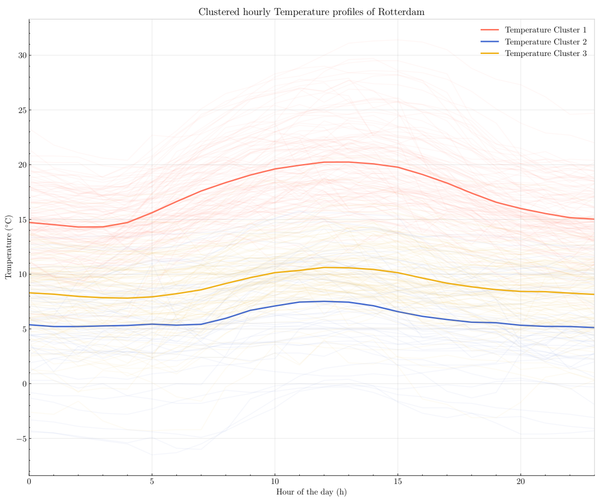

Figure 4.10: Overview of selected hourly temperature profiles

The mean values of the clustered groups are chosen as to not neglect the outliers present in one of the groups for electricity price, as can be seen in Figure 4.11. This choice is less relevant for the other clustered groups in electricity and the respective temperature profiles where the difference between median and mean values are less significant.

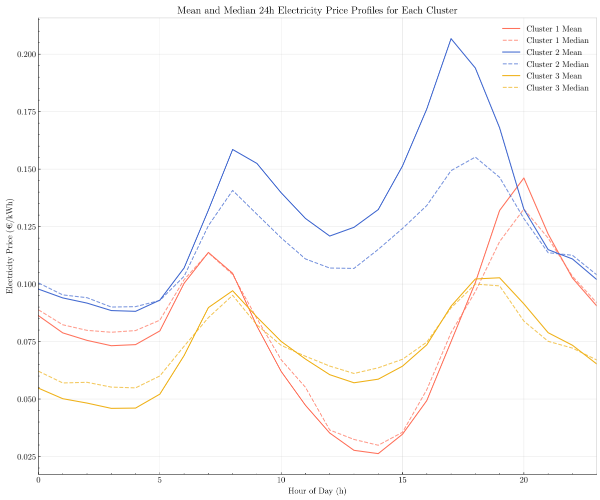

Figure 4.11: Difference between mean and median electricity price values for clusters

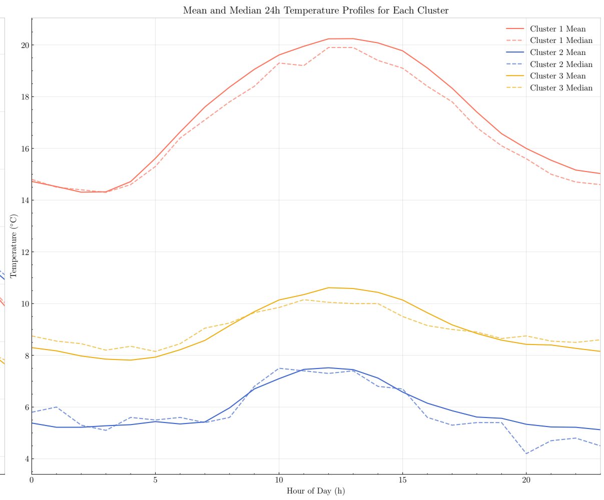

Figure 4.12: Difference between median and mean temperature values for clusters

Figure 4.13: The difference between mean and median values for the clustered groups

To the clustered buying price of electricity additional levies and taxes will be added which are present in the Netherlands, as noted in Section 2.2.3. The three temperature scenarios will also be used for fixed electricity price to compare the difference between the two on an equal basis, resulting in a total of 6 scenarios.

4.2.6. Ship arrivals and uncertainty

From the Estimated Time of Arrivals (ETA) and Actual Time of Arrivals (ATA) gathered at these terminals the delay was calculated. As the gathered data size is not significantly large a distribution will be fitted to remove the roughness. These distributions were fitted within bounded IQR ranges to reduce extremities and outliers and decrease the width of the distribution, which can be sampled for possible ship arrivals. This fitting was performed with the fitter library [31] and scipy distributions [109] were tested with the Sum Squared Error, Akaik Information Criterion (AIC), Bayesian Information Criterion (BIC), and Kolmogorov Smirnov (KS) test. The top 10 best fitting distributions can be found in Table 4.7 and all the fitted distributions can be found in the appendix. It should be noted that the p-values for the KS test however are optimistic or unrealistic as they are performed with the same sample as which the distribution was generated with, which classifies as a type 1 error. The KS statistic value however does give an indication of the performance of the Cumulative Distribution Function (CDF) compared to the data, which gives the maximum distance between the two CDFs of the sampled data and the distribution.

Distribution scipy	Sum Squared Error	AIC	BIC	KS statistic	KS p-value
genhyperbolic	1.5743	451.6611	468.3967	0.0534	0.5694
laplace_asymmetric	1.6141	445.8787	455.9200	0.0498	0.6559
dgamma	1.6355	444.5963	454.6376	0.0626	0.3683
skewcauchy	1.6467	488.0257	498.0670	0.0798	0.1303
foldcauchy	1.6598	457.1731	467.2144	0.0932	0.0486
laplace	1.6719	440.7989	447.4931	0.0617	0.3853
cauchy	1.6787	483.5927	490.2869	0.0672	0.2867
dweibull	1.6815	445.1109	455.1522	0.0605	0.4095
gennorm	1.7837	435.6970	445.7383	0.0667	0.2948
hypsecant	1.9587	433.5909	440.2851	0.0645	0.3332

Table 4.7: Distribution testing

From Table 4.7 it can be concluded that the best fit is from distributions with a high kurtosis, meaning a high peak and bigger tails. The Cauchy distributions overestimate these tails more than the other distributions listed in this table, while the generalized hyperbolic, asymmetric Laplace and generalize normal distribution both match the tails the best when inspecting the QQ plots. To not over complicate the fitting of a distribution further and avoid overfitting, the generalized normal distribution is chosen for this thesis to simulate the delay from the estimated time of arrival. The resulting distribution can be seen in Figure 4.14.

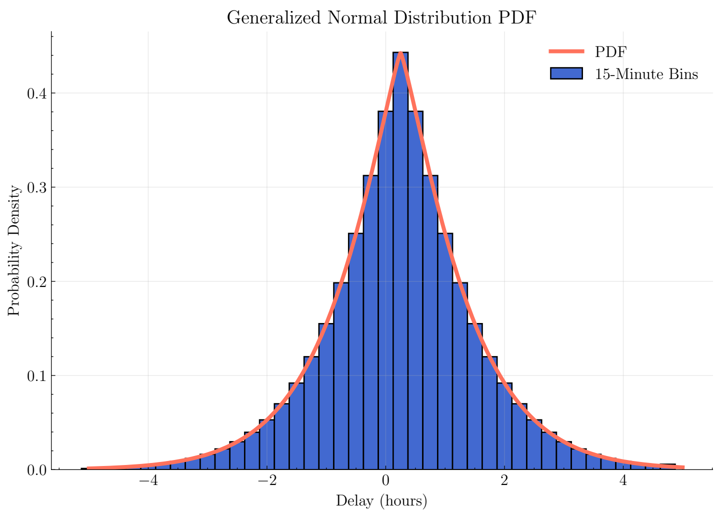

Figure 4.14: Generalized normal distribution of delays

From this generalized normal distribution will be sampled to create possible arrival scenarios of these ships. However, not all ship arrivals are possible by just sampling from this distribution, either because they would arrive outside working hours or because they would arrive outside of the time range of this model. To counteract this the generalized normal distribution will be truncated in these edge cases to fit inside the range of working hours by truncating the distribution to these edge values with equations 4.4.

$$f^{PDF}_{X|a\leq X\leq b}(x) = \begin{cases} \dfrac{f_X(x)}{F_X(b) - F_X(a)}, & a \leq x \leq b \\ 0, & \text{otherwise} \end{cases}, \quad F^{CDF}_{X|a\leq X\leq b}(x) = \begin{cases} 0, & x < a \\ \dfrac{F_X(x) - F_X(a)}{F_X(b) - F_X(a)}, & a \leq x \leq b \\ 1, & x > b \end{cases} \tag{4.4}$$

As mentioned in the limitations, inserting every possible ship arrival from this distribution multiplied by its probability for each 15 minute bin would increase the amount of scenarios significantly. To give an example, for 5 arriving ships it would result in 25^5 scenarios, assuming a spread between three hours early and three hours late arrival time. Therefore a limited amount of samples will be taken to approximate the possible arrival scenarios. These samples are then rounded to the nearest 15 minute interval to be used in the model.

To sample from this distribution different sampling techniques exist instead of just pseudo randomly sampling, also known as Monte Carlo (MC) sampling, from this distribution for each ship, Random Quasi-Monte Carlo (RQMC) sampling could also be used. These methods sometimes have a better convergence rate to the distribution compared to random sampling (Monte Carlo). QMC methods will give a better spread and will reduce the possibility of clumps, because of their Low discrepancy property. However this behavior is not true to real natural randomness, where ships delays not need to be spread out as much and grouped events are also relevant, for example all ships arriving late or all arriving on time. Therefore MC sampling will be chosen for sampling from the distribution, although it might perform worse in estimating the true distribution.

A medium and heavier operational working day have been chosen with their respective ETAs to generate the uncertain arrivals on and to depict different operational levels of the port, which will also have influence on total energy use and charging and cooling possibilities. A total of 100 ship arrival scenarios will be created by sampling a delay for each ship. A higher number of ship arrival scenarios is preferable to reflect many possible arrival scenarios. However, the model can only handle a limited amount of scenarios, which 100 is on the high end of reasonable running time.

5

Results & Discussion

To solve and run this two stage optimization model the pyomo mpi-sppy [58] module was used and utilized the Gurobi solver [38]. The pc on which it was run has Intel(R) Core(TM) i7-8750H CPU @ 2.20 GHz and 16 GB of RAM. Message Passing Interface (MPI) was used to run the scenarios on 6 cores in parallel to speed up the total computation time as it solves all scenarios individually. The stopping criteria for the progressive hedging algorithm is a convergence metric gap of 1x10^{-5} specified in equation 5.1. This equation gives the distance between the common or average nonanticipativity variables $\bar{x_n}$ (i.e. first stage variables) and the nonanticipative variables used in every scenario $x_{s,n}$ divided by the total number of scenarios, as in this case each scenario is equally likely. The maximum number of iterations has been set high enough to ensure all results atleast have a gap of 1x10^{-5} even for instances where the problem converges slowly, this especially occurs when the given contracted capacity is not sufficient and would result in occurring penalties with the added penalty term for exceeding contracted capacity as can be seen in the objective or when the contracted capacity is set as a variable. The solve time for every result is on average 20-30 minutes.

$$\bar{x}_n = \frac{1}{|S|}\sum_{s\in S} x_{n,s}, \quad CM = \frac{1}{|S|}\sum_{s\in S}\left[\frac{1}{N_f}\sum_{n\in N_f}|x_{n,s} - \bar{x}_n|\right], \quad \frac{\rho_n}{2}||x_{n,s} - \bar{x}_n||^2 \tag{5.1}$$

Choosing proper values for the penalty term is not an easy endeavor [112] and requires tuning. A fixed rho parameter could be chosen for all first stage variables, it could be set individually per first stage variable and there are also methods which can update rho per iteration of the progressive hedging algorithm [120]. As this model has many first stage variable values in total and has to be solved for 100 arrival scenario combinations which differ quite significantly, i.e. ship arrivals deviate quite much, it is important to choose proper penalty values and also base it on the variable and the objective size. To fine tune this for every first stage variable per different scenario were running, for example weather, electricity price, operational load, with or without batteries etc, it would take too much time. Because of this, consistent use of the same rhos will be used for all the generated results.

A popular method that can be chosen for finding ρ values is mentioned in equation 5.2 and depicts a ρ calculation by its effect on the objective [112]. In this equation $c(i)$ represents the cost coefficient per first-stage variable and the denominator reflects the sum of the difference of that variable over all scenarios multiplied with its probability.

$$\rho(i) = \frac{c(i)}{\max\left((\sum_{s\in S} Pr(s)\cdot|x_s(i) - \bar{x}(i)|), 1\right)} \tag{5.2}$$

The primary advantages of this ρ heuristic is that its problem-independent and parameter-free, eliminating the need for repeated execution of PH in the search for high-quality ρ values [112]. But it is mentioned there exist more effective methods for any specific problem which is the case for this model considering many first stage variables, also including ones which are indexed by time t or other. The rho values will be calculated by running an example scenario with BES and dynamic pricing to obtain a more sensitive rho value and determine the order of magnitude. This approach has been chosen as having different rho values per time index for the same variable did not help converge the problem to a satisfactory result. The problem here lies in the trade-off between a high quality solution and convergence speed for this specific problem. As choosing a large rho will reach consensus faster among the first stage variables, however this does not have to be an optimal one. Choosing a smaller rho will not force consensus fast after the initial phase as the penalty size will become very small, but can reach a more optimal solution compared to higher rho starting values which could drive the solution towards suboptimal solutions [120]. With these rho characteristics an increasing rho value approach [120] has been chosen as specified in equation 5.3.

$$\rho^{k+1} = \tau_\rho \cdot \rho^k, \quad \tau_\rho \geq 1 \tag{5.3}$$

- The starting ρ^0 penalty has been set to 1x10^{-4} for every variable.
- With each iteration the rho penalty will be increased with a factor τ_ρ of 1.04.
- Iterations stop when the convergence metric of 1x10^{-5} has been reached.

More finetuning of the initial rho value and multiplication factor can be done to improve the results, but these parameters have been chosen as they provided the best and most stable results in the time spent testing, also given a reasonable computation time is desired.

Furthermore, progressive hedging does not give an optimality gap as this is a heuristic algorithm. However, it does give a Trivial Bound (TB), which is the objective value of the scenarios in the list without enforcing non-anticipativity, meaning optimization of the scenarios with perfect information. It can be interpreted as the average of all individually optimized scenarios. This does not give a very tight lower bound which can be used to compare the solution with, as it does not solve the exact same problem. It does give the objective value of what can be achieved with real-time perfect information, which is also known as Wait and See (W&S), refering to no decisions being made before others and all information is known. To obtain a more realistic lower bound to quantify the performance of the model, mutiple runs are made for case 2 where the full extensive form is run for an extended duration to obtain a lower bound it has computed in this time, similar as is done in [112].

Finally, the xhatclosest extension from mpisppy [58] was used to obtain a final xhat result, which utilizes a truncated z-score and obtains these values according to steps depicted in equations 5.4, 5.5, 5.6, and 5.7. It will choose the first-stage variable from scenario s which is closest to the value of xbar, this will give a much more likely feasible outcome for this model compared to directly using xbar, even when the convergence gap is not very low, due to for example equality constraints that have to be enforced.

$$\textbf{Given:} \quad \bar{x}_n = \frac{1}{|\mathcal{S}|}\sum_{s\in\mathcal{S}} x_n^s, \quad \sigma_n = \sqrt{\frac{1}{|\mathcal{S}|}\sum_{s\in\mathcal{S}} (x_n^s)^2 - \bar{x}_n^2}, \tag{5.4}$$

Compute for each scenario $s \in \mathcal{S}$:

$$d(s) = \sum_{n\in\mathcal{N}} \min\left(3, \frac{|x_n^s - \bar{x}_n|}{\sigma_n}\right), \tag{5.5}$$

$$\textbf{Select:} \quad s^* \in \arg\min_{s\in\mathcal{S}} d(s), \tag{5.6}$$

$$\textbf{Define:} \quad \hat{x} := x^{s^*}, \text{by resolving the model for scenario } s^*. \tag{5.7}$$

As can be seen in equation 5.1 when solving to a convergence gap of 1e-5 there might be slight discrepancy between the first stage variables (total sum of absolute distance between scenario first stage decision values and xbar) to obtain valid first stage results which are identical among all scenarios this extension is used to obtain the final first stage variables. It takes the values for a scenario closest to $\bar{x}$, as it is not always guaranteed that the averaged result allows for feasibility. Afterwards it is checked that all scenarios are feasible given the nonanticipativity variables.

An overview is provided of which scenario for electricity price and temperature is solved for, Table 5.1 denotes which electricity price and which temperature profile is used by stating their average value. The electricity prices are adjusted to account for electricity levies and taxes.

Scenario	**Electricity Price**	**Temperature**
Scenario 1	Fixed EP (0.239 €/kWh Eurostat)	Cluster 1 Temp. (17.20 °C Avg.)
Scenario 2	Fixed EP (0.239 €/kWh Eurostat)	Cluster 2 Temp. (5.94 °C Avg.)
Scenario 3	Fixed EP (0.239 €/kWh Eurostat)	Cluster 3 Temp. (8.97 °C Avg.)
Scenario 4	Cluster 1 EP (0.18 €/kWh Avg.)	Cluster 1 Temp. (17.20 °C Avg.)
Scenario 5	Cluster 2 EP (0.24 €/kWh Avg.)	Cluster 2 Temp. (5.94 °C Avg.)
Scenario 6	Cluster 3 EP (0.17 €/kWh Avg.)	Cluster 3 Temp. (8.97 °C Avg.)

Table 5.1: Electricity price and temperature scenarios

Furthermore a distinction will also be made to what flexible asset is used for the EP, Temperature and operational level scenario. This consists of adopting a BES or not and whether the reefers can be flexibly cooled or wether they are fixed at their temperature set point.

Three different cases will be discussed:

- **Case 1 (5.1):** Full electrification with currently limited contracted capacity. Is it feasible to transition to a fully electrified port with optimal management?
- **Case 2 (5.2):** What would be the necessary required contracted capacity for full electrification for this port considering electricity pricing schemes and DSO costs.
- **Case 3 (5.3):** Time Constrained Transport Right, DSO contract for large electricity consumers.

5.1. Full electrification currently

Currently there is limited grid availability, because most of the equipment has not yet been replaced with an electric alternative and the contracted capacity has not yet been increased to account for this additional electricity consumption. To examine whether its still feasible for the port to fully electrify, without having to get a larger contracted capacity which is not as easily obtainable with the current grid congestion in the Netherlands. For this test flexibility is allowed using a scenario with Battery Energy Storage (BES) system and of course when the charging of battery electric equipment is performed, but the reefer cooling is fixed as it currently the case for these terminals. The current contracted grid capacity is assumed at 200 kW and only the fixed electricity cost will be used as there is currently little room to adjust power consumption and are focused wether this capacity is feasible for the operational and weather scenarios.

Operation	Scenarios	Max & Exceeded power	Max & Exceeded power (W&S)
Medium, average operations	Scenario 1	247.90 kW, 1085.76 kWh	200.00 kW, 0.00 kWh
	Scenario 2	199.93 kW, 0.00 kWh	168.69 kW, 0.00 kWh
	Scenario 3	200.00 kW, 0.00 kWh	179.91 kW, 0.00 kWh
Heavy operations	Scenario 1	301.11 kW, 2723.55 kWh	214.56 kW, 1397.68 kWh
	Scenario 2	200.06 kW, 2.40 kWh	181.94 kW, 0.00 kWh
	Scenario 3	229.71 kW, 828.32 kWh	192.49 kW, 0.00 kWh

Table 5.2: Full electrification with flexible batteries and reefers

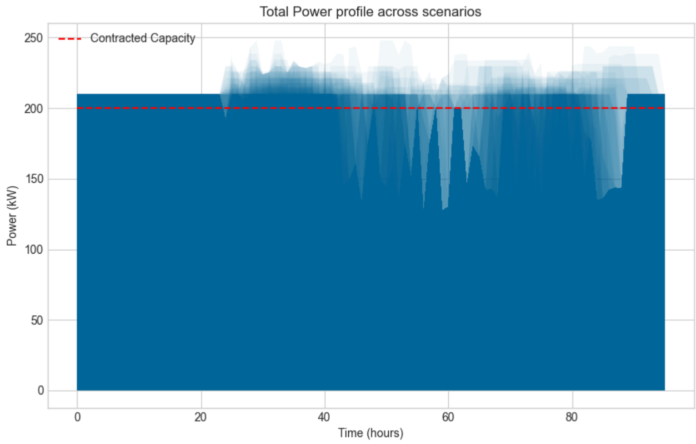

Figure 5.1: Scenario 1 overlapping power profiles of all scenarios

As can be seen from Table 5.2 and in Figure 5.1, the current contracted capacity is not sufficient to accommodate the operations even for a medium operation level load. What could be added is an energy storage system to capture energy during lowering from the cranes which could reduce the electric load by approximately 50% referring back to the literature in section 2.1.1. However, even with the help of such an energy capture device for cranes it will not be able to overcome the limited contracted capacity for the medium and heavier operational day, as seen in table 5.3. Furthermore, each day would be very difficult to stay within the contracted capacity range and schedule around the logistic planning. Therefore full electrification with current contracted capacity will not be feasible and additional capacity will be required.

Operation	Scenarios	Max & Exceeded power	Max & Exceeded power (W&S)
Medium, average operations	Scenario 1	203.87 kW, 64.70 kWh	183.26 kW, 0.00 kWh
	Scenario 2	186.23 kW, 0.00 kWh	145.5 kW, 0.00 kWh
	Scenario 3	196.40 kW, 0.00 kWh	155.67 kW, 0.00 kWh
Heavy operations	Scenario 1	249.77 kW, 1007.34 kWh	199.40 kW, 0.00 kWh
	Scenario 2	200.001 kW, 0.005 kWh	161.66 kW, 0.00 kWh
	Scenario 3	200.002 kW, 0.013 kWh	171.81 kW, 0.00 kWh

Table 5.3: Full electrification with flexible batteries, reefers and ESS for cranes

5.2. Full electrification ideally sized

The optimum required contracted capacity given the logistic and electric loads will be determined by changing the fixed contracted capacity parameter to a variable which will be added to the list of first-stage variables decisions. Per result the objective value (OBJ) found by PHA; the optimal contracted capacity (CC); the Trivial Bound/ Wait and See (TB/ W&S) objective value; the Convergence Metric (CM) gap of the solution and the number of iterations it took for the PHA to converge to this solution will be denoted.

Config.	Scenario	OBJ (€)	CC (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Flex Reef	Scenario 1	1140.82	231.78	1130.22	2.43 x 10^{-6}	334
	Scenario 2	917.37	191.98	906.71	9.60 x 10^{-6}	296
	Scenario 3	977.15	205.12	966.78	5.15 x 10^{-6}	292
	Scenario 4	778.15	552.11	769.16	5.90 x 10^{-6}	231
	Scenario 5	844.73	328.15	842.18	4.88 x 10^{-6}	282
	Scenario 6	673.22	292.79	669.27	9.46 x 10^{-6}	272
With BES, Flex Reef	Scenario 1	1140.80	230.89	1130.23	4.56 x 10^{-6}	317
	Scenario 2	916.76	192.76	906.71	9.57 x 10^{-6}	286
	Scenario 3	977.27	201.72	966.78	8.23 x 10^{-6}	295
	Scenario 4	776.81	592.43	758.93	9.96 x 10^{-6}	332
	Scenario 5	845.14	324.65	832.62	8.13 x 10^{-6}	268
	Scenario 6	673.72	292.35	664.59	9.13 x 10^{-6}	281

Table 5.4: Average operation level results grouped by their configurations 1 of 2

To compare the quality of the results obtained with the progressive hedging method a comparison will be made by running the extensive form for 3 hours per scenario, notating the best incumbent and the associated gap and compared with the solution from PHA. In table 5.5 the difference between the objective value obtained from the progressive hedging algorithm and the extensive form of the problem can be seen. The gap between the optimal solution found in the extensive form and the progressive hedging is determined and the optimal gap in the EF solution is denoted.

Config	Scenario	OBJ PH (€)	OBJ EF (€)	Opt. Gap EF-PH	EF gap
No BES, Flex Reef	Scenario 1	1140.82	1140.14	0.060 %	0.02 %
	Scenario 2	917.37	916.16	0.13 %	0.02 %
	Scenario 3	977.15	976.40	0.077 %	0.02 %
	Scenario 4	778.15	777.73	0.054 %	0.02 %
	Scenario 5	844.73	844.18	0.065 %	0.00 %
	Scenario 6	673.22	672.86	0.053 %	0.00 %
With BES, Flex Reef	Scenario 1	1140.80	1140.11	0.061 %	0.02 %
	Scenario 2	916.76	916.15	0.067 %	0.02 %
	Scenario 3	977.27	976.40	0.089 %	0.02 %
	Scenario 4	776.81	776.20	0.078 %	0.02 %
	Scenario 5	845.15	844.14	0.12 %	0.00 %
	Scenario 6	673.72	672.86	0.13 %	0.00 %

Table 5.5: Comparison PH results and solved EF

Two main differences can be noticed between the optimal solution found in the extensive form and when solved with progressive hedging method. Firstly, when the battery energy storage system is added and is used in the individually solved scenarios (As can be seen by the difference in TB/W&S values with and without BES in Table 5.4), with the current rho values the progressive hedging algorithm aims to use the battery as well, although very little. This happens despite the fully solved extensive form concluding that using the battery energy storage system in scenario 5 and 6 is not actually beneficial, as can be seen that there is almost no difference between the solution with and without BES. Something similar happens as well when assessing the assigned contracted capacity, as the PHA assigns a lower contracted capacity compared to the extensive form solution which is closer to the originally individually solved solutions. This is something that can be fine tuned further by decreasing the initial rho penalty either specifically for: BES charging, discharging and the assignment of the contracted capacity or a lower starting penalty value entirely or reducing the multiplication factor. However, these changes would result in greater computational time and is a trade-off that should be made whether this tiny improvement in objective is worth it. The reasons why the use of BES in this scenario is not beneficial is two fold, both charging and discharging decisions are made beforehand while ship arrival is only know afterwards leading to difficulty in aligning battery discharging for ship arrivals when the power is close to zero. Furthermore, the flexible cooling of the reefers and charging of battery equipment already "take up" most of the power during times with low electricity prices and the BES does not have significant benefit here as there is no renewable generation either and the model gives preference to the cooling of reefers and charging of battery equipment as these are neccasry loads and the BES also has round trip losses.

Config.	Scenario	OBJ (€)	CC (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Scenario 1	1147.67	227.82	1144.54	9.82×10^{-6}	294
	Scenario 2	923.46	189.66	919.68	8.50×10^{-6}	293
	Scenario 3	983.78	200.06	980.11	5.27×10^{-6}	317
	Scenario 4	846.40	383.62	836.75	9.49×10^{-6}	244
	Scenario 5	895.50	225.46	894.59	4.32×10^{-6}	186
	Scenario 6	695.73	219.38	692.50	9.95×10^{-6}	219
With BES, Fix Reef	Scenario 1	1147.68	228.17	1142.36	8.02×10^{-6}	282
	Scenario 2	923.30	189.48	917.71	7.19×10^{-6}	289
	Scenario 3	983.82	199.52	978.10	5.35×10^{-6}	303
	Scenario 4	817.91	429.66	807.90	9.62×10^{-6}	287
	Scenario 5	874.62	263.95	869.57	9.95×10^{-6}	261
	Scenario 6	688.93	262.47	683.47	8.06×10^{-6}	235

Table 5.6: Average operation level results grouped by their configurations 2 of 2

However, when it is not possible to flexibly cool the containers, either because of constraints of the costumers or because of lack of control over these refrigerated systems, the BES becomes more useful. In table 5.6 the same scenarios are run but the flexibility in temperature which had a tolerance of ± 1 degree has been set to 0, so the reefers cool as much as necessary needed to overcome the difference in temperature from the reefer and the ambient temperature. Now in every scenario with dynamic electricity prices the BES is actually able to be used as a flexible asset, by charging during low electricity prices and discharging to accommodate other port power loads such as the now fixed reefers, cold-ironing for ships and crane power.

Similar to the previous two tables for average operation for this port, energy profiles during heavy operations will also be analyzed. The same two tables are created for the different configurations and electricity price and weather scenarios.

Config.	Scenario	OBJ (€)	CC (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Flex Reef	Scenario 1	1270.49	257.40	1260.60	4.86×10^{-6}	270
	Scenario 2	1046.65	218.88	1037.10	9.53×10^{-6}	302
	Scenario 3	1107.13	229.25	1097.18	7.11×10^{-6}	268
	Scenario 4	864.96	586.47	858.30	9.76×10^{-6}	301
	Scenario 5	980.30	364.09	977.80	8.26×10^{-6}	225
	Scenario 6	766.24	313.25	762.31	9.23×10^{-6}	253
With BES, Flex Reef	Scenario 1	1270.61	255.23	1260.60	9.22×10^{-6}	305
	Scenario 2	1046.80	217.37	1037.10	6.13×10^{-6}	316
	Scenario 3	1106.98	227.61	1097.18	8.16×10^{-6}	310
	Scenario 4	863.53	622.47	846.89	9.53×10^{-6}	317
	Scenario 5	980.25	376.68	961.55	7.54×10^{-6}	376
	Scenario 6	767.04	306.33	756.63	7.42×10^{-6}	333

Table 5.7: Heavy operation level results grouped by their configurations 1 of 2

Config.	Scenario	OBJ (€)	CC (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Scenario 1	1277.52	246.04	1271.87	8.92×10^{-6}	279
	Scenario 2	1052.95	208.41	1046.78	6.58×10^{-6}	296
	Scenario 3	1113.36	218.54	1107.26	1.67×10^{-6}	336
	Scenario 4	932.33	417.10	925.89	7.90×10^{-6}	264
	Scenario 5	1031.73	254.46	1029.75	7.27×10^{-6}	150
	Scenario 6	788.69	240.75	785.90	4.66×10^{-6}	242
With BES, Fix Reef	Scenario 1	1277.23	246.43	1271.26	1.94×10^{-6}	341
	Scenario 2	1052.96	208.70	1046.31	8.75×10^{-6}	289
	Scenario 3	1113.31	218.84	1106.75	7.77×10^{-6}	322
	Scenario 4	904.77	463.97	897.09	9.37×10^{-6}	264
	Scenario 5	1009.67	293.90	1003.74	8.36×10^{-6}	258
	Scenario 6	781.98	288.24	776.69	9.55×10^{-6}	254

Table 5.8: Heavy operation level results grouped by their configurations 2 of 2

The contracted capacity is however not something that can be changed on a day by day basis so ensuring that there is enough capacity, the hottest day in 2024 will be tested along with a heavy operational day, to give an upper case of how much capacity would be necessary. The average temperature for this day was 25.1 degrees Celsius and the average day-ahead electricity including levies and taxes was 0.18 €/kWh. This day's day-ahead electricity price will again be used to compare the ideal contracted capacity for both fixed electricity price and dynamic electricity pricing.

Config.	Electricity price	OBJ (€)	CC (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Fixed	1437.47	273.42	1434.00	7.79 x 10^{-6}	273
	Dynamic	1011.81	522.55	1004.67	9.40 x 10^{-6}	250
With BES, Fix Reef	Fixed	1437.42	273.61	1432.62	9.40 x 10^{-6}	295
	Dynamic	947.70	589.50	940.14	6.61 x 10^{-6}	315
No BES, Flex Reef	Fixed	1431.90	284.44	1421.88	9.71 x 10^{-6}	300
	Dynamic	875.37	655.11	868.24	8.76 x 10^{-6}	268
With BES, Flex Reef	Fixed	1432.00	282.31	1421.88	9.68 x 10^{-6}	315
	Dynamic	858.15	722.25	838.14	9.38 x 10^{-6}	299

Table 5.9: Hottest day of 2024 and heavy operation level results grouped by their configuration

An interesting note, counterintuitively for the fixed price scenarios a lower contracted would save cost but the flexible reefer configuration appears to be cheaper despite having a higher contracted capacity, while the prices would be the same. However, the average maximum power used across these scenarios is lower which compensated for this difference. Furthermore it can be seen that a contracted capacity around 280 kW would be the minimum requirement to meet the electricity demand throughout such a day. So for the final comparison fixed electricity price and a contracted capacity of 300 kW will be compared against day-ahead pricing with a contracted capacities based on previous tables as this is not constrained by this maximum case scenario. The following contracted capacities will be chosen based on weighted averages of the scenarios. Size of the first cluster is 115 days, the second is composed of 43 days and the third cluster consists of 104 day.

	No BES, Fix reef	BES, Fix reef	No BES, flex reef	BES, flex reef
Fixed pricing	300 kW	300 kW	300 kW	300 kW
Dynamic pricing	320 kW	360 kW	440 kW	455 kW

Table 5.10: Capacities, for chosen configurations

	No BES, Fix reef	BES, Fix reef	No BES, Flex reef	BES, Flex reef
Fixed pricing				
Cluster 1	€ 1156.95	€ 1159.86	€ 1147.20	1147.69
Cluster 2	935.54	937.73	926.76	926.76
Cluster 3	995.08	997.33	985.95	985.94
Weighted Avg.	1056.36	1058.89	1047.01	1047.22
Dynamic pricing				
Cluster 4	861.72	839.60	800.22	803.84
Cluster 5	904.30	892.36	853.78	867.76
Cluster 6	705.01	703.90	686.47	702.84
Weighted Avg.	806.50	794.39	763.86	774.24

Table 5.11: Results for chosen configurations and contracted capacities

Looking into the results listed in Table 5.11 it can be seen that the dynamic electricity pricing is currently always the better option compared to fixed electricity pricing. In Appendix Section A.4 all the first stage power decision are plotted for each of the scenarios. In these pictures the top left plot depicts the total power used for each of these scenarios, its mean, minimum and maximum along with the electricity price for that scenario. The other three plots display the scheduled first stage power decisions, with the top right plot showing the power the reefers use and its internal temperature. The bottom left plot displaying the charging throughout the day and the aggregated SOC. The bottom right plot shows the charging, discharging and change in charge if applicable. As mentioned in the limitations it can be seen that not explicitly disallowing simultaneous charging and discharging of the BES can lead to an outcome doing just that, as can be seen in for example Figure 5.2. The reason for this is that the BES will be used in the first iteration when each scenario is solved individually, but these scenarios differ quite significantly so the charging and discharging will be penalized. However, these are acting as two different variables so when they are pushed to a common first stage value they can overlap. Furthermore, from the figures in Section A.4 it can be seen that the battery capacity for the BCHE is on the high end as its not fully utilizing the range of its SOC. Other battery capacities for these BCHE can be tested using this model, but it should be noted that this is an aggregated SOC so some play within this range is desired. Additionally, even the lowest offered charging speed for this reach stacker brand is on the high end for this container terminal and could possibly get away with slower charging stations if possible.

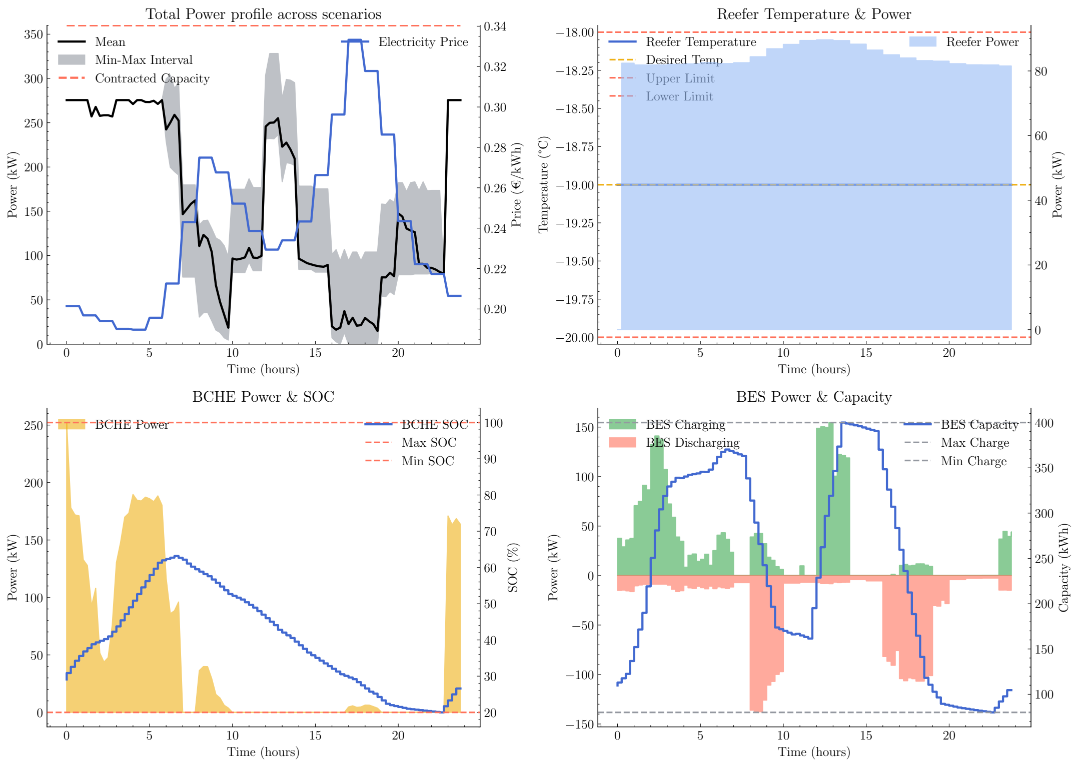

Figure 5.2: Dynamic electricity price cluster 5, fixed reefers, with battery energy storage

To summarize these results, currently dynamic electricity pricing is always the better option, as given in percentages in Table 5.12 and Table 5.13. No BES and no flexible reefer cooling will be set as base case, from which the other configurations are compared. Furthermore, flexible cooling of reefers will be the best option given the possibility. BES could perform better after taking into account its sometimes simultaneous charging and discharging behavior by accounting for this after the optimization. However, this would not perform much better alongside the flexible reefers, as the W&S difference is also only slightly better.

Fixed EP	No BES	with BES
No Flexible Reefer	0.0 %	+0.24%
With Flexible Reefer	-0.89 %	-0.87 %

Table 5.12: Case 2, Fixed EP

Dynamic EP	No BES	with BES
No Flexible Reefer	-23.65 %	-24.80%
With Flexible Reefer	-27.69 %	-26.71 %

Table 5.13: Case 2, Dynamic EP

5.3. Capacity limiting contracts

There are multiple flexible contracts that can be analyzed with this day-ahead model. The TCTR contract, static CBC contract and dynamic day-ahead CBC contracts. These contracts all depend on the local grid congestion and when peak power withdrawal and insertion are. The TCTR contract which is making its introduction in the Netherlands is usually offered between the hours of 0:00 and 6:00, which could make it suitable for businesses with battery equipment such as this container terminal. For this case the necessary extra capacity will be analyzed which would be necessary between these hours on top of the already existing 200 kW contracted capacity. A similar approach will be taken as done in the second case, however instead the contracted capacity variable can only be increased in the aforementioned time range. This will provide information if the addition of this contract would be feasible and whether this would be more incentivized compared to the usual continuously fixed contracted capacity.

This table will include the following information: The configuration of BES and reefers; the weather and electricity scenario; the objective value; the Extra Contracted Capacity (ECC) between 00:00 and 06:00; The maximum Power Exceeded (PE) if applicable in any of the scenarios and thereby occurring penalties; the Trivial Bound (TB) or Wait and See (W&S) objective value; the Convergence Metric (CM) and the number of iterations

Config.	Scenario	OBJ (€)	ECC (kW)	Max PE (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Scenario 1	-	112.4	27.28	-	4.71×10^{-6}	106
	Scenario 2	927.94	2.93	0.00	921.94	9.54×10^{-6}	123
	Scenario 3	986.62	18.25	0.00	981.51	7.08×10^{-7}	154
	Scenario 4	-	90.98	27.28	-	5.23×10^{-6}	99
	Scenario 5	897.32	38.06	0.00	893.85	2.38×10^{-9}	51
	Scenario 6	700.13	14.60	0.00	692.61	9.19×10^{-6}	104
With BES, Fix Reef	Scenario 1	1169.87	102.80	0.00	1142.85	1.41×10^{-6}	180
	Scenario 2	930.90	5.01	0.00	921.26	3.82×10^{-10}	143
	Scenario 3	992.48	13.61	0.00	980.82	1.74×10^{-6}	92
	Scenario 4	893.38	121.07	0.00	850.14	8.22×10^{-6}	109
	Scenario 5	887.50	128.74	0.00	867.92	3.80×10^{-6}	111
	Scenario 6	700.44	139.69	0.00	683.12	9.73×10^{-6}	95
No BES, Flex Reef	Scenario 1	1160.68	116.11	0.00	1130.96	9.61×10^{-6}	222
	Scenario 2	919.58	0.00	0.00	910.58	7.02×10^{-6}	85
	Scenario 3	980.11	0.00	0.00	969.82	1.74×10^{-6}	168
	Scenario 4	884.07	179.18	0.00	836.77	9.67×10^{-6}	240
	Scenario 5	852.68	218.77	0.00	842.02	8.08×10^{-6}	69
	Scenario 6	685.51	123.12	0.00	671.22	1.05×10^{-6}	122
With BES, Flex Reef	Scenario 1	1165.35	108.33	0.00	1130.96	8.1×10^{-7}	153
	Scenario 2	921.00	0.00	0.00	910.58	3.77×10^{-6}	140
	Scenario 3	982.22	0.00	0.00	969.82	9.99×10^{-6}	171
	Scenario 4	883.53	192.25	0.00	834.97	1.01×10^{-6}	171
	Scenario 5	860.41	296.59	0.00	831.21	6.63×10^{-6}	91
	Scenario 6	691.00	182.72	0.00	667.49	1.42×10^{-6}	92

Table 5.14: Average operation level results grouped by their configurations for capacity limited contract

Config.	Scenario	OBJ (€)	ECC (kW)	Max PE (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Scenario 1	-	138.26	8.48	-	9.18×10^{-6}	102
	Scenario 2	1057.57	22.46	0.00	1048.50	3.63×10^{-7}	215
	Scenario 3	1121.55	52.03	0.00	1108.09	7.51×10^{-6}	150
	Scenario 4	-	135.74	8.48	-	9.90×10^{-6}	143
	Scenario 5	1034.36	71.25	0.00	1027.98	2.76×10^{-6}	33
	Scenario 6	794.03	49.55	0.00	785.77	1.98×10^{-6}	147
With BES, Fix Reef	Scenario 1	1305.50	149.94	0.00	1279.39	1.63×10^{-8}	182
	Scenario 2	1061.24	10.37	0.00	1048.22	2.72×10^{-7}	224
	Scenario 3	1127.39	43.4	0.00	1107.81	9.38×10^{-7}	202
	Scenario 4	991.04	211.22	0.00	960.04	1.77×10^{-7}	237
	Scenario 5	1025.82	165.81	0.00	1001.48	9.24×10^{-6}	63
	Scenario 6	794.35	189.57	0.00	776.35	1.50×10^{-6}	124
No BES, Flex Reef	Scenario 1	1297.40	154.34	0.00	1266.81	3.98×10^{-6}	136
	Scenario 2	1051.09	3.28	0.00	1039.18	9.43×10^{-6}	200
	Scenario 3	1117.43	39.49	0.00	1098.44	6.84×10^{-6}	175
	Scenario 4	978.99	239.78	0.00	946.81	1.11×10^{-6}	211
	Scenario 5	988.61	249.92	0.00	977.28	6.72×10^{-7}	110
	Scenario 6	780.53	160.17	0.00	765.35	9.33×10^{-6}	58
With BES, Flex Reef	Scenario 1	1300.87	151.30	0.00	1266.80	2.12×10^{-6}	199
	Scenario 2	1052.94	2.94	0.00	1039.18	3.51×10^{-6}	153
	Scenario 3	1120.04	38.90	0.00	1098.43	9.81×10^{-6}	177
	Scenario 4	976.95	268.10	0.00	944.60	5.92×10^{-6}	279
	Scenario 5	998.97	338.45	0.00	959.29	2.56×10^{-6}	138
	Scenario 6	785.10	229.24	0.00	760.61	3.02×10^{-6}	132

Table 5.15: Heavy operation level results grouped by their configurations for capacity limited contract

Similarly to the previous section the hottest day of 2024 and a heavy operational day will be analyzed to assess the feasibility of this contract.

Config.	Elec. price	OBJ (€)	ECC (kW)	Max PE (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Fixed	-	135.53	45.54	-	1.98 x 10^{-6}	132
	Dynamic	-	128.64	45.54	-	7.15 x 10^{-6}	128
With BES, Fix Reef	Fixed	-	251.36	36.62	-	9.66 x 10^{-6}	319
	Dynamic	-	249.15	36.62	-	2.22 x 10^{-6}	295
No BES, Flex Reef	Fixed	1483.32	325.16	0.00	1442.97	9.93 x 10^{-6}	188
	Dynamic	1153.11	320.66	0.00	1096.55	7.59 x 10^{-6}	126
With BES, Flex Reef	Fixed	1480.22	275.22	0.00	1442.96	2.91 x 10^{-6}	235
	Dynamic	1136.57	339.59	0.00	1090.62	5.57 x 10^{-6}	207

Table 5.16: Hottest day of 2024 and heavy operation level results grouped by their configuration

As can be seen in Table 5.16 having no flexibility in cooling with reefers will not allow for this contract to work on top of the existing contracted capacity in the heaviest conditions. The amount of extra contracted capacity differs in these results due to early converging values of this contracted capacity, especially as the costs for this extra contracted capacity are now lower when compared to the previous case. It can be seen as a very large search space and where the impact of cost for contracted capacity is even lower, resulting in more deviation. Furthermore, the configuration with BES and fixed reefers would be able to work with an even larger BES, but this is not deemed as a reasonable solution. Therefore in Table 5.17 only the cases with flexible reefers will be considered. The values listed in this table is the required extra capacity between 00:00 and 06:00 on top of the original 200 kW contracted capacity. This means that between 00:00 and 06:00 there is a capacity of 500 kW and for the rest of the day it will be 200 kW.

	No BES, Fix reef	BES, Fix reef	No BES, flex reef	BES, flex reef
Fixed pricing	-	-	300 kW	300 kW
Dynamic pricing	-	-	300 kW	300 kW

Table 5.17: Extra capacity necessary for chosen configurations

Similar as for case 2, the determined capacities will be fixed to assess the costs of this contract for average working days throughout the year to be compared against the normal contract type. In Table 5.18 the results from each configuration and scenario for the TCTR contract can be seen. All the figures corresponding to the table values can be found in Section A.5, which display type of plots as mentioned in Section 5.2

	No BES, Flex reef	BES, Flex reef
Fixed pricing		
Cluster 1	1164.71	1169.53
Cluster 2	925.67	927.13
Cluster 3	986.25	988.36
Weighted Avg.	1054.64	1057.83
Dynamic pricing		
Cluster 4	886.90	886.21
Cluster 5	854.97	860.29
Cluster 6	687.49	690.30
Weighted Avg.	802.50	804.19

Table 5.18: Results for chosen configurations and contracted capacities

In Figure 5.3 an illustration of the TCTR contract can be seen. During this time with additional extra capacity the reefers will be cooled, BCHE will be charged and also the BES in this case. Reefers must be able to adjust their cooling to cool in the morning, otherwise the contracted capacity would be exceeded later in the day when the ships would start arriving, especially when considering a hot day.

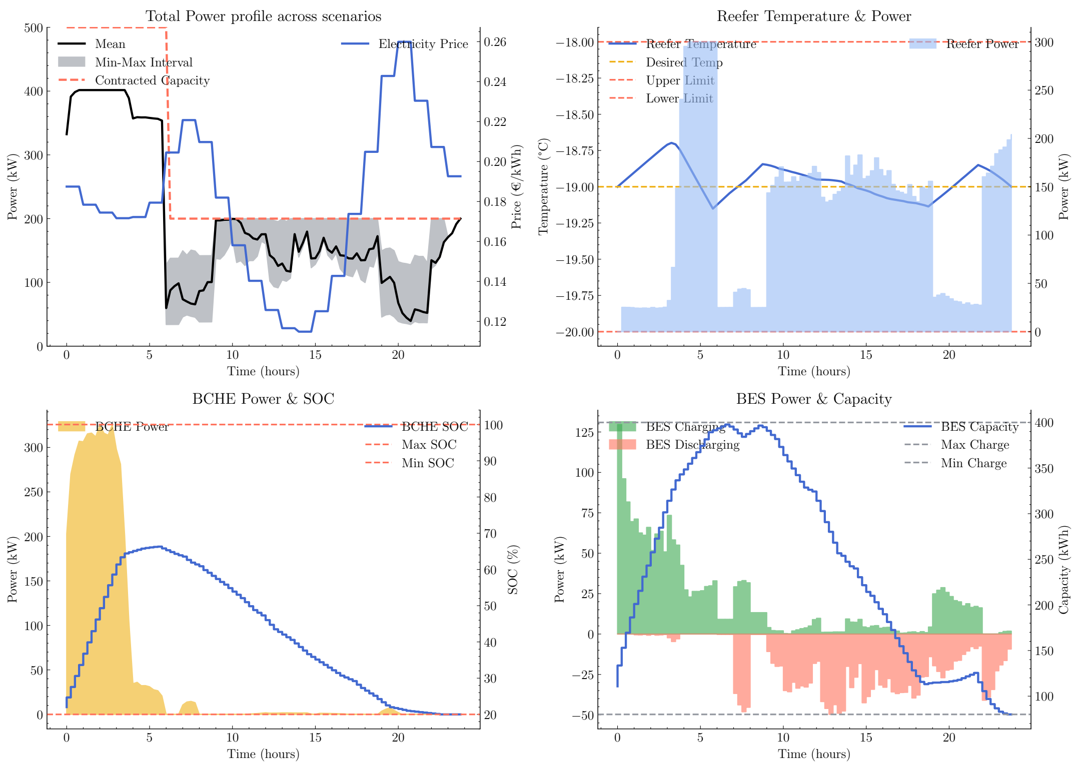

Figure 5.3: TCTR, Dynamic electricity price cluster 4, flexible reefers, with battery energy storage

The obtained average daily costs for this TCTR contract will again be compared against the No BES, No flexible reefer cooling from case 2, Table **??**. From this table it can be concluded that this contract is not beneficial for terminal operators in terms of costs and would also require more precise scheduling considering the tight power limits for the rest of the day.

Fixed EP	No BES	with BES
With Flexible Reefer	-0.16 %	+0.14 %

Table 5.19: TCTR, Fixed EP

Dynamic EP	No BES	with BES
With Flexible Reefer	-24.0 %	-23.9 %

Table 5.20: TCTR, Dynamic EP

5.4. Future research

This model is intended to tackle the optimal power demand use for different electricity contracts as well as DSO costs. To analyze this historic electricity pricing from 2024 was used. However, it must be considered that electricity pricing have fluctuated pretty significantly the last few years as can be seen in Figure 5.4. It can not be ensured that the currently obtained values will be the same for future electricity prices. Future energy demand can also differ due to more renewable integration. DSO costs could also increase as they have to maintain a larger infrastructure with the increasing electrification. These elements combined will have effect on the total and hourly power use and could also be analyzed further as these costs will change. Similarly for weather, this thesis made three clusters for temperature and electricity pricing and also considered the hottest day in 2024. The outlier for such events with very high temperatures during heatwaves could also be considered further. However, it is not expected that such a unique event would have a very large impact as this will most likely not be significantly hotter than the hottest day also considered in this model.

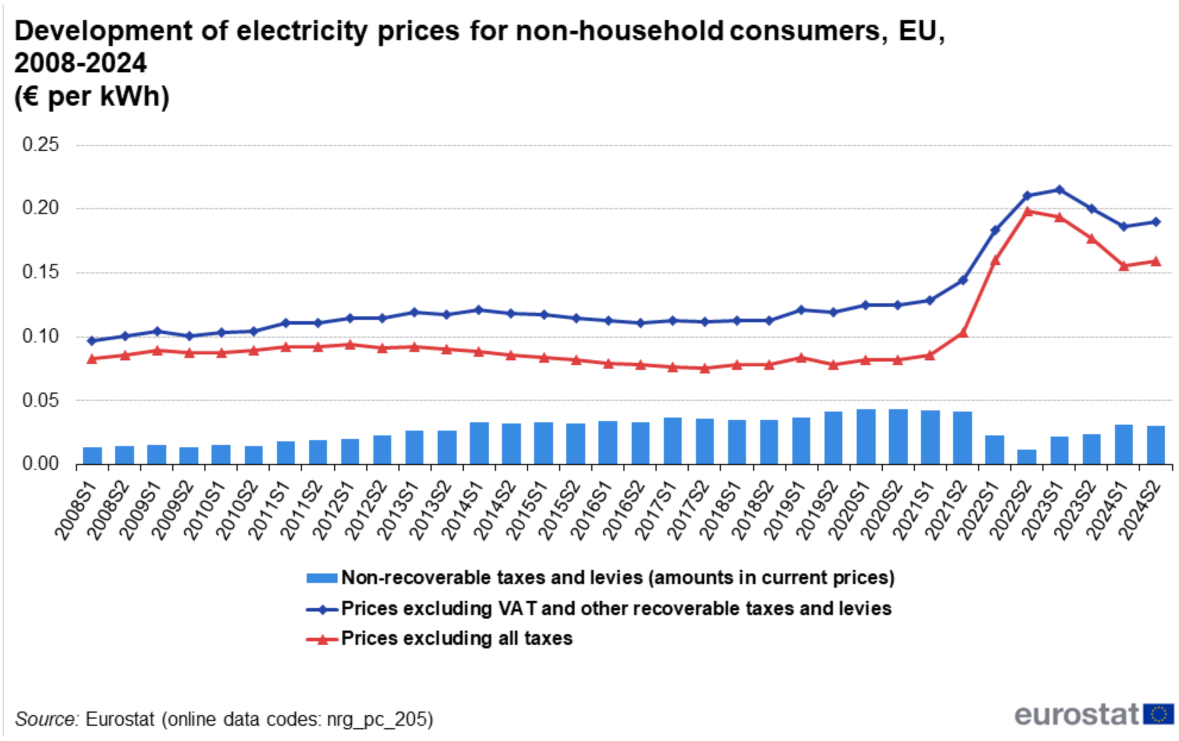

Figure 5.4: History of electricity prices EUROSTAT

Furthermore, the model is conservative in the fact that it assumes it has no knowledge when the ship will arrive except the ETA and a delay corresponding to a distribution. However, in reality a ship will for example notify if its running later or coming in earlier ahead of actually arriving. This could also give time to change decisions, which could be explored with a model predictive controller with a rolling horizon, which could take this initial power allocation as a base.

For small fleet sizes it would be more accurate to model the working and charging decisions as binary or integer decisions as well as individual SOC tracking. However, due to the complexity of the model with uncertainty it is chosen to model them as continuous values and aggregated SOC. The benefit of this is that it does scale well with larger ports with more equipment, but looses out on per vehicle planning. This is also the case for the binary indicator for the BES as this could charge and discharge simultaneously due to no strict enforcement. Adding this binary indicator would improve the results for the BES cases, but would come at a significant computational cost. Further improvements in modeling these characteristics, while still maintaining reasonable solve time can be investigated further

Additionally, the model currently dictates how much power should go to the cluster of Reefers and battery handling equipment. This could be analyzed further by a model/optimization which delegates this power on an individual level, i.e. per reefer from the total power allocation in this model. This could allow for per level equipment scheduling instead of pooled power

Also, if container terminals will start to carry more chilled reefers instead of frozen reefers, more power will be required. The port analyzed mostly adapts frozen containers and is also modeled this way in the optimization model. Chilled reefers however are less flexible in temperature tolerance ranges and will also require more power for these types of chilled goods. Modeling this behavior for chilled goods could be very significant for container terminals these types of reefers.

The actual demand for shore power can also be further analyzed as there is inconsistency in the reported required demand. Many reports in the Netherlands examined the emissions from inland vessels, but these values range quite significantly and an analysis for expected shore power demand per inland vessel type will be insightful to more accurately depict this additional demand.

Sizing of batteries and charging speed limits can also be tweaked further or optimized to a container terminals operational desires by changing these parameters or by making additional first stage or multi stage decisions. A container terminal might for example prefer more BCHE with smaller battery size compared to fewer BCHE with higher capacities. The current battery size chosen for this particular terminal was large and might be too costly, but can also easily be replaced by one of the smaller options available on the market.

Integration of renewable energy sources within this energy management system can be investigated as well. Currently the BES is only used for shifting loads, but would work better with integration of for example solar energy, which terminals could implement to reduce their electricity bill further.

6 Conclusion

Main question: *How can power scheduling scheduling of flexible loads for container terminal equipment be optimized to minimize electricity and distribution system operator cost and what are the resulting operational and economic impacts for an electrified terminal?*

Sub questions:

1. What is the literature on power demand and management for container terminal equipment?

   There is extensive literature about managing and optimzing power for single equipment such as cranes, agvs and reefers as well as energy management systems for the entire container terminal. These energy management systems for container terminals are often referred to as micro-grids and typically implement power loads such as cold-ironing, crane power and renewable energy. These micro-grids can also implement logistic loads related to container handling in these terminals. This energy and logistic equipment are intertwined in an energy-logistic problem and tackling this problem can reduce energy costs as well as possibly optimizing the logistics around container terminal operation.

2. What are the relevant system operator contracts and costs for electricity consumers such as container terminals?

   Large electricty consumers such as container terminals also have to pay for the transmission fees and their installed capacity. These costs consider the type of station to which they are connected; monthly costs for their contracted capacity; monthly costs for the maximum power used in a 15 minute interval and other fixed and flat rate fees. DSO Stedin also offer flexible contracts to help mitigate grid congestion and help avoid disturbances or congestion during maintenance which limit the capacity on fixed times, day-ahead or even intraday and real-time. Partaking in these contracts is also incentivize by for example reducing the system operator feed or by reimbursement. For container terminals these intraday and real-time contracts can be complex to manage and are also often not the typical applicant for these type of contracts. But the static limits such as the TCTR and fixed static reductions could be implemented considering the port has flexible loads, such as: the cooling of reefers, charging of equipment and possibly the use of a battery energy storage. This is also the case for the day-ahead capacity limiting contract. However these contracts can only be used if their is mutual benefit for both the container terminal and the DSO, as for example the TCTR can not be used if a region or station is congested.

3. How can the operations and power demand be modeled, considering all equipment's energy consumption and ship arrival uncertainty?

   The logistics and power scheduling of the equipment can be modeled with mixed integer programming. To also take into account uncertain ship arrival this problem is turned into a two-stage stochastic optimization. This allows for decisions to be made before the uncertain ship arrival is known, which avoids optimizing the problem with perfect information which is often not very practical in a dynamic logistic setting such as container terminals

. The flexible power loads such as charging or discharging of batteries and the cooling of reefers can be manipulated and scheduled beforehand to accommodate for the uncertain ship arrival.

4. Can full electrification of container terminal be achieved with limited grid capacity and current working scheme? − Case study

   After the model has been formalized and all the parameters for the specific case have been determined it can be assessed wether full electrification with current contracted capacity is feasible. However, despite using many flexible assests such as the battery energy storage, charging of equipment and energy storage system for cranes it is still not feasible for the container terminal to make the transition towards full electrification given the current contracted capacity. Therefore additional capacity will have to be obtained for this transition.

5. How much capacity would be necessary for a port considering full electrification and different operational levels, electricity pricing contracts and dso fees

   The necessary contracted capacity will be optimized as a first stage variable along side other first stage power variables to minimize the costs for electricity as well as costs associated to fees from the distribution system operator. The resulting determined contracted capacity depends on the flexible assets implemented in the port as well as electricity price and operational load and ambient temperature. As the contracted capacity is not something that can be continuously changed day by day, a sufficiently high contracted capacity will be chosen which would still allow for feasible operation as well as allow for optimal power usage with the associated electricity contract. From the results it can be seen that the contracted capacity used for a dynamic electricity price contract will be higher compared to a fixed electricity price. This is because the model tries to maximize power usage during times with low electricity prices which will result in lower costs compared to having a lower contracted capacity costs and having to use more power during times with higher electricity prices. But for fixed electricity pricing the only incentive is to minimize the maximum power and contracted capacity as there is no difference between electricity prices over time. Furthermore it can be observed that additional flexibility

6. What energy contracts and contracted capacity contracts would be most beneficial for the studied port and could other contract options offered by DSO work for studied port.

   The Time Costrained Tranport Right contract(TCTR) has been analyzed which is a capacity that is only available for certain time blocks considering local congestion. The most common case is for example between 00:00-06:00, during this time additional capacity is availble during which flexible assests can be charged or cooled. This contract will be analyzed on top of the already existing contracted capacity and the additional capacity required between 0:00 and 6:00 will be optimized. From the results for an average working day it can already be seen that with no Battery energy storage or flexible cooling of reefers that this contract would not be sufficient on top of the existing contracted capacity, no matter how high the additional starting capacity would be. As there is not enough flexibility to use the power during these early hours. The configuration with just a battery energy storage system will also not succeed during the hottest day and an even larger battery would be required to make this happen. When there is flexible reefer cooling the required additional capacity necessary for the hottest day and heavy operational load is determined to be 300 kW. However, when this contract is calculated through for the rest of the year it is deemed as more costly

To answer the main research question. This thesis aimed in assisting container terminals towards fully electrifying, by scheduling powers such as charging batteries and cooling of reefers to ensure the container terminal stays within its contracted capacity even with uncertain arrival of ships. This contracted capacity can be optimized with this model for a terminals flexible assets configuration by considering the fees from the DSO to determine an appropriate capacity based on analyzing multiple scenarios. It is found that with current electricity prices, the dynamic electricity pricing is always more beneficial (Table 5.12 & 5.13) despite the slightly higher DSO costs by utilizing a higher contracted capacity (Table 5.10), as can be seen in and maximum power, which would put more strain on the grid in the Netherlands. Equipment is charged more and reefers cool more during these times of low electricity prices avoiding the higher electricity peaks throughout the day. For fixed electricity pricing, cooling and charging is spread out as much as possible throughout the day to reduce the cost related to contracted capacity and maximum power used

Fees related to this maximum power usage could increase in the future as the electric infrastructure in the Netherlands is increasing and grid congestion becomes a larger topic. The TCTR contract aimed at providing power outside peak-hour demand, often between 00:00-06:00 would also come with an incentive in the form of a reduction in DSO fees. The required extra capacity in this contract type would be 300 kW (Table 5.17) and would only be feasible if the container terminal had the ability to flexibly cool the refrigerated containers, as reefers who strictly maintain there internal set temperature would exceed the contracted capacity later during the day as ships and cranes would be operating. When there are refrigerated containers that can flexibly cool their internal load within a 1 °C temperature tolerance, they would be cooling extra in the morning between 00:00 and 06:00. Similarly, the battery container handling equipment would also charge more during this interval as well as the battery energy storage, if applicable. However for this specific terminal this reduction in DSO fees is not enough to consider this type of contract (Table 5.19 & 5.20), especially as it also involves significant load shifting and would likely choose for a larger continuous contracted capacity. For avoiding local grid congestion, adjustments in power behavior would need more incentive to help alleviate congestion further.

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A

Additional Pictures & Tables

A.1. Electricity prices 2024

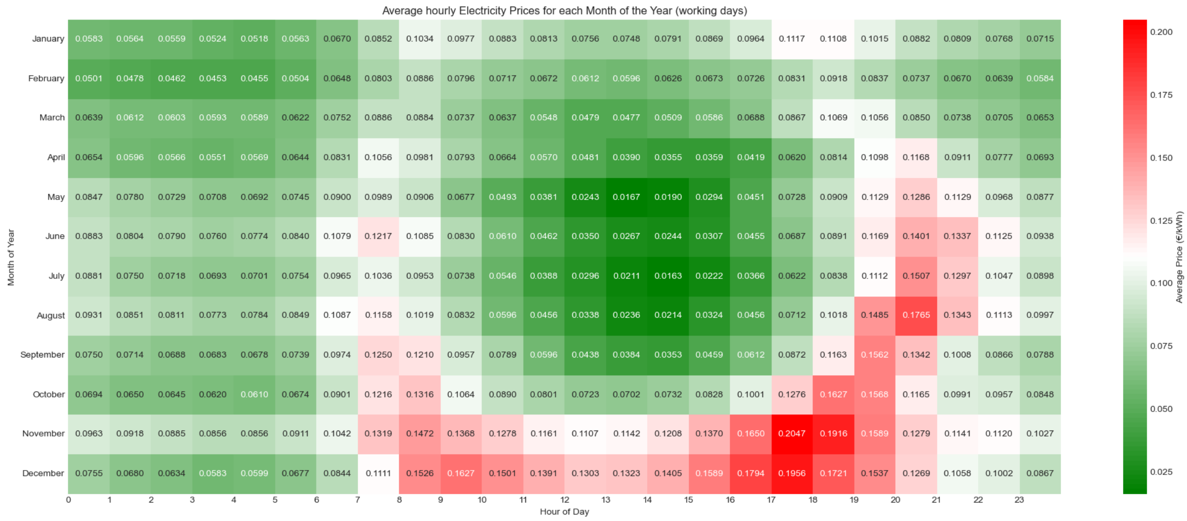

Figure A.1: Varying hourly prices for 2024 workdays (buy cost without taxes and fees), data from

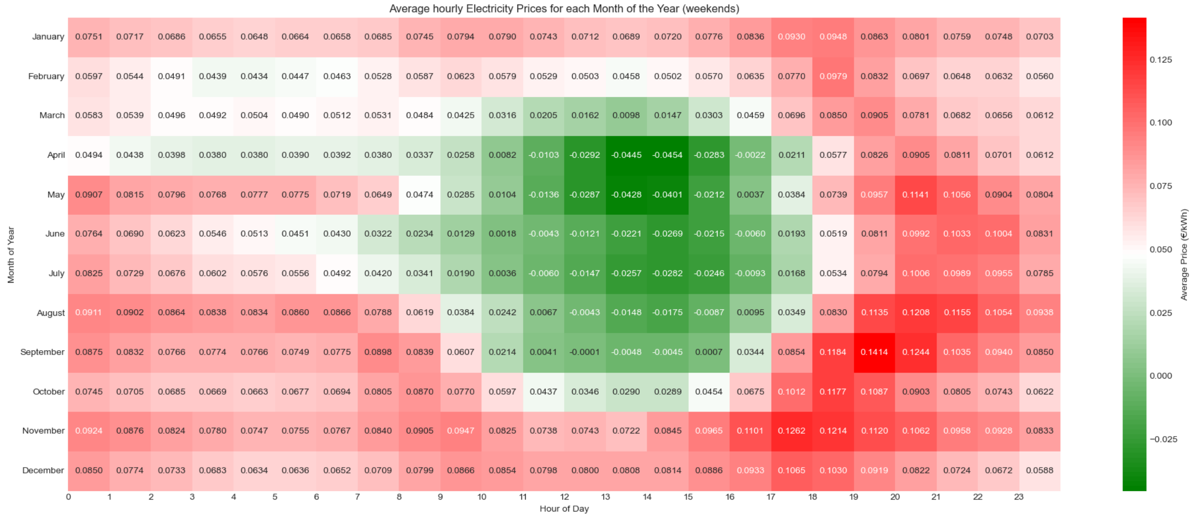

Figure A.2: Varying hourly prices for 2024 weekends (buy cost without taxes and fees), data from

A.2. Ship classes

CEMT-Klasse	Motorvrachtschepen (Motorvessels)							Duwstellen (Barges)			
	RWS Klasse	Karakteristieken maatgevend schip**				Classificatie		RWS Klasse	Karakteristieken maatgevend duwstel**		
		Naam	Breedte	Lengte	Diepgang (geladen)	Laad-vermogen	Breedte en lengte		Combinatie	Breedte	Lengte
			m	m	m	t	m			m	m
	M0	Overig				1-250	B<= 5,00 of L<= 38,00				
I	M1	Spits	5,05	38,5	2,5	251-400	B= 5,01-5,10 en L>=38,01	BO1		5,2	55
II	M2	Kempenaar	6,6	50-55	2,6	401-650	B=5,11-6,70 en L>=38,01	BO2		6,6	60-70
III	M3	Hagenaar	7,2	55-70	2,6	651-800	B=6,71-7,30 en L>=38,01	BO3		7,5	80
	M4	Dortmund Eems (L < = 74 m)	8,2	67-73	2,7	801-1050	B=7,31-8,30 en L=38,01-74,00	BO4		8,2	85
	M5	Verl. Dortmund Eems (L > 74 m)	8,2	80-85	2,7	1051-1250	B=7,31-8,30 en L>=74,01				
IVa	M6	Rijn-Herne Schip (L <= 86 m)	9,5	80-85	2,9	1251-1750	B=8,31-9,60 en L=38,01-86,00	BI	Europa I duwstel	9,5	85-105
	M7	Verl. Rijn-Herne (L > 86 m)	9,5	105	3,0	1751-2050	B=8,31-9,60 en L>=86,01				
IVb											
Va	M8	Groot Rijnschip (L <=111 m)	11,4	110	3,5	2051-3300	B= 9,61-11,50 en L=38,01-111,00	BII-1	Europa II duwstel	11,4	95-110
	M9	Verlengd Groot Rijnschip (L >111 m)	11,4	135	3,5	3301-4000	B= 9,61-11,50 en L>= 111,01	BIIa-1	Europa IIa duwstel	11,4	92-110
								BIIL-1	Europa II Lang	11,4	125-135
Vb								BII-2l	2-baksduwstel lang	11,4	170-190
VIa	M10	Maatg. Schip 13,5 * 110 m	13.50	110	4,0	4001-4300	B=11.51-14.30 en L=38.01-111.00	BII-2b	2-baksduwstel breed	22,8	95-145
	M11	Maatg. Schip 14.2 * 135 m	14.20	135	4,0	4301-5600	B=11.51-14.30 en L>= 111.01				
	M12	Rijnmax Schip	17,0	135	4,0	>= 5601	B>= 14.31 en L>= 38.01				
VIb								BII-4	4-baksduwstel (incl. 3-baks lang)	22,8	185-195
VIc								BII-6l	6-baksduwstel lang (incl 5-baks lang)	22,8	270
VIc								BII-6b	6-baksduwstel breed (incl. 5-baks breed)	34,2	195

Figure A.3: CEMT Classes of ships part 1 [101]

Duwstellen (Barges)			Koppelverbanden (Convoys)							Doorvaart-hoogte*
	Classificatie		RWS Klasse	Karakteristieken maatgevend koppelverband**				Classificatie		
Diepgang (geladen)	Laad-vermogen	Breedte en lengte		Combinatie	Breedte	Lengte	Diepgang (geladen)	Laad-vermogen	Breedte en lengte	incl. 30 cm schrikhoogte
m	t	m			m	m	m	t	m	m
1,9	0-400	B<=5,20 en L= alle	C1l C1b	2 spitsen lang 2 spitsen breed	5,05 10,1	77-80 38,5	2,5 2,5	<= 900 <= 900	B<= 5,1 en L=alle B=9,61-12,60 en L<= 80,00	5,25* 5,25*
2,6	401-600	B=5,21-6,70 en L=alle								6,1
2,6 2,7	601-800 801-1250	B=6,71-7,60 en L=alle B=7,61-8,40 en L=alle								6,4 6,6 6,4
3,0	1251-1800	B=8,41-9,60 en L=alle								7,0* 7,0*
			C2l	Klasse IV + Europa I lang	9,5	170-185	3,0	901-3350	B=5,11-9,60 en L=alle	7,0*
3,5 4,0 4,0	1801-2450 2451-3200 3201-3950	B=9,61-15,10 en L<=111,00 B=9,61-15,10 en L<=111,00 B=9,61-15,10 en L=111,01-146,00								9,1* 9,1* 9,1*
3,5-4,0	3951-7050	B=9,61-15,10 en L>=146,01	C3l	Klasse Va + Europa II lang	11,4	170-190	3,5-4,0	3351-7250	B=9,61-12,60 en L>=80,01	9,1*
3,5-4,0	3951-7050	B=15,11-24,00 en L<=146,00	C2b C3b	Klasse IV + Europa I breed Klasse Va +Europa II breed	19,0 22,8	85-105 95-110	3,0 3,5-4,0	901-3350 3351-7250	B=12,61-19,10 en L<=136,00 B>19,10 en L<=136	7,0* alleen voor klasse IV koppelverband 9,1*
3,5-4,0	7051-12000 (7051-9000)	B=15,11-24,00 en L=146,01-200	C4	Klasse Va + 3 Europa II	22,8	185	3,5-4,0	>=7251	B>12,60 en L>=136,01	9,1*
3,5-4,0	12001-18000 (12001-15000)	B=15,11-24,00 en L>=200,01								9,1*
3,5-4,0	12001-18000 (12001-15000)	B>=24,01 en L=alle								9,1*

Figure A.4: CEMT Classes of ships part 2 [101]

A.3. Distribution fitting

Table A.1: Fit Statistics for Various Distributions

Distribution	sumsquare_error	AIC	BIC	KS Statistic	KS p-value
genhyperbolic	1.5743	451.6611	468.3967	0.0534	0.5694
laplace_asymmetric	1.6141	445.8787	455.9200	0.0498	0.6559
dgamma	1.6355	444.5963	454.6376	0.0626	0.3683

Continued on next page

Table A.1 – *Continued from previous page*

Distribution	sumsquare_error	AIC	BIC	KS Statistic	KS p-value
skewcauchy	1.6467	488.0257	498.0670	0.0798	0.1303
foldcauchy	1.6598	457.1731	467.2144	0.0932	0.0486
laplace	1.6719	440.7989	447.4931	0.0617	0.3853
cauchy	1.6787	483.5927	490.2869	0.0672	0.2867
dweibull	1.6815	445.1109	455.1522	0.0605	0.4095
gennorm	1.7837	435.6970	445.7383	0.0667	0.2948
hypsecant	1.9587	433.5909	440.2851	0.0645	0.3332
vonmises_line	1.9963	397.0896	407.1309	0.1125	0.0090
vonmises	2.0076	407.6059	417.6473	0.0768	0.1592
burr	2.0461	431.8706	445.2590	0.0710	0.2288
genlogistic	2.0467	429.6601	439.7014	0.0710	0.2293
mielke	2.0493	430.9419	444.3303	0.0718	0.2187
logistic	2.0578	426.8034	433.4976	0.0747	0.1827
triang	2.1495	395.3594	405.4008	0.1048	0.0184
recipinvgauss	2.1659	420.3240	430.3654	0.0861	0.0839
alpha	2.1709	424.0231	434.0644	0.1026	0.0222
invgamma	2.1716	418.1867	428.2281	0.0922	0.0526
skewnorm	2.1747	417.5261	427.5674	0.0817	0.1146
betaprime	2.1764	419.3890	432.7775	0.0819	0.1133
powerlognorm	2.1770	419.3060	432.6944	0.0824	0.1092
fatiguelife	2.1786	417.1670	427.2083	0.0824	0.1089
johnsonsu	2.1787	419.1949	432.5833	0.0827	0.1070
lognorm	2.1790	417.1516	427.1929	0.0826	0.1080
geninvgauss	2.1790	419.1447	432.5331	0.0826	0.1079
pearson3	2.1790	417.1428	427.1841	0.0826	0.1079
erlang	2.1792	417.1286	427.1699	0.0826	0.1077
gamma	2.1792	417.1307	427.1721	0.0826	0.1076
nakagami	2.1794	417.1029	427.1443	0.0824	0.1088
norminvgauss	2.1798	419.1544	432.5428	0.0838	0.0992
powernorm	2.1823	416.8787	426.9200	0.0831	0.1040
jf_skew_t	2.1825	418.9512	432.3397	0.0844	0.0948
exponnorm	2.1844	416.7979	426.8392	0.0851	0.0899
nct	2.1849	418.7245	432.1129	0.0851	0.0900
exponweib	2.1862	424.4012	437.7896	0.1054	0.0175

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Table A.1 – *Continued from previous page*

Distribution	sumsquare_error	AIC	BIC	KS Statistic	KS p-value
norm	2.1868	414.6128	421.3070	0.0858	0.0854
t	2.1868	416.6128	426.6541	0.0858	0.0854
crystalball	2.1868	418.6128	432.0012	0.0858	0.0854
loggamma	2.1929	416.0787	426.1200	0.0879	0.0734
invgauss	2.1974	419.0100	429.0513	0.1078	0.0141
gengamma	2.2110	415.7296	429.1181	0.0846	0.0937
johnsonsb	2.2194	415.1149	428.5033	0.0852	0.0892
genextreme	2.2210	411.9507	421.9920	0.0868	0.0793
burr12	2.2310	413.3938	426.7822	0.0856	0.0871
beta	2.2391	413.1070	426.4954	0.0869	0.0790
gausshyper	2.2442	416.5542	436.6369	0.0876	0.0752
weibull_min	2.2447	410.1221	420.1634	0.0866	0.0805
truncnorm	2.2737	401.6395	415.0279	0.1193	0.0046
cosine	2.3292	399.2923	405.9865	0.0929	0.0500
maxwell	2.3429	407.6702	414.3644	0.1342	0.0009
invweibull	2.3801	427.7861	437.8274	0.1343	0.0009
gumbel_r	2.3802	425.7813	432.4755	0.1343	0.0009
anglit	2.4681	385.3705	392.0648	0.1173	0.0057
gompertz	2.4750	387.9245	397.9658	0.1100	0.0114
kstwobign	2.5465	416.8699	423.5641	0.1603	0.0000
rayleigh	2.6061	395.1970	401.8912	0.1810	0.0000
moyal	2.6199	429.5415	436.2358	0.1544	0.0001
gumbel_l	2.6204	409.4865	416.1808	0.1413	0.0004
genexpon	2.6550	398.2858	415.0214	0.1902	0.0000
semicircular	2.7172	368.6038	375.2981	0.1478	0.0002
rice	2.7201	401.6817	411.7230	0.2239	0.0000
argus	2.7830	382.3719	392.4132	0.1850	0.0000
truncweibull_min	2.8649	368.3400	385.0755	0.1297	0.0015
landau	2.9329	460.1989	466.8931	0.2255	0.0000
powerlaw	3.0589	366.5878	376.6291	0.1875	0.0000
halfgennorm	3.1017	374.7006	384.7419	0.2361	0.0000
kappa3	3.1147	369.6128	379.6541	0.1995	0.0000
genhalflogistic	3.1260	365.8746	375.9159	0.1953	0.0000
uniform	3.1642	358.4247	365.1189	0.1793	0.0000

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Table A.1 – *Continued from previous page*

Distribution	sumsquare_error	AIC	BIC	KS Statistic	KS p-value
bradford	3.1651	360.4274	370.4687	0.1800	0.0000
wrapcauchy	3.1680	367.8540	377.8953	0.2047	0.0000
truncpareto	3.2377	397.1820	410.5705	0.2381	0.0000
ksone	3.2444	396.8890	406.9303	0.2123	0.0000
kappa4	3.2707	362.8017	376.1901	0.1935	0.0000
tukeylambda	3.3138	360.8329	370.8742	0.1890	0.0000
loglaplace	3.4199	440.5424	450.5837	0.2540	0.0000
trapz	3.4669	417.0040	430.3924	0.3445	0.0000
trapezoid	3.4669	417.0040	430.3924	0.3445	0.0000
truncexpon	3.5086	365.9021	375.9434	0.2706	0.0000
halfnorm	3.6633	393.7620	400.4562	0.2890	0.0000
wald	3.7130	436.0183	442.7125	0.2135	0.0000
rdist	3.7368	474.0611	484.1024	0.4778	0.0000
halflogistic	3.7726	402.7726	409.4668	0.2833	0.0000
gibrat	3.7891	434.8511	441.5453	0.2236	0.0000
lomax	4.0484	426.1490	436.1903	0.2626	0.0000
halfcauchy	4.1049	453.0134	459.7076	0.2899	0.0000
ncx2	4.1333	413.9079	427.2964	0.3249	0.0000
expon	4.3408	420.0438	426.7380	0.3143	0.0000
pareto	4.3408	422.0438	432.0851	0.3143	0.0000
levy_l	4.3427	509.3691	516.0633	0.4151	0.0000
levy	4.4107	515.4518	522.1460	0.4563	0.0000
genpareto	4.6447	478.9464	488.9877	0.3317	0.0000
arcsine	4.9469	389.5935	396.2877	0.2500	0.0000
foldnorm	5.1856	441.4405	451.4819	0.4780	0.0000
fisk	7.1879	495.7968	505.8381	0.4567	0.0000
ncf	7.2153	535.1780	551.9135	0.3799	0.0000
weibull_max	8.6321	497.2179	507.2592	0.5293	0.0000
f	9.5573	555.0858	568.4742	0.4673	0.0000
rel_breitwigner	10.5522	678.8219	688.8632	0.7396	0.0000
chi2	11.7276	524.7258	534.7671	0.6492	0.0000
chi	12.8766	684.0877	694.1291	0.7265	0.0000
exponpow	16.5439	590.4606	600.5019	0.7246	0.0000
dpareto_lognorm	32.1787	80.8865	100.9691	0.3303	0.0000

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Table A.1 – *Continued from previous page*

Distribution	sumsquare_error	AIC	BIC	KS Statistic	KS p-value
vonmises_fisher	inf	inf	inf	NaN	NaN
multivariate_normal	inf	inf	inf	NaN	NaN
rv_histogram	inf	inf	inf	NaN	NaN
rv_continuous	inf	inf	inf	NaN	NaN
reciprocal	inf	inf	inf	NaN	NaN
irwinhall	inf	inf	inf	NaN	NaN
kstwo	inf	inf	inf	NaN	NaN
levy_stable	inf	inf	inf	NaN	NaN
loguniform	inf	inf	inf	NaN	NaN
studentized_range	inf	inf	inf	NaN	NaN
_fit	inf	inf	inf	NaN	NaN

A.4. Case 2 Pictures

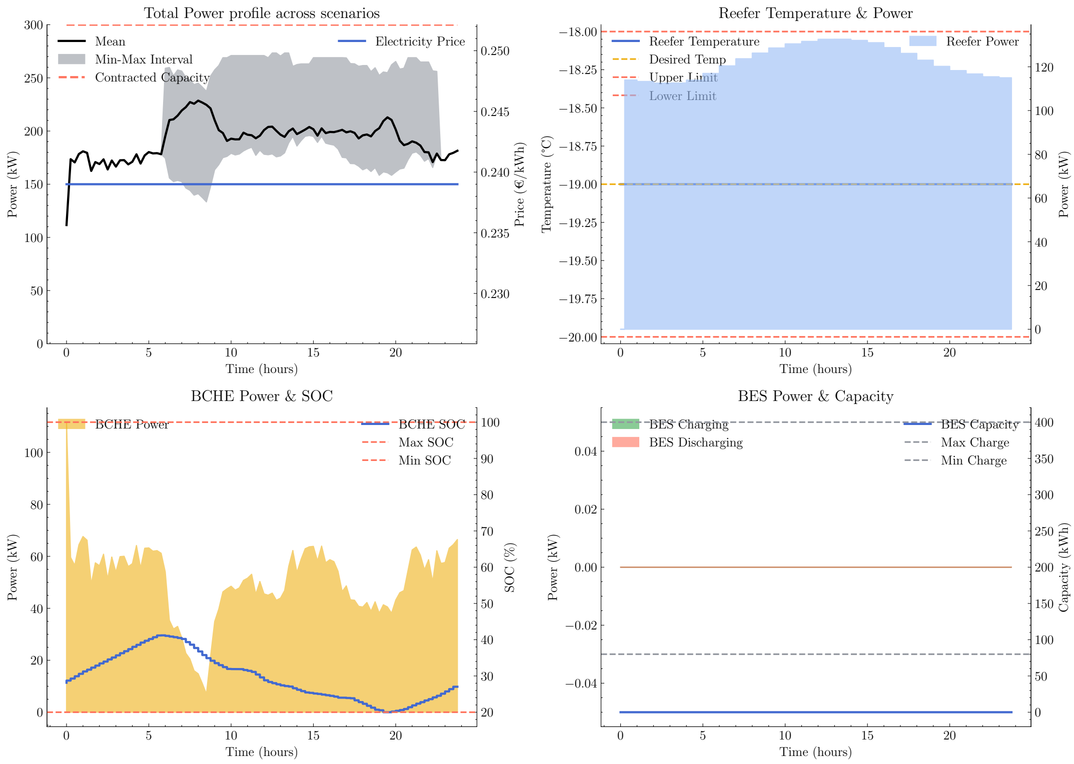


Figure A.5: Fixed electricity price cluster 1, fixed reefers, no battery energy storage

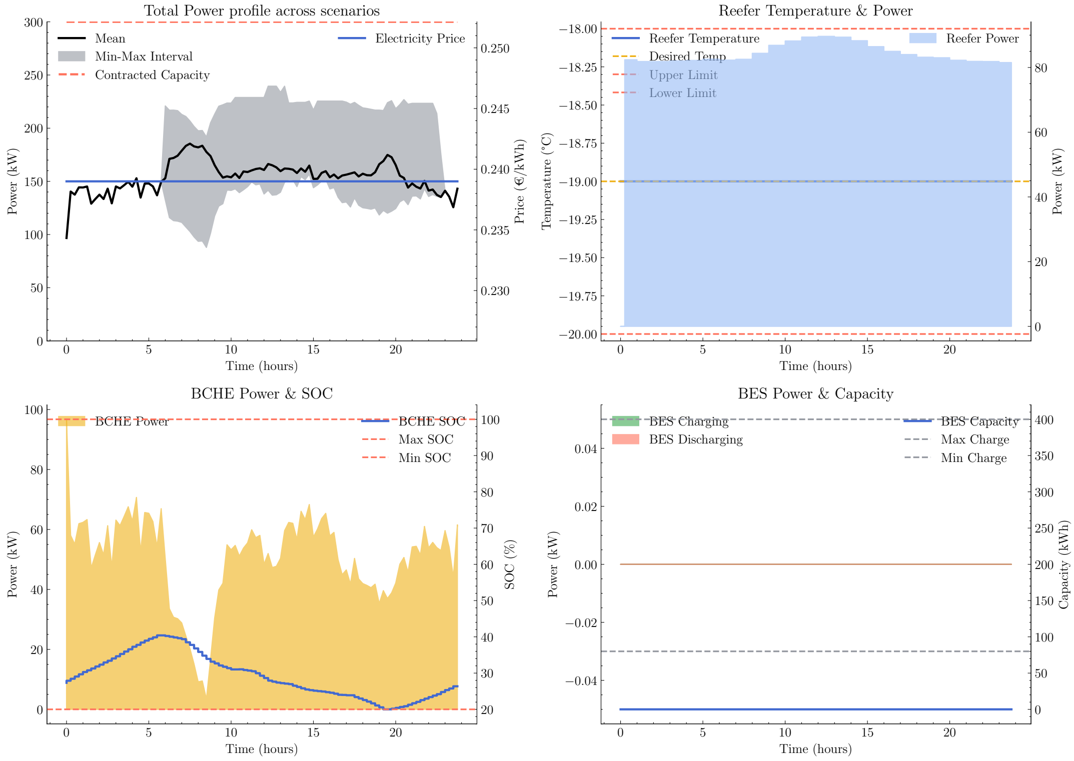


Figure A.6: Fixed electricity price cluster 2, fixed reefers, no battery energy storage

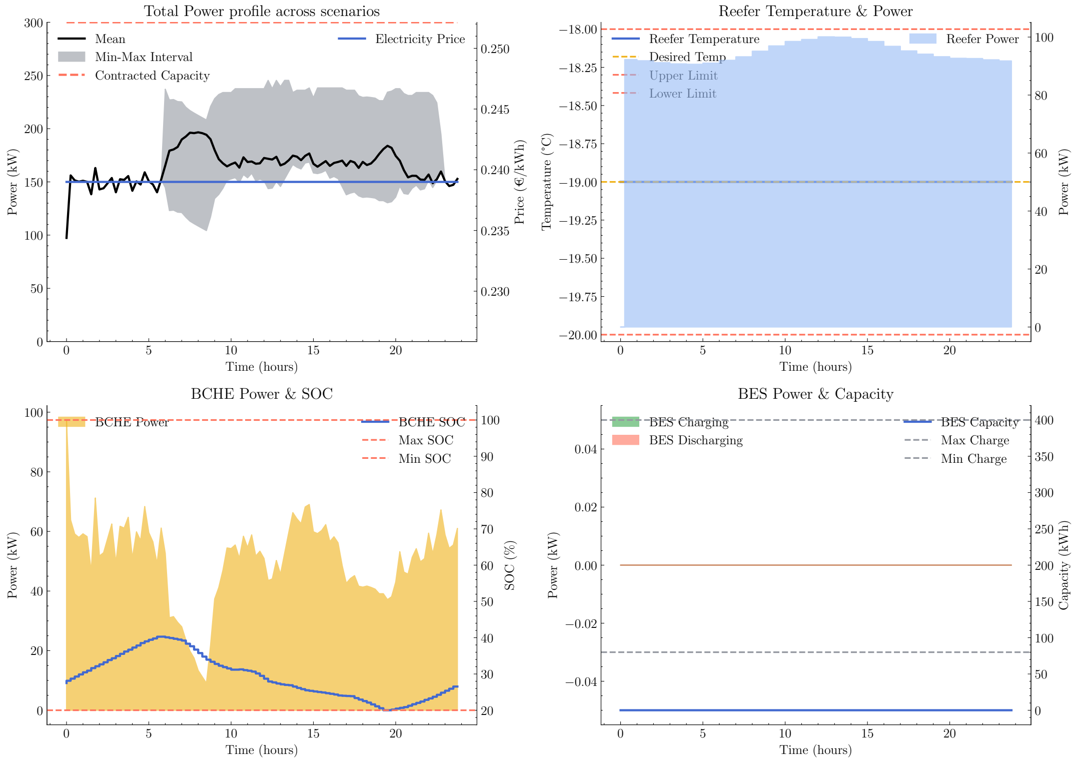


Figure A.7: Fixed electricity price cluster 3, fixed reefers, no battery energy storage

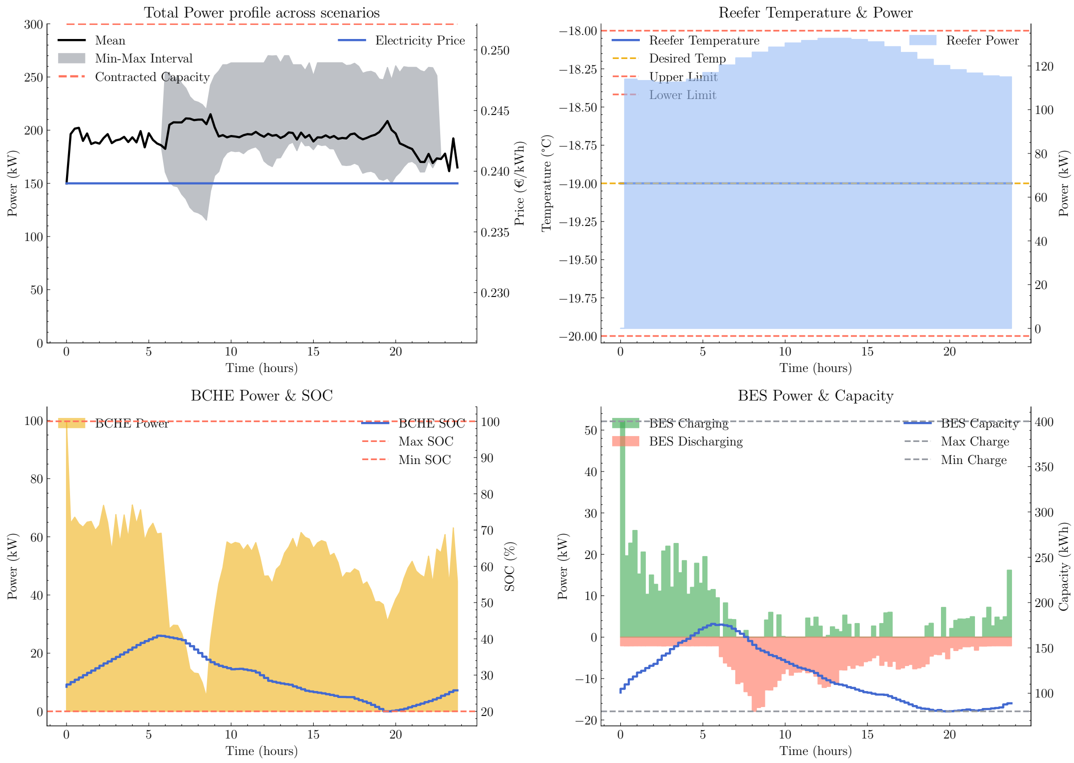


Figure A.8: Fixed electricity price cluster 1, fixed reefers, with battery energy storage

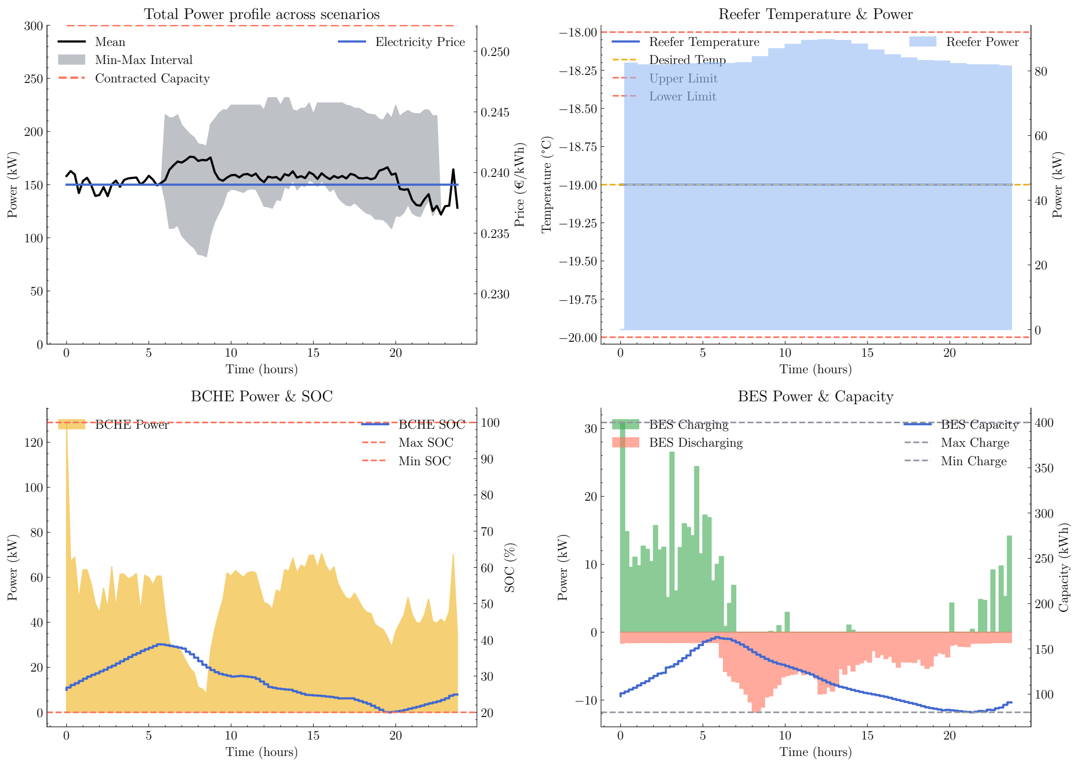


Figure A.9: Fixed electricity price cluster 2, fixed reefers, with battery energy storage

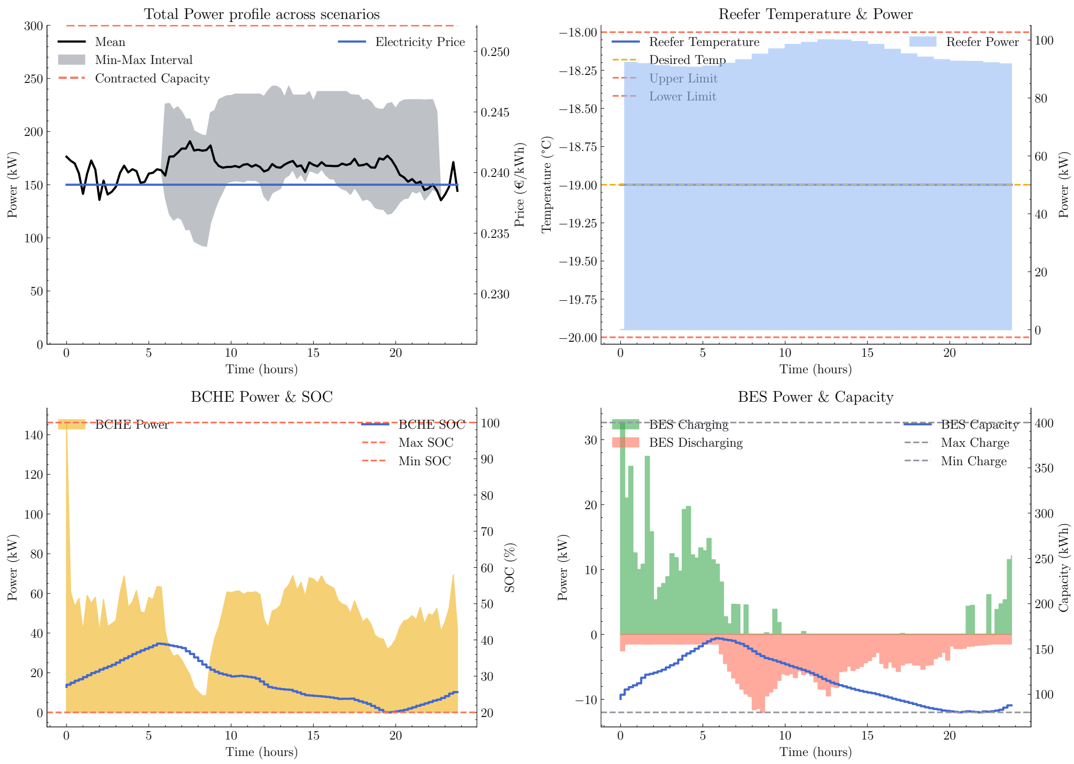


Figure A.10: Fixed electricity price cluster 3, fixed reefers, with battery energy storage

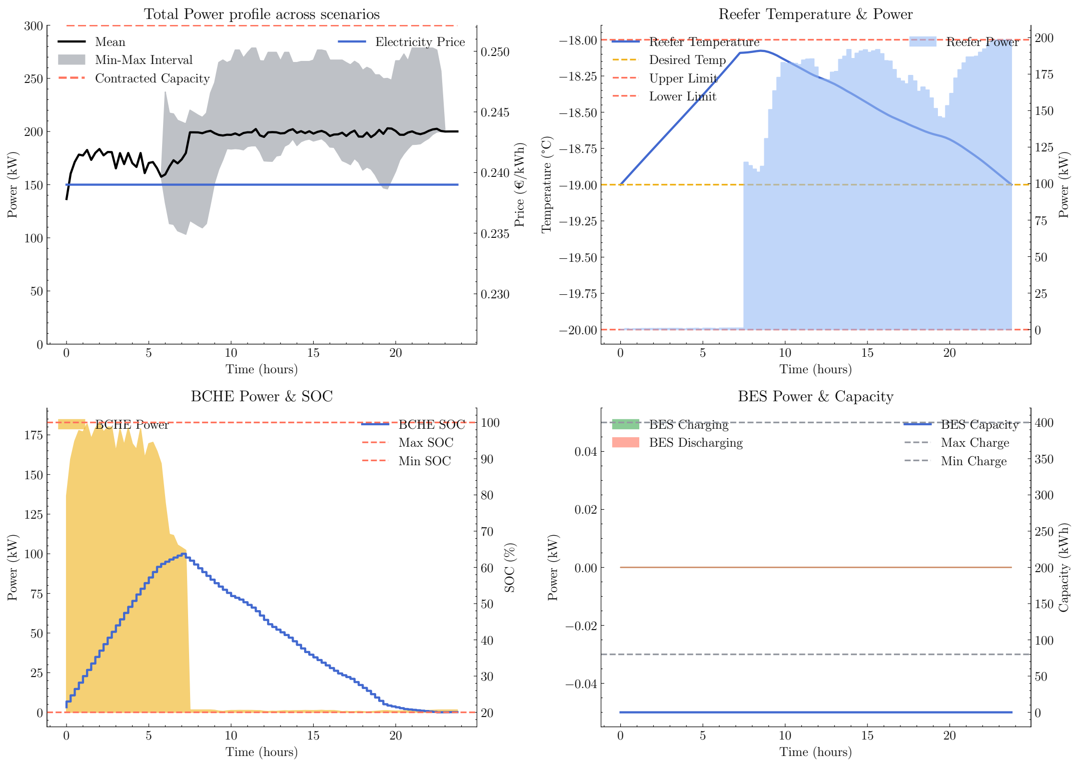
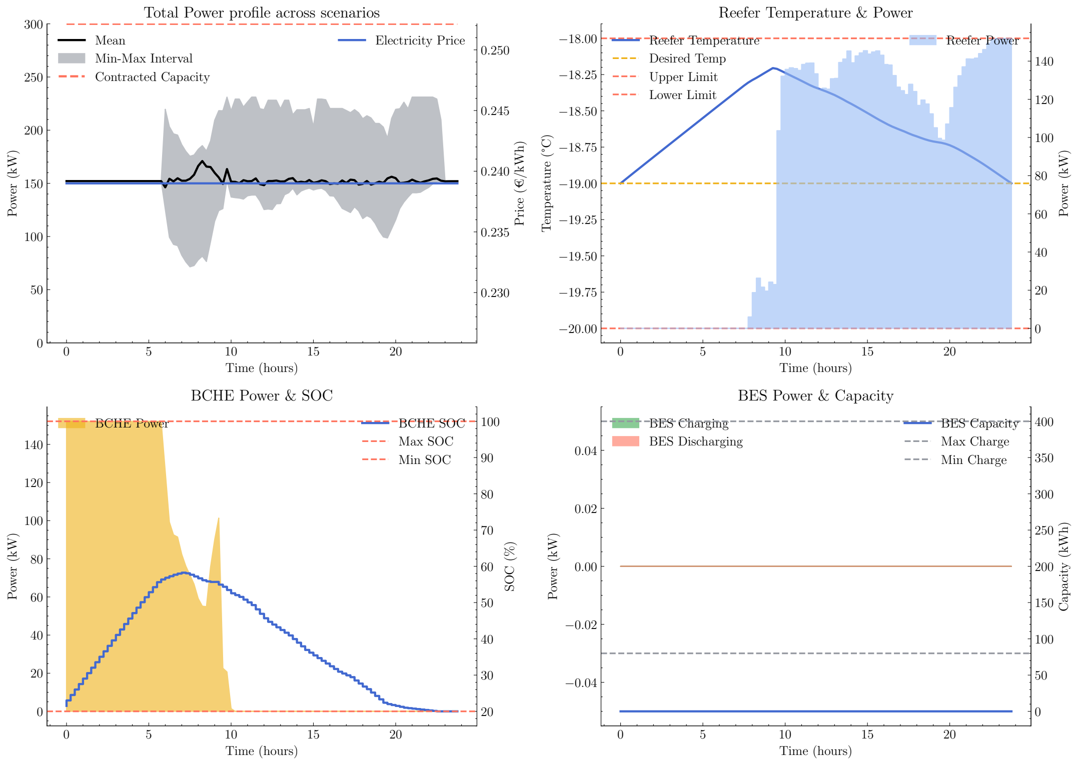


Figure A.11: Fixed electricity price cluster 1, flexible reefers, no battery energy storage



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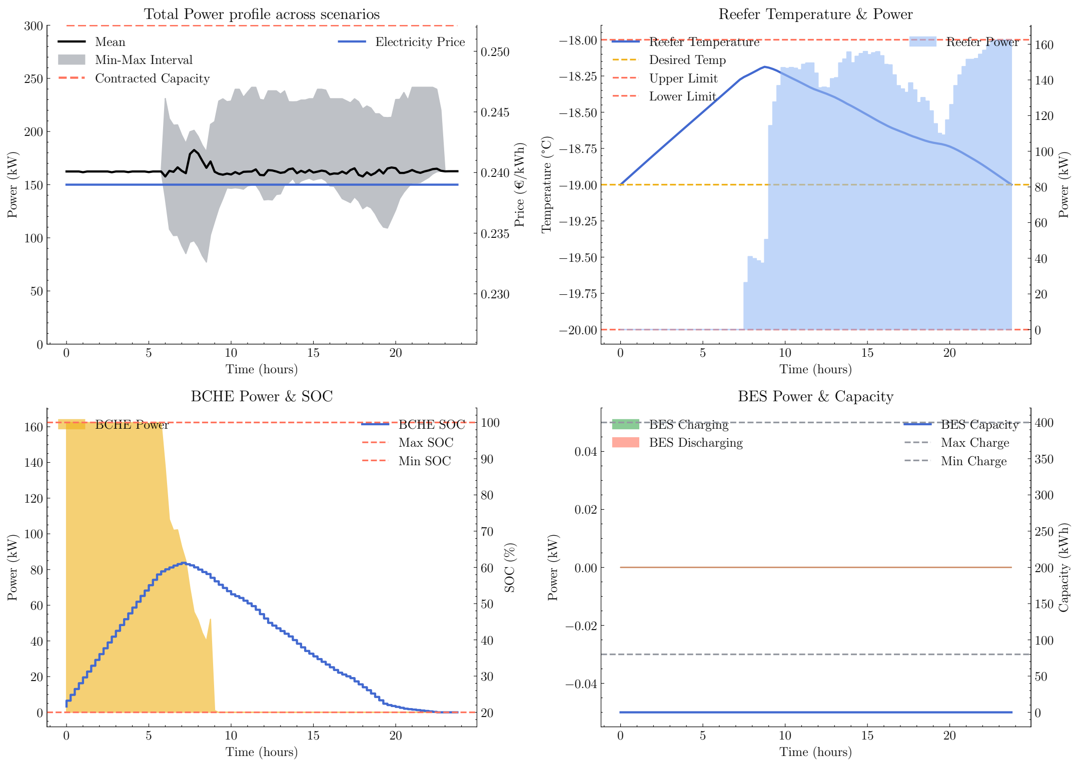

Figure A.13: Fixed electricity price cluster 3, flexible reefers, no battery energy storage

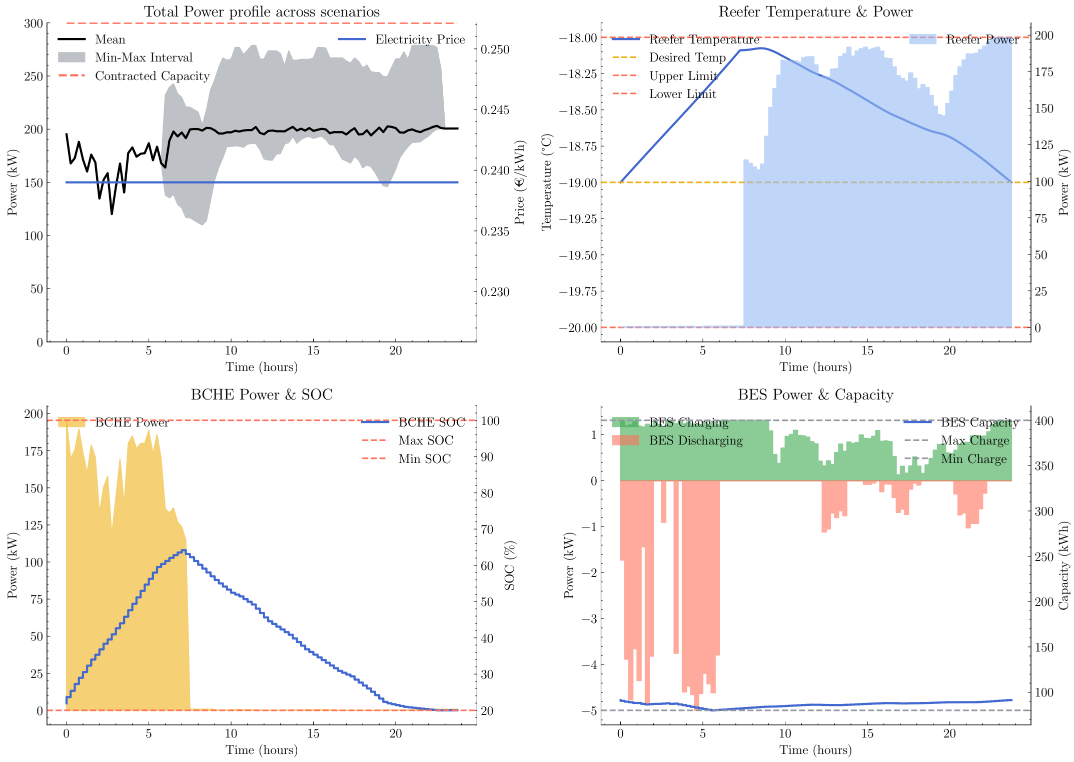

Figure A.14: Fixed electricity price cluster 1, flexible reefers, with battery energy storage

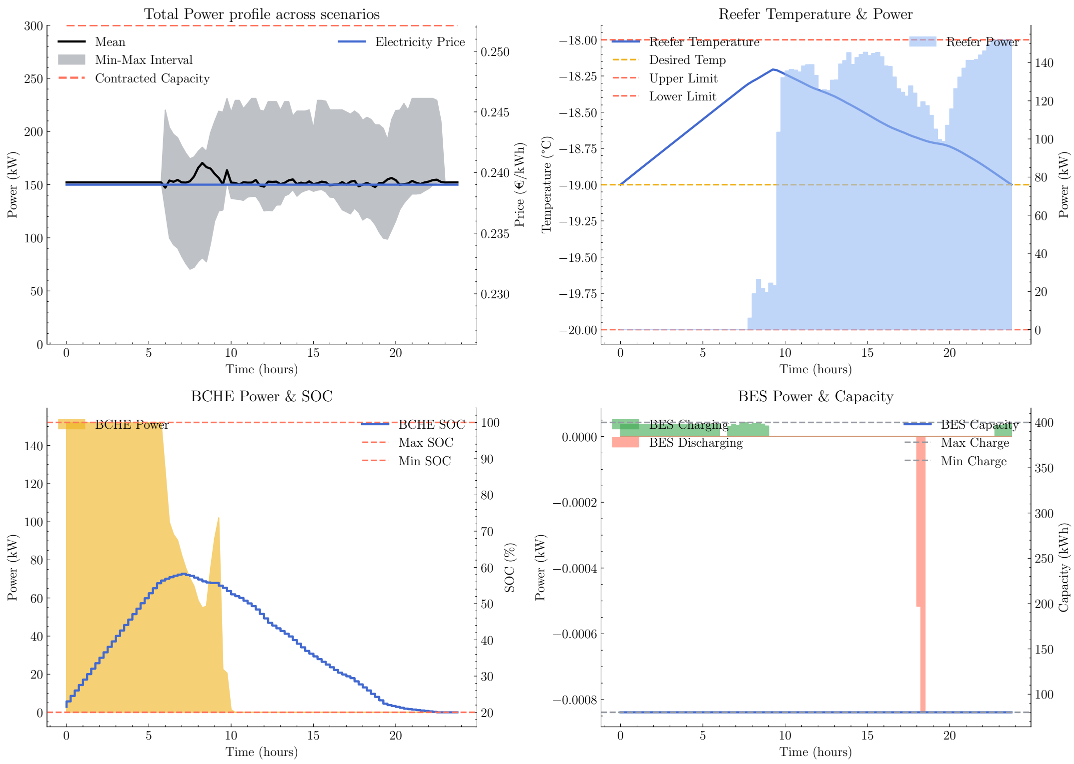

Figure A.15: Fixed electricity price cluster 2, flexible reefers, with battery energy storage

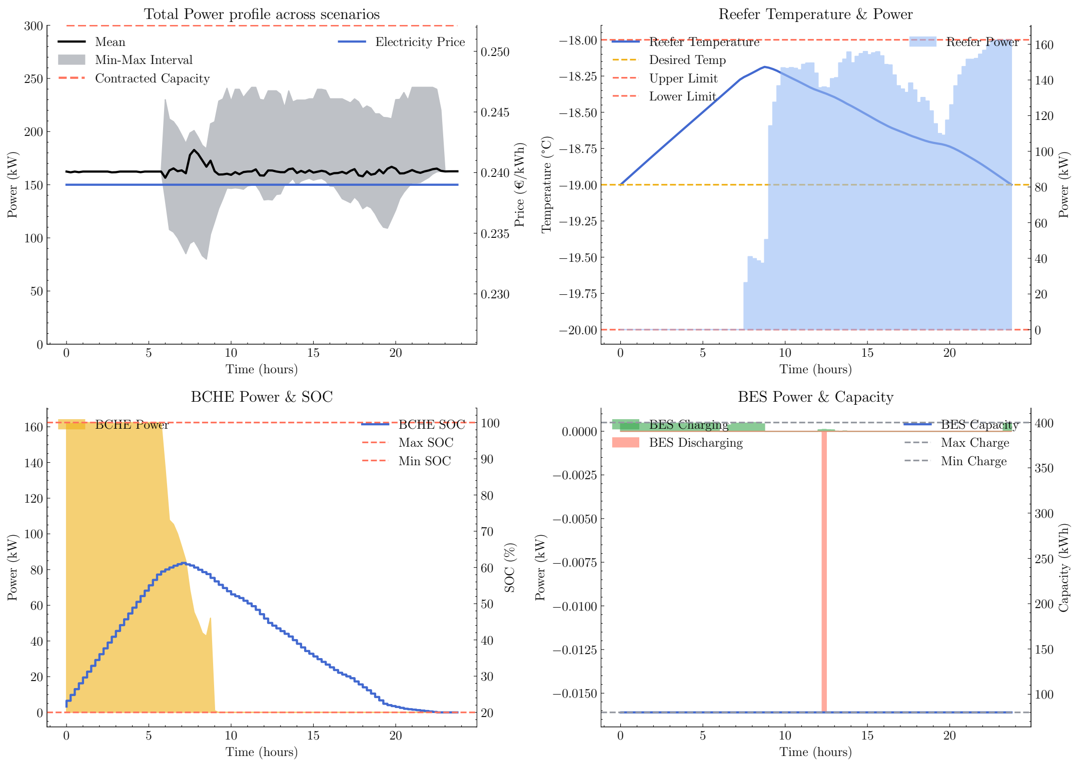

Figure A.16: Fixed electricity price cluster 3, flexible reefers, with battery energy storage

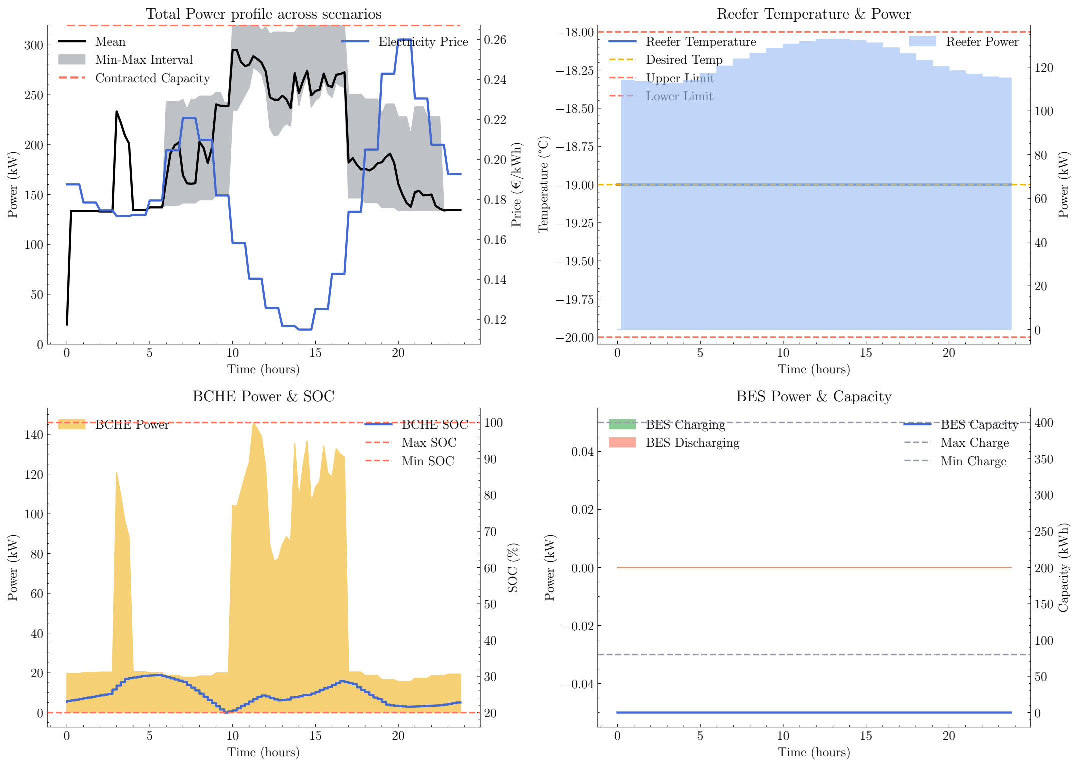

Figure A.17: Dynamic electricity price cluster 4, fixed reefers, no battery energy storage

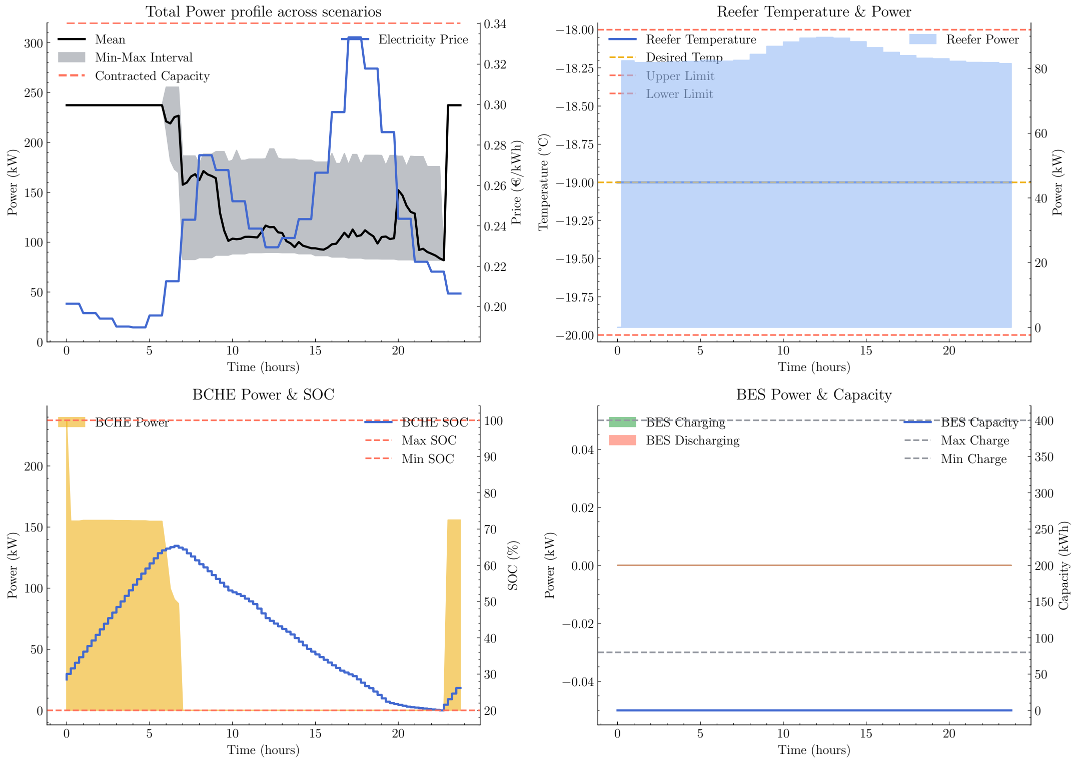

Figure A.18: Dynamic electricity price cluster 5, fixed reefers, no battery energy storage

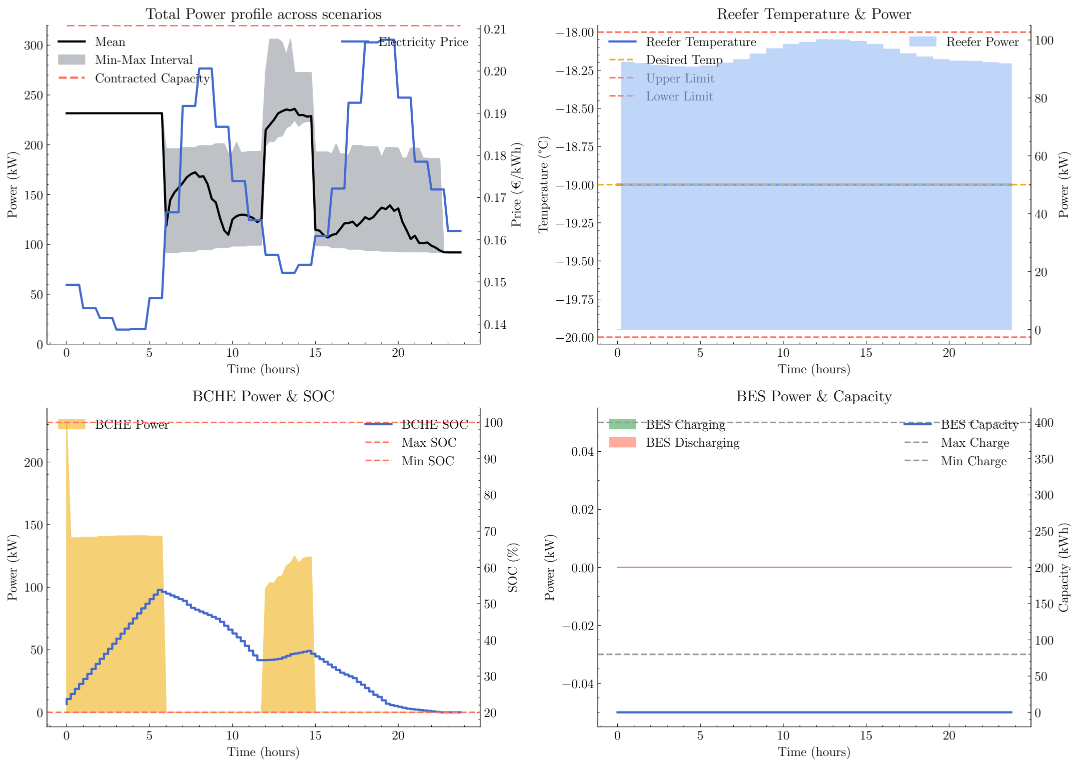

Figure A.19: Dynamic electricity price cluster 6, fixed reefers, no battery energy storage

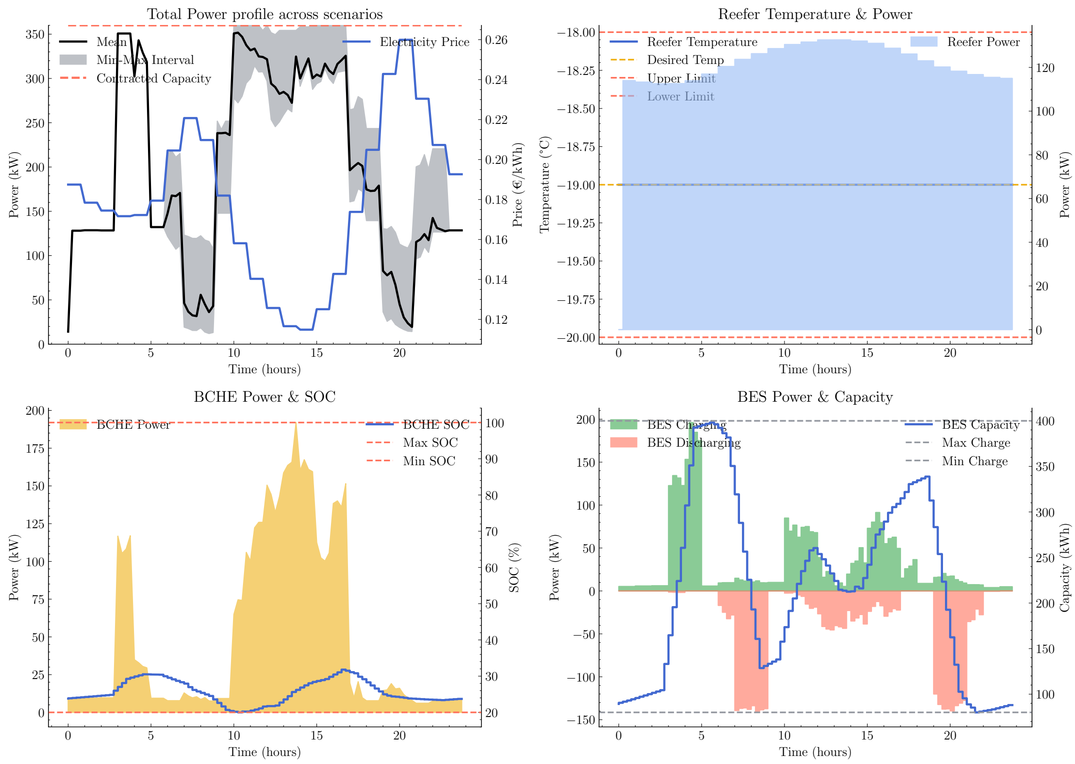

Figure A.20: Dynamic electricity price cluster 4, fixed reefers, with battery energy storage

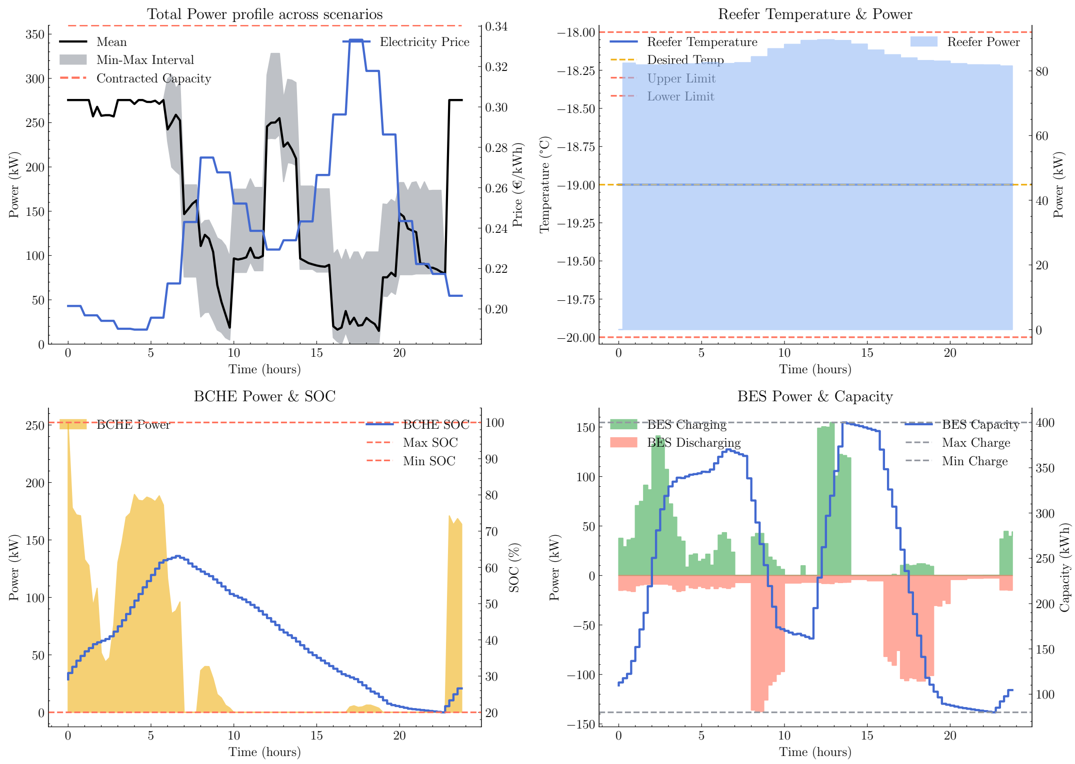

Figure A.21: Dynamic electricity price cluster 5, fixed reefers, with battery energy storage

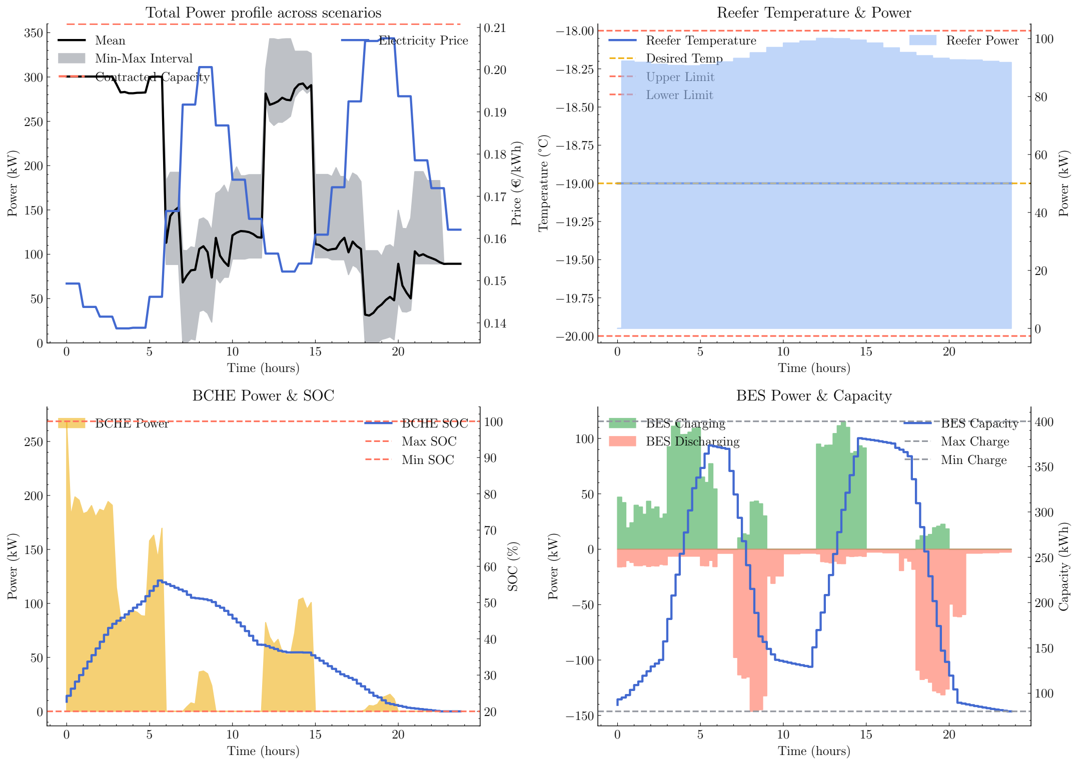

Figure A.22: Dynamic electricity price cluster 6, fixed reefers, with battery energy storage

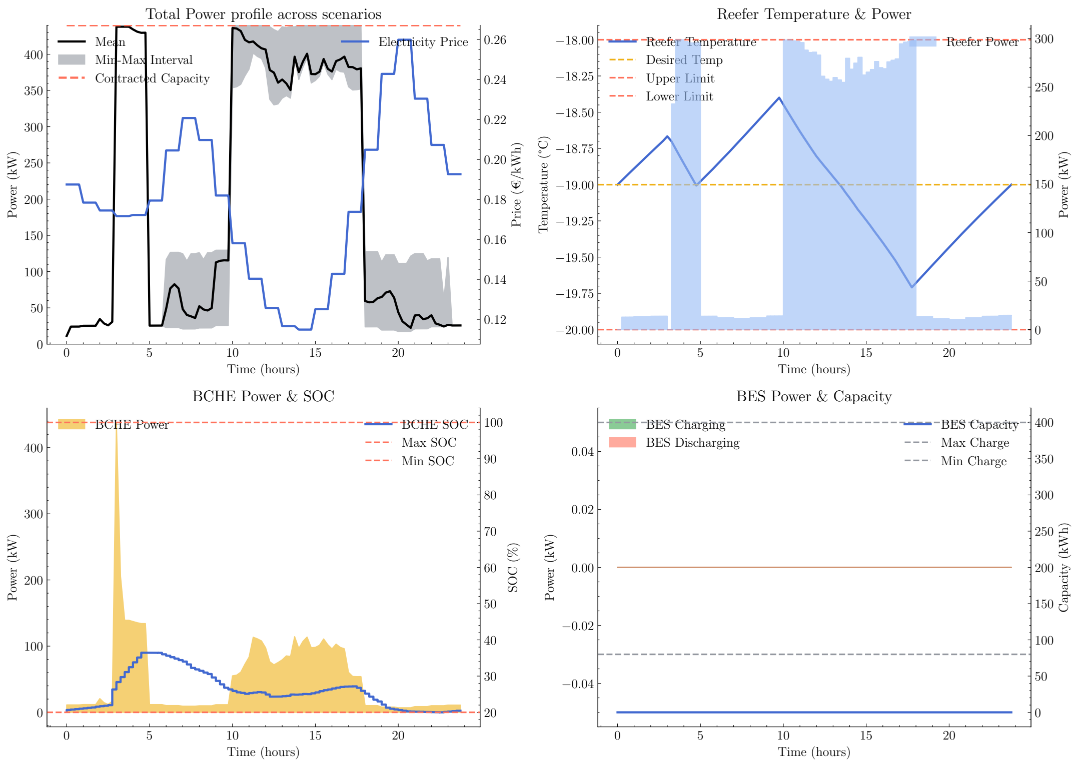

Figure A.23: Dynamic electricity price cluster 4, flexible reefers, no battery energy storage

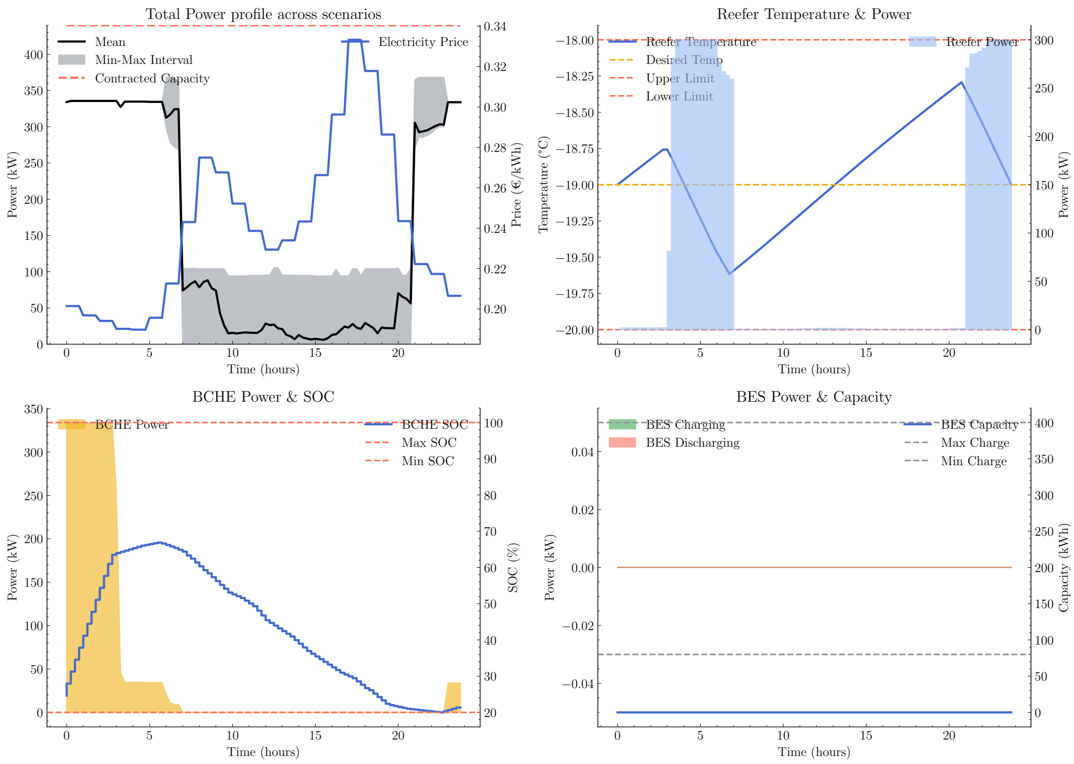

Figure A.24: Dynamic electricity price cluster 5, flexible reefers, no battery energy storage

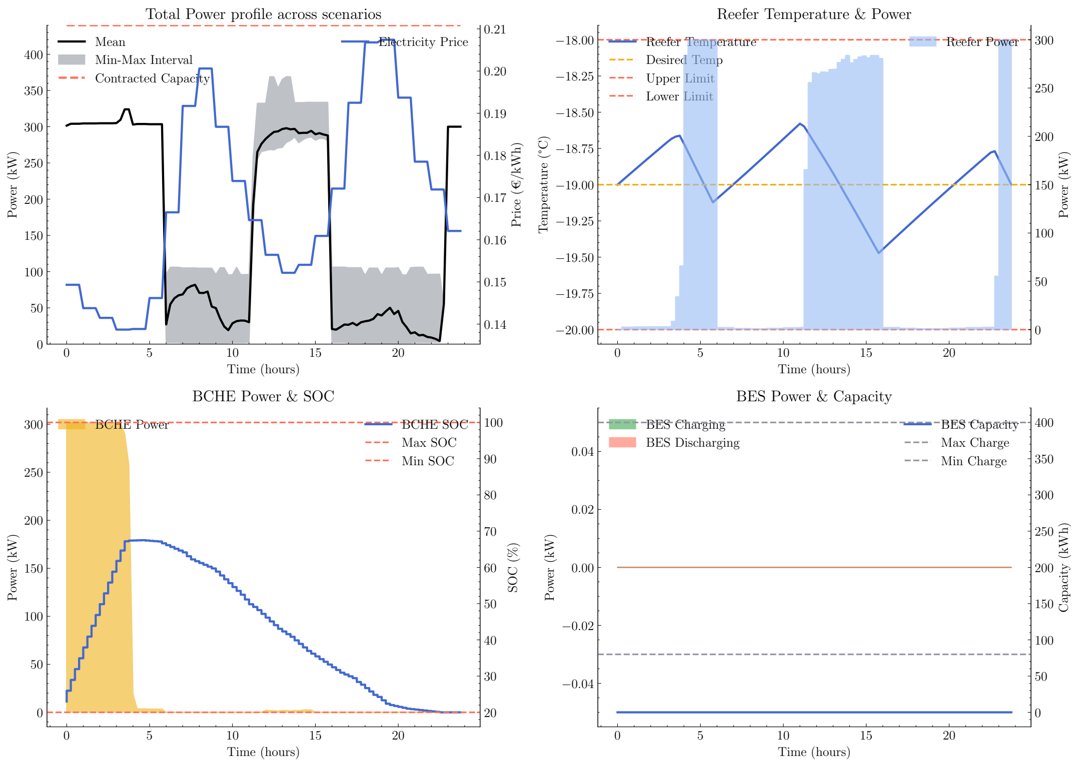

Figure A.25: Dynamic electricity price cluster 6, flexible reefers, no battery energy storage

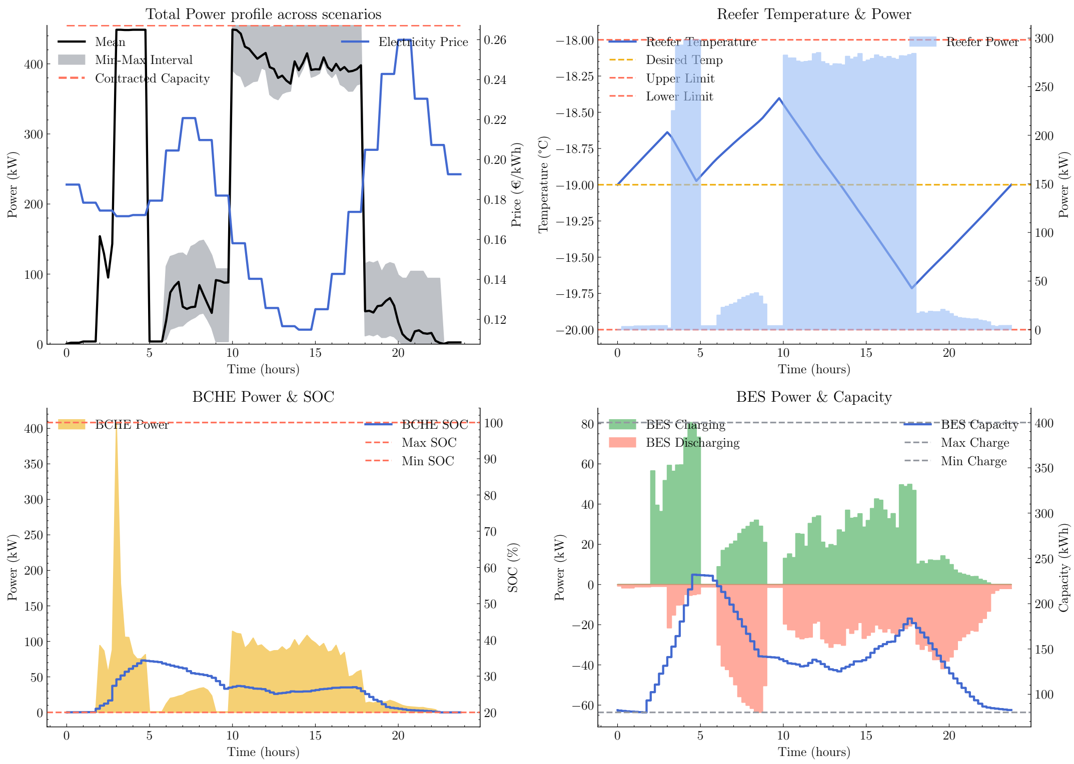

Figure A.26: Dynamic electricity price cluster 4, flexible reefers, with battery energy storage

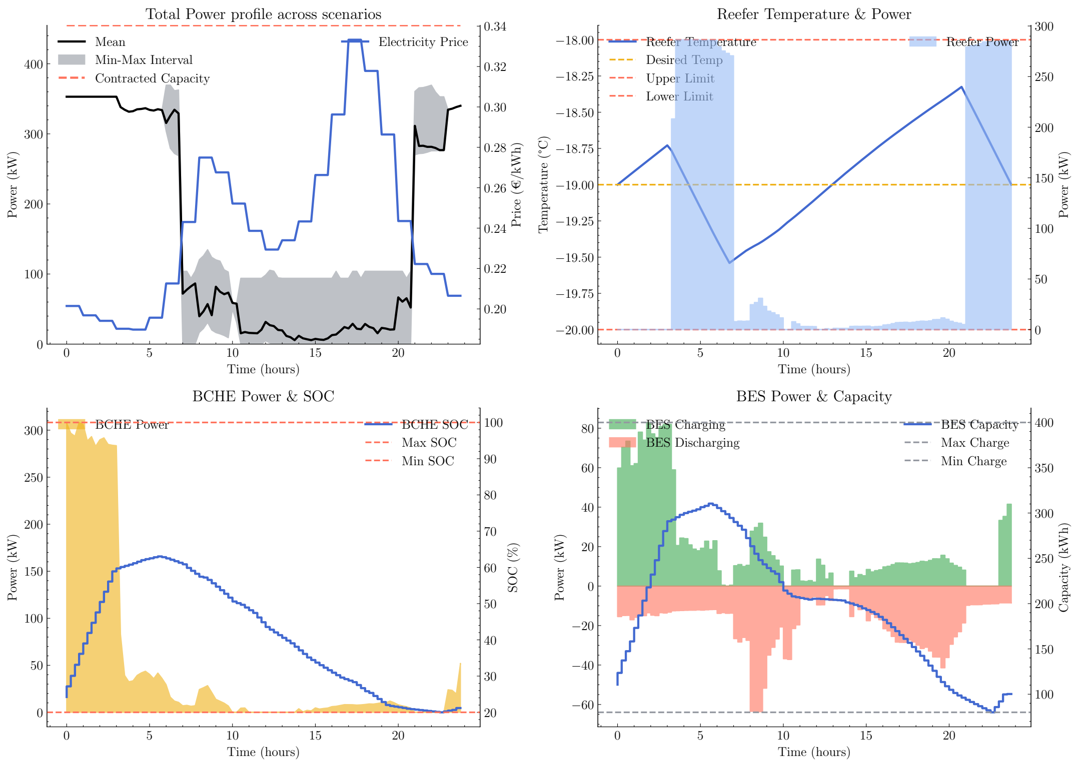

Figure A.27: Dynamic electricity price cluster 5, flexible reefers, with battery energy storage

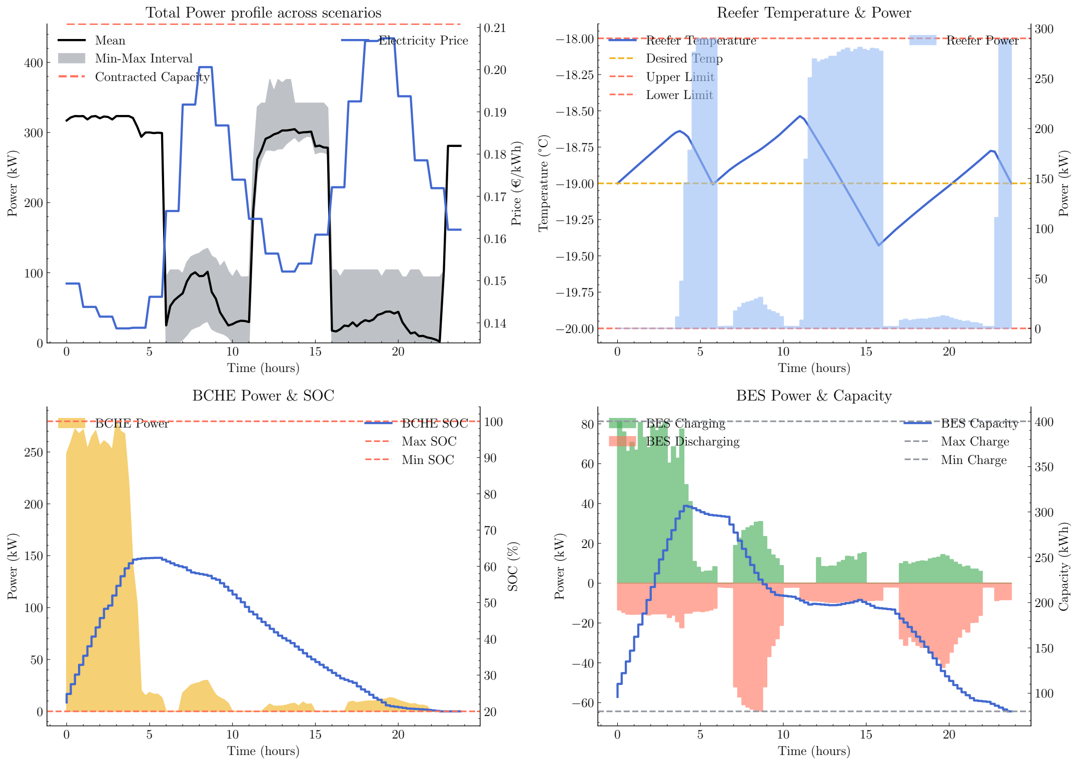

Figure A.28: Dynamic electricity price cluster 6, flexible reefers, with battery energy storage

A.5. Case 3 Pictures

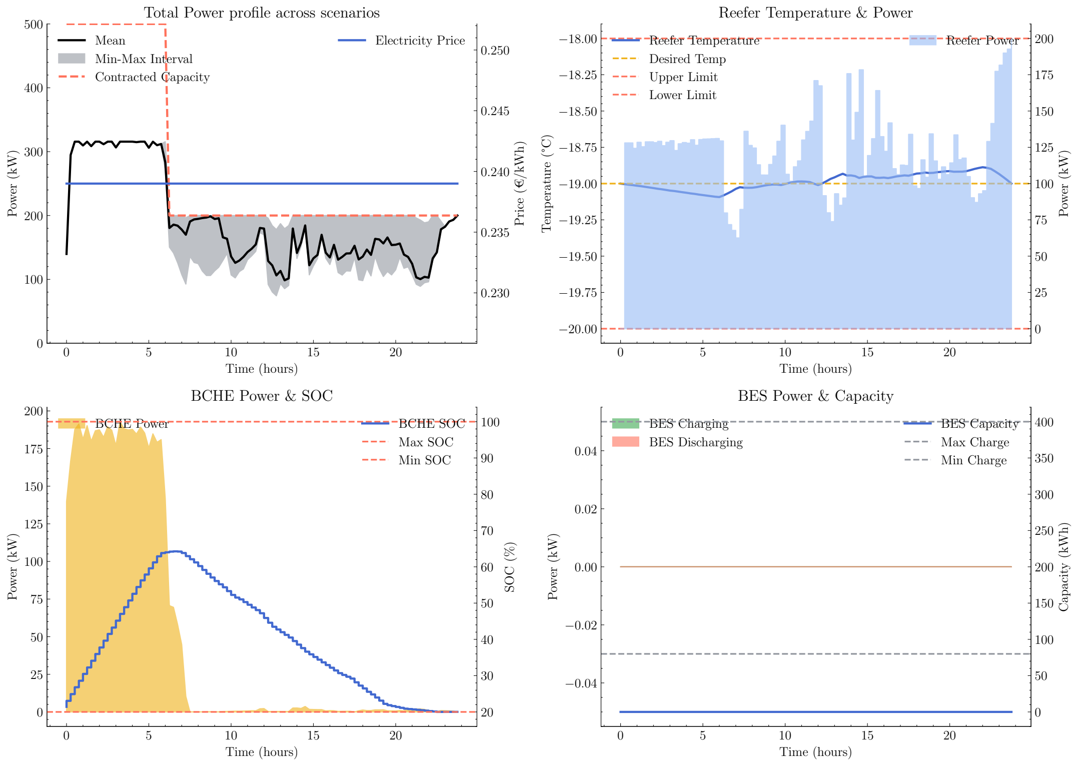

Figure A.29: TCTR, Fixed electricity price cluster 1, flexible reefers, no battery energy storage

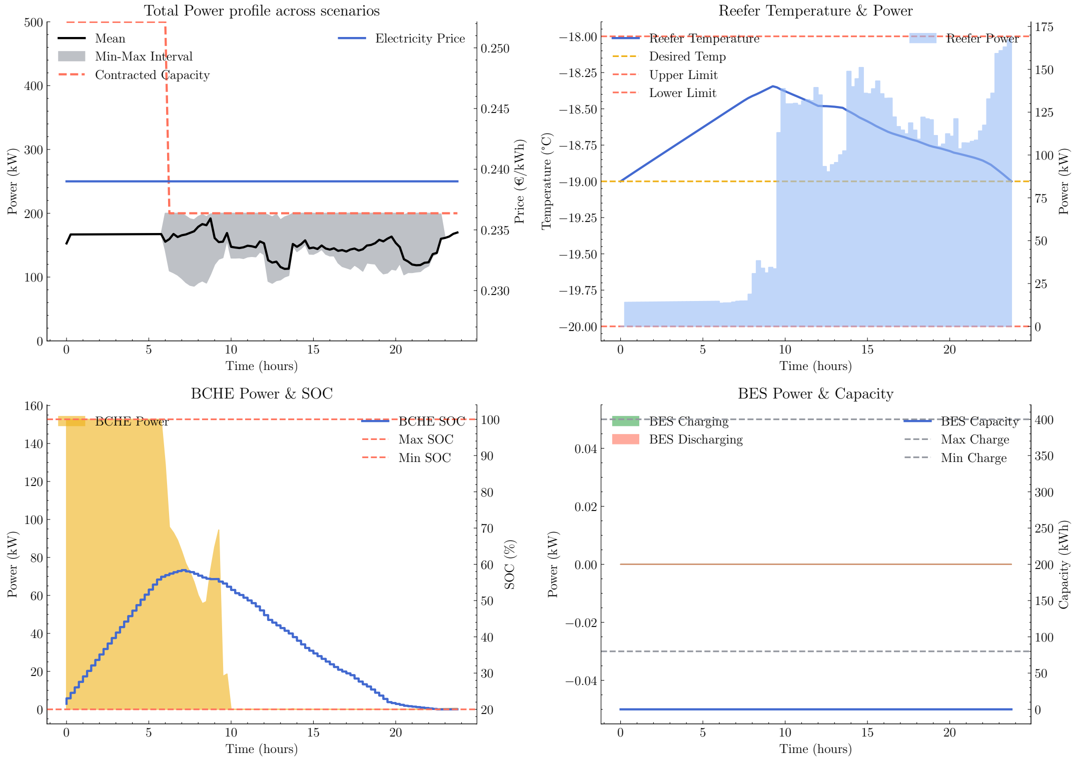

Figure A.30: TCTR, Fixed electricity price cluster 2, flexible reefers, no battery energy storage

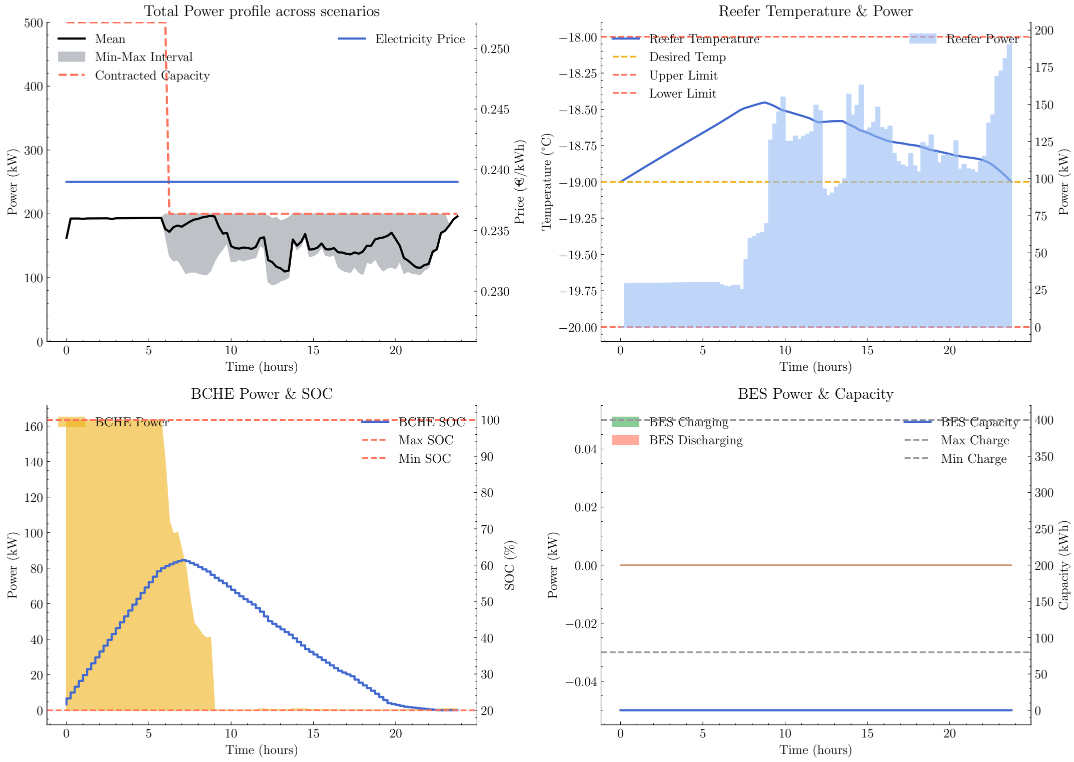

Figure A.31: TCTR, Fixed electricity price cluster 3, flexible reefers, no battery energy storage

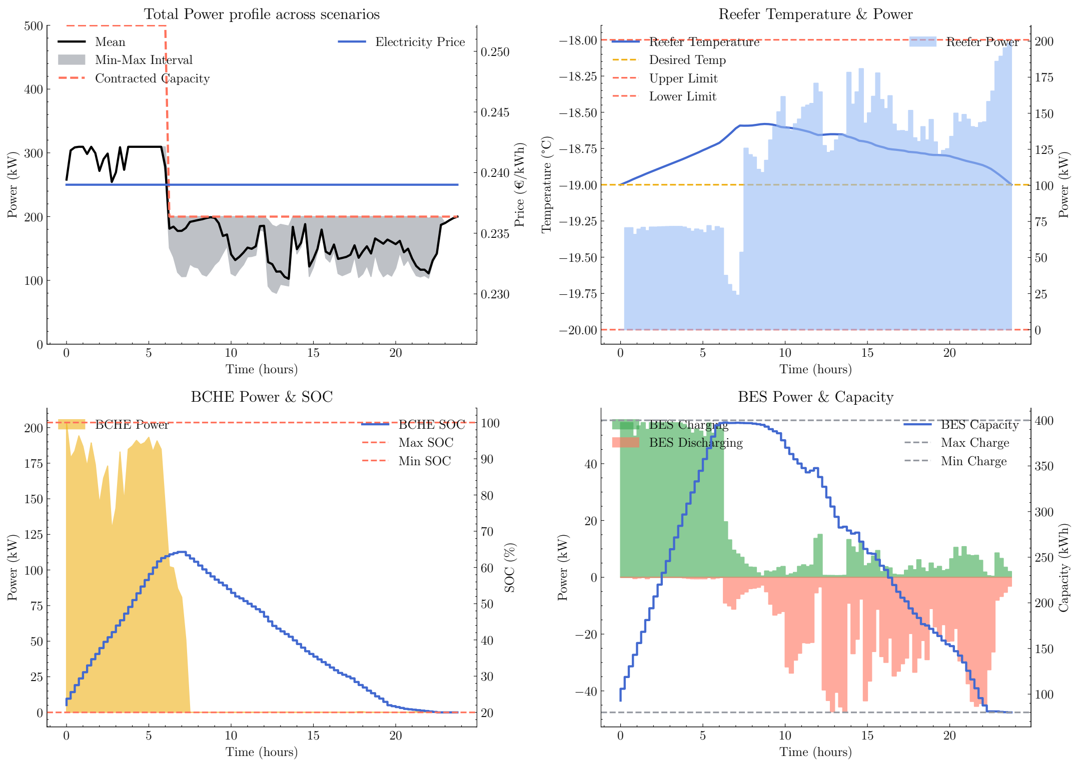

Figure A.32: TCTR, Fixed electricity price cluster 1, flexible reefers, with battery energy storage

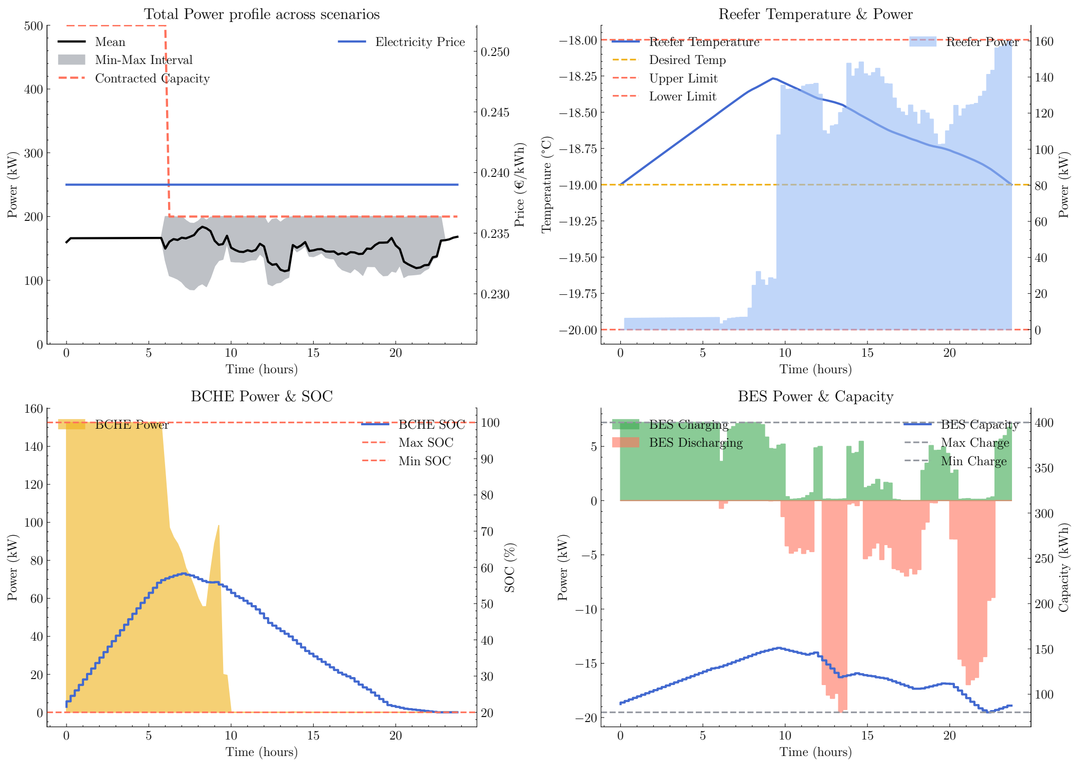

Figure A.33: TCTR, Fixed electricity price cluster 2, flexible reefers, with battery energy storage

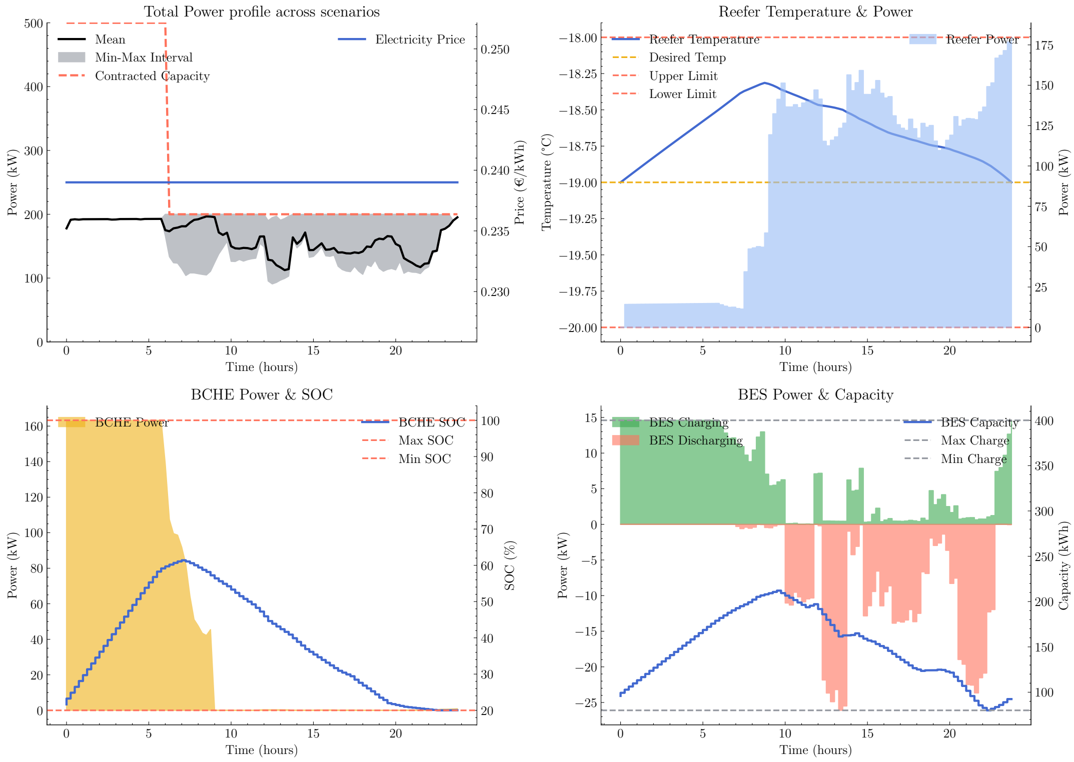

Figure A.34: TCTR, Fixed electricity price cluster 3, flexible reefers, with battery energy storage

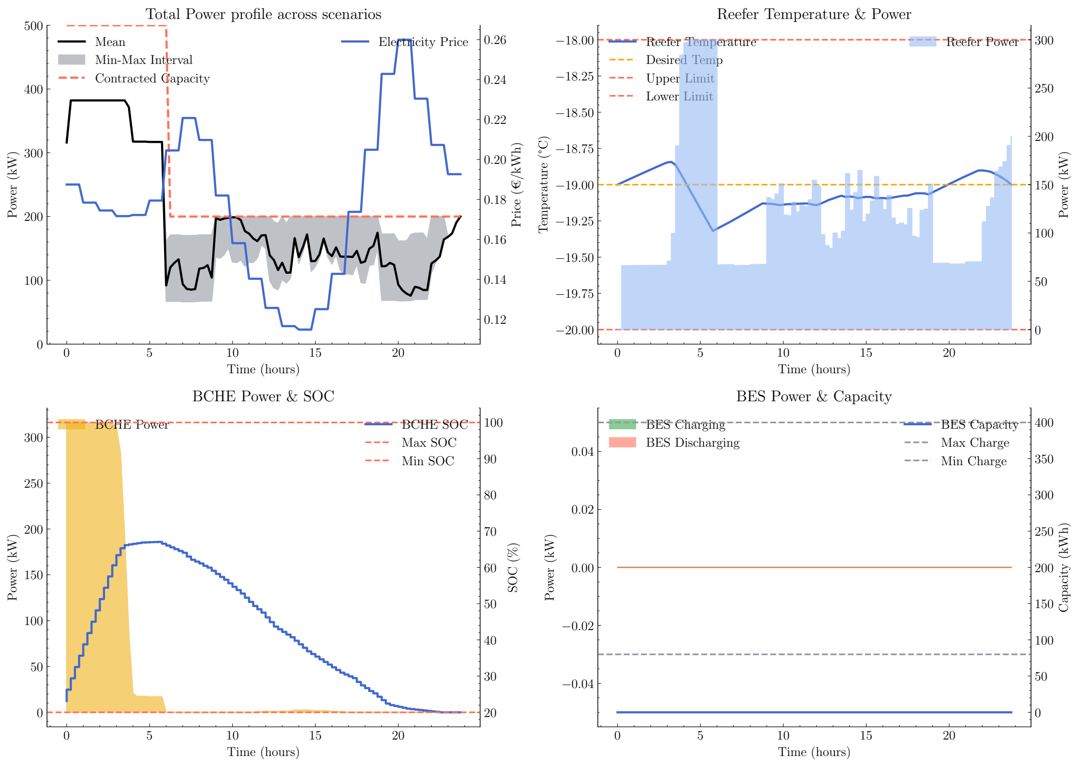

Figure A.35: TCTR, Dynamic electricity price cluster 4, flexible reefers, no battery energy storage

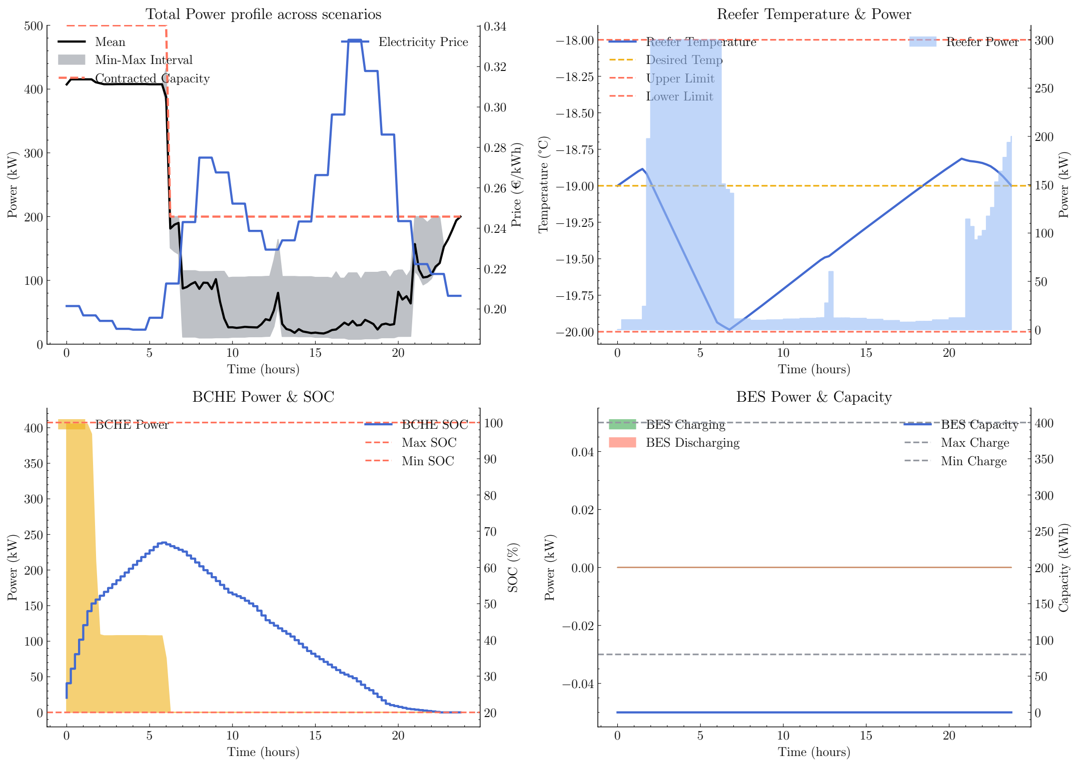

Figure A.36: TCTR, Dynamic electricity price cluster 5, flexible reefers, no battery energy storage

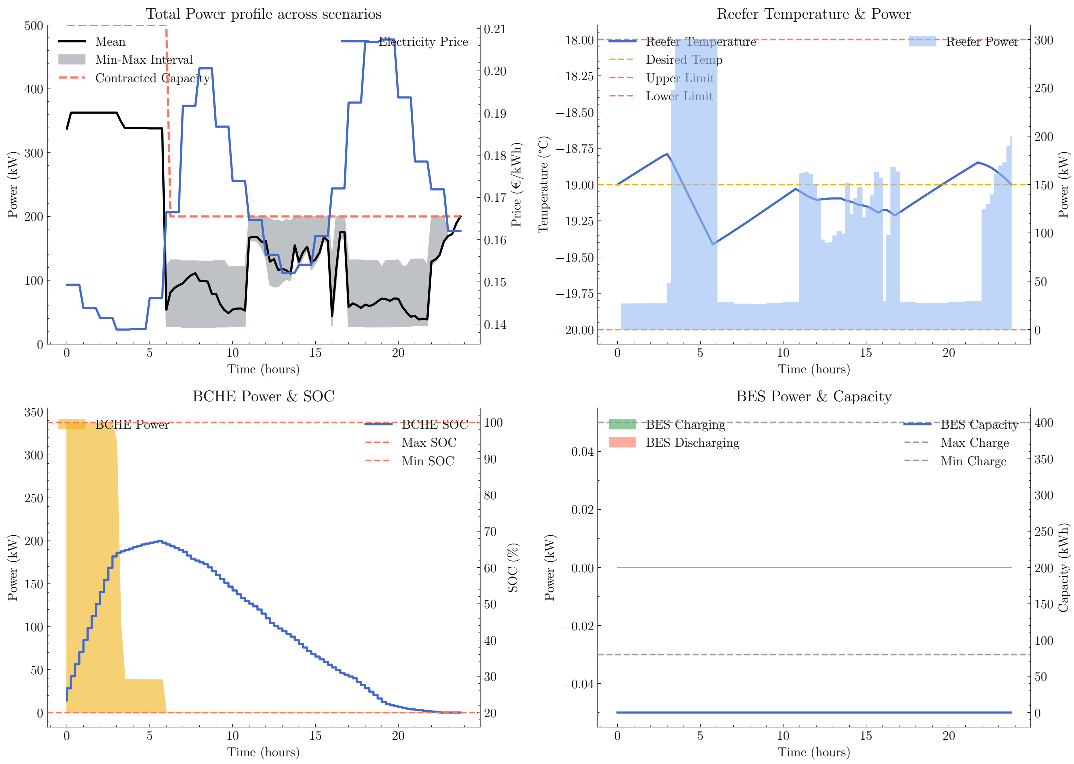

Figure A.37: TCTR, Dynamic electricity price cluster 6, flexible reefers, no battery energy storage

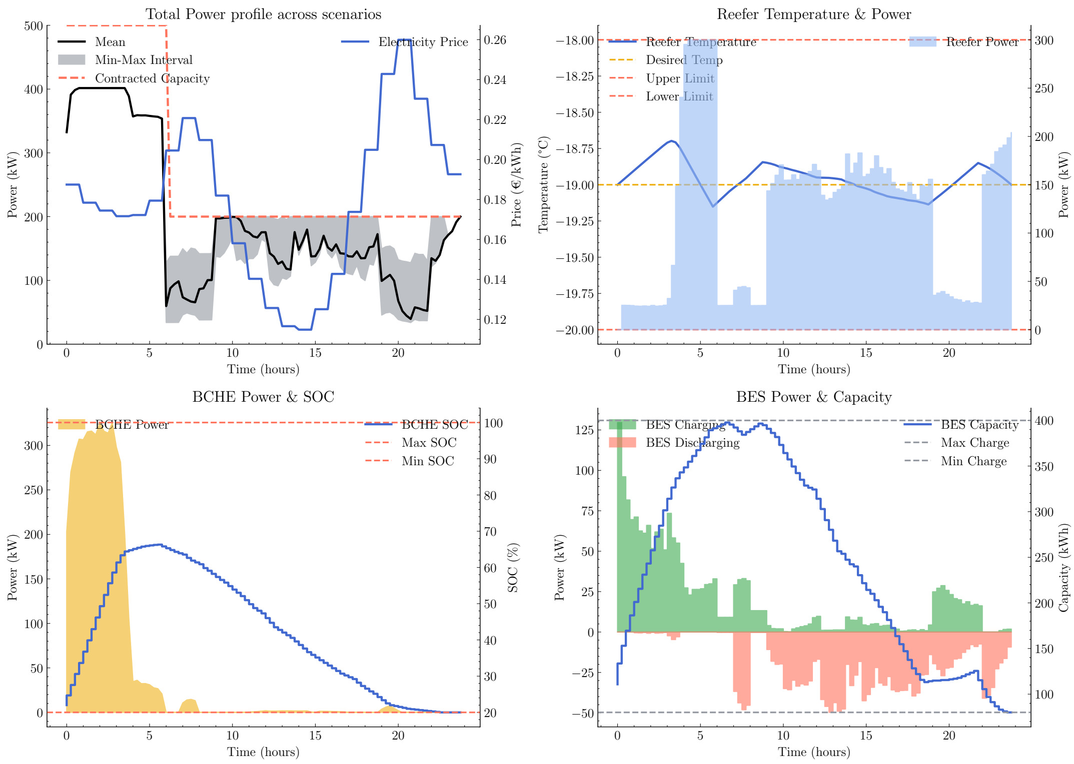

Figure A.38: TCTR, Dynamic electricity price cluster 4, flexible reefers, with battery energy storage

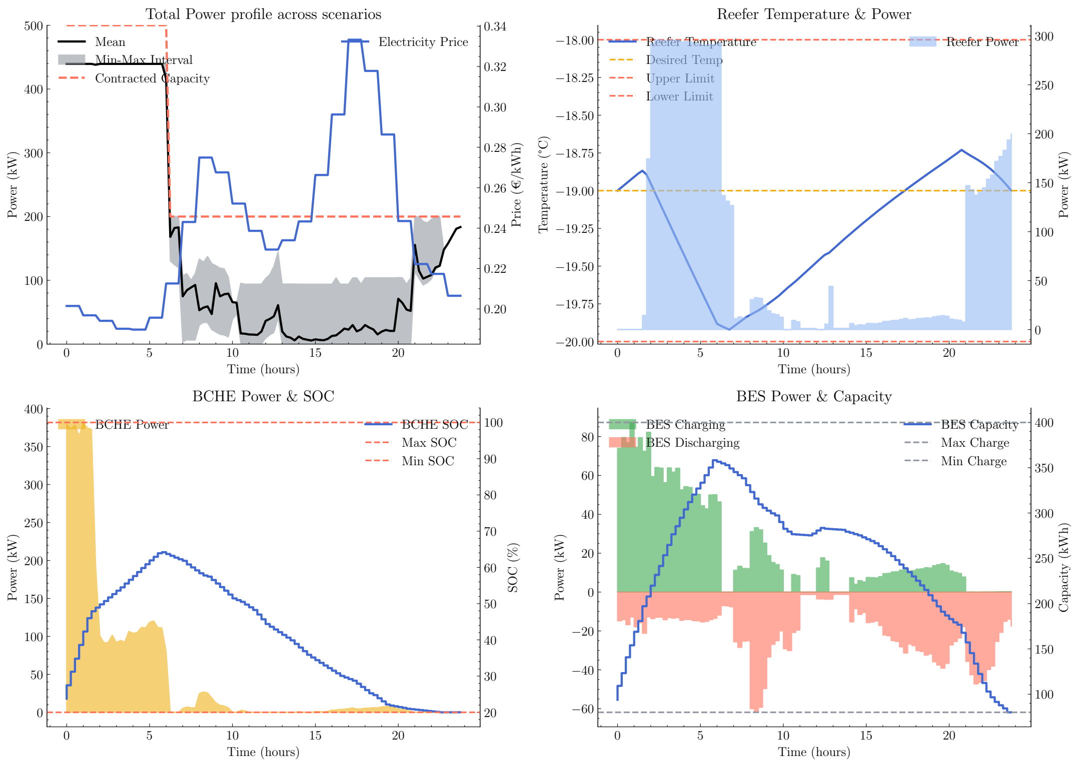

Figure A.39: TCTR, Dynamic electricity price cluster 5, flexible reefers, with battery energy storage

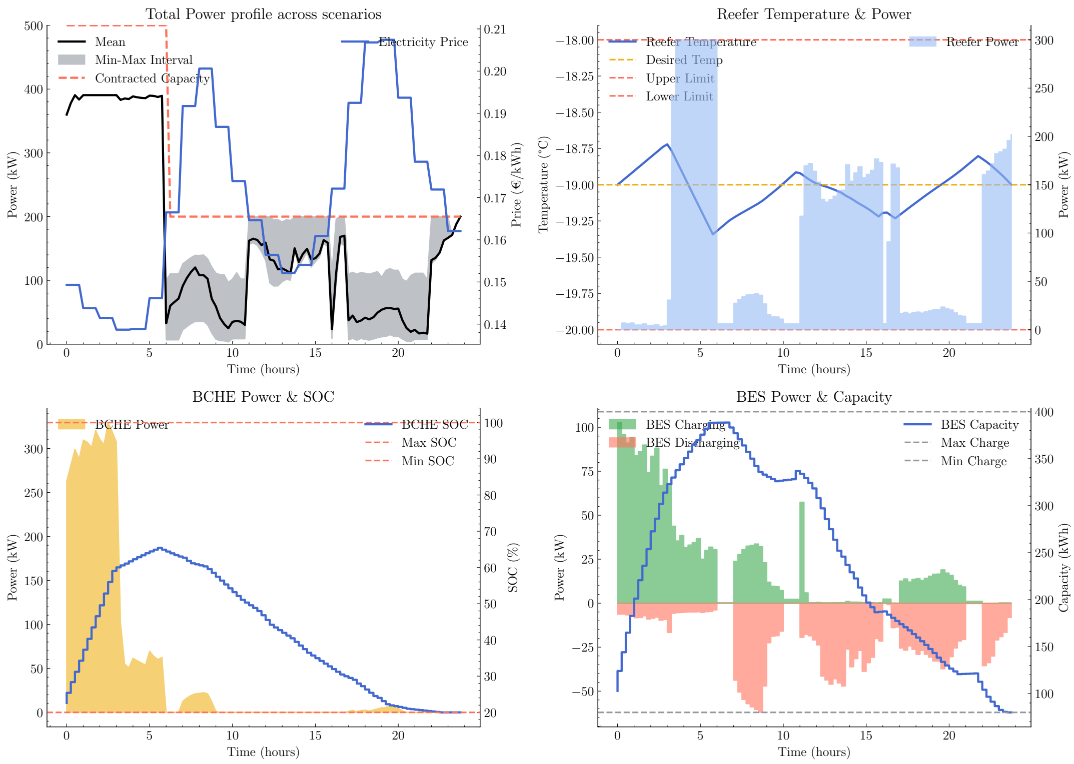

Figure A.40: TCTR, Dynamic electricity price cluster 6, flexible reefers, with battery energy storage

B

Literature

Planning and charging scheduling for battery and energy storage systems in ports and intralogistics: A critical review

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Abstract. The encouraged transition to more sustainable ports and the increased cost of energy prices has lead to improved energy efficiency measures and reduction in greenhouse gas emissions. For the transition away from diesel fuels, electrification of port has become a promising solution due to their efficiency, regeneration capabilities and the increasing integration of renewable energy into the grid. To support this transition, port equipment can be either directly powered by electricity or for mobile equipment equipped with batteries. These batteries and energy storage systems can also be implemented on equipment directly powered with electricity to capture and store the regenerated electricity, further optimizing energy efficiency. Beyond powering equipment and storing renewables these batteries also present an opportunity to enhance port energy management through demand response strategies through load management and electricity markets. This paper conducts a literature review of the implementation of batteries and battery electric energy storage systems in container terminal equipment and as a resource for demand response. Analyzing the literature shows that implementing battery and energy storage systems in electrified container terminals have significant benefits for energy efficiency, reduction of peak loads, reducing the energy bill and reduction of greenhouse gas emissions.

Keywords: Electrification · Charging · Battery · Logistics decarbonisation · B-AGV · Systematic literature review

1 Introduction

The objective of container terminals has for a long time been to maximize container throughput as competitively as possible. However, there is a shift towards more sustainable operations as ports as an industry account for 3% of global greenhouse gas (GHG) emissions [27]. In light of these recent changes towards greater sustainability, port authorities will have to take on a new role to include more energy efficient measures and better management of their energy [5]. This can lead to energy savings, improve the green image of the port and provide a competitive advantage. The approach to a more sustainable electric port has two sides, the generation and the consumption side.

In terms of energy generation, port authorities can continue to invest in renewable energy generation for their own use, such as wind power or photovoltaic cells and the possibility of storing the excess energy generated in large stand alone batteries for later use.

From the consumption side, ports can achieve more sustainable operations and reduce greenhouse gas (GHG) emissions by adapting their energy consumption through alternative energy sources, efficiency measures and better energy management. This can be applied to port equipment by replacing typical diesel fuel powered equipment with electric, hydrogen or other more sustainable fuels. It also involves assessing energy consumption within port operations and minimizing it while still maintaining the high operational throughput a container terminal requires. Additionally, managing available energy in an efficient manner whether through self-generated electricity, from the grid, or other energy sources , ensures more efficient and sustainable power use.

For this transition to more sustainable port operations, electrification is a promising solution [47]. All of the equipment used in container terminals can be electrified, from quay cranes, cold-ironing, gantry cranes, reefers to battery powering equipment such as automated guided vehicles. The power train of electric vehicles also have a higher efficiency when compared to the diesel ICE [3], while also having regenerative capabilities with for example regenerative breaking. Furthermore, full electrification also offers a universal solution to manage the energy usage in the port. However a fully electric port has its problems, it can introduce large peaks of electricity demand when multiple equipment or ships are drawing power simultaneously. Another logistical difficulty that arises is the downtime of battery equipment due to charging, as this process still takes significantly longer than simply refueling.

This literature review will discuss the implementation of battery and electric energy storage systems for equipment in a container terminal and the extra possibilities for demand response. It will include the potential benefits from adding a battery or electric energy storage system to port equipment and the integration into port logistics. It will also discuss the use of batteries from a port power management perspective.

The structure of this paper is as follows: Chapter 2 explains the methodology used to find the relevant articles for this literature review. Chapter 3 briefly discusses the different energy consumptions of container terminals. This is followed in Chapter 4 by an overview of the current literature on battery and electric energy storage for equipment in container terminals. This chapter is split into two parts, the first part discusses the equipment which is fixed and directly supplied with electricity and the second part an overview of the charging strategies for mobile equipment. Chapter 5 discusses the battery as a means of stabilizing, storing and optimizing the use of electricity within a container terminal. Chapter 6 discusses the gaps in the literature and future research opportunities and finally in Chapter 7 the conclusion.

2 Methodology

This literature review was conducted using the Scopus database to identify relevant articles and possible gaps in this area. A number of search strings were created using keywords relevant to this topic and scanned to check suitability. To find the relevant articles, the titles and abstracts were read first to check suitability before analysing the full text. A table 1 is provided of the search process used to find the relevant articles for this paper. This table also gives an overview of the search terms used and the resulting number of articles found and how many were selected and found from related articles or snowballing.

Table 1: Finding of relevant articles

Search	Results
(battery OR ess OR "energy storage system") AND (rtg OR rmg OR qc OR gantry OR crane) AND ("container terminal" OR seaport OR port)	56

Continued on next page

Table 1 – continued from previous page

Search	Results
Relevant articles found for chapter 4 through search expression & articles found by related articles and/or snowballing	26
(charging OR swap OR battery) AND ("straddle carrier" OR "yard truck" OR agv OR "automated guided vehicle" OR "container handler" OR "reach stacker" OR "reachstacker") AND ("container terminal" OR seaport OR port)	49
Relevant articles found for chapter 4 through search expression & articles found by related articles and/or snowballing	28
(microgrid* OR smartgrid* OR "smart grid*" OR "demand response" OR "energy system" OR "energy management system") AND ("container terminal*") OR ((port* OR seaport*) AND (qc OR "quay crane*" OR "shore power" OR "cold-ironing" OR "cold ironing" OR reefer* OR "refrigerated container*" OR "automated guided vehicle*" OR "battery swapping station" OR rtg OR crane)) OR (seaport AND "charging station") AND ALL ((battery OR ess OR "energy storage system" OR "energy storage"))	121
Relevant articles found for chapter 5 through search expression & articles found by related articles and/or snowballing Articles found by related articles or snowballing	47

The chosen articles will be divided into three chapters based on how the Battery Energy Storage System (BESS) or electric Energy Storage System (ESS) is integrated into the port, as can been seen in Fig. 1. The first chapter will include the articles about the ESS/BESS for the energy and peak shaving of stationary equipment, e.g. Ship-to-Shore cranes (STS). This is then followed by the literature of batteries in mobile equipment and their charging strategies. Lastly an overview of the literature for large stand alone BESS used in port microgrids and energy management systems will be given.

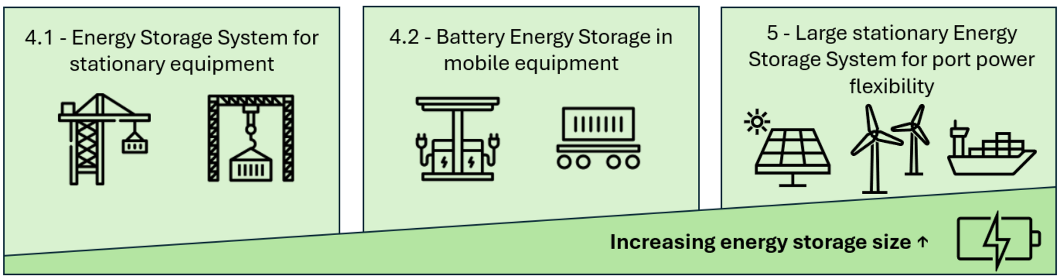

Fig. 1: Overview of Chapters

3 Energy consumption

To get a better understanding of what the major drivers are for the energy consumption in container terminals and where the possibilities lie for improvement, Wilmsmeier and Spengler [19] made an analysis of trends in energy consumption by activity cluster, as seen in Fig. 2. It takes into account the static energy consumption such as energy for building and lighting as well as quay cranes (QC) and horizontal transport. It revealed that horizontal activities accounted for the greatest and fastest-growing share of energy consumption in the period between 2012 and 2015. In this research horizontal activities were defined as activities that are carried out by RTGs, reach stackers, RMGs, etc. which are for a large part based on diesel consumption. This means that impacting this cluster with cleaner and more energy efficient equipment and measures, will have a significant impact. The variations in Fig. 2 are due to differences in the operational layout of different terminals, with the share of undefined and other energy consumption decreasing over time because of higher quality data over the years. Another major share of energy, which is not shown in the figure, will go to the cooling of reefers and providing shore power for large ships while they are berthed and will replace the power from their auxiliary engines.

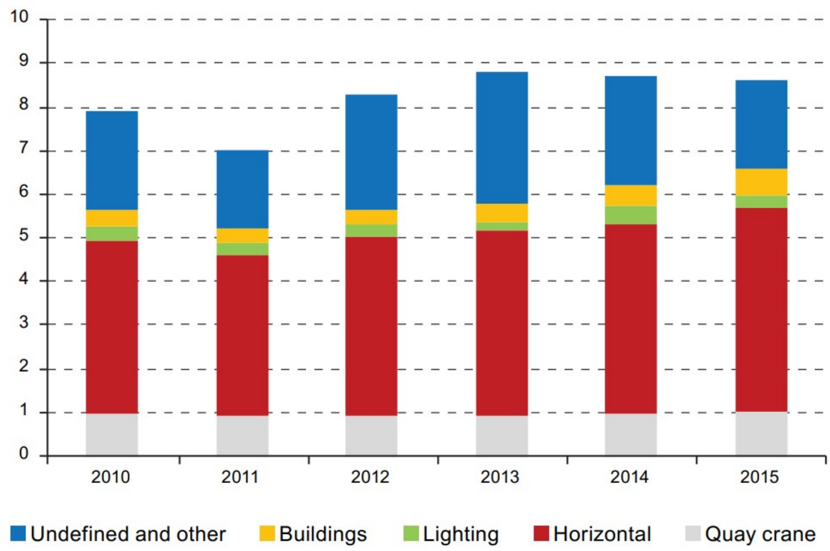

Fig. 2: Median litres of diesel equivalent consumed per activity cluster (excluding reefer cooling), 2012-2015 [19]

4 Battery and energy storage for equipment

Electrifying port equipment such as Automated Guided Vehicles (AGVs), terminal trucks, empty container handlers and reachstackers present a challenge due to the fact that charging increases the down time. Unlike diesel-powered equipment, which can operate continuously with quick refueling, battery-electric alternatives require downtime for recharging, potentially reducing operational efficiency. To maintain the same level of operations, ports must either invest in a larger fleet of vehicles or adopt other energy management solutions. These vehicles operate dynamically across large areas, making fixed power connections difficult. As a result, their transition to electric power depends heavily on advancements in battery technology and charging infrastructure.

While several types of port equipment have successfully transitioned to direct electrical supply, such as: quay cranes (QC), yard cranes (YC), and both rubber-tired and rail-mounted gantry cranes (RTG, RMG) with e.g. a cable reel or busbar [4]. However, cranes can still profit from the implementation of an electric ESS to optimize their power flows and make use of the regenerative capabilities, predominantly from the lowering of containers.

This chapter will discuss the use for batteries and ESS for equipment with direct power supply from the grid in chapter 4.1 and the equipment without a direct electrical supply and how these mobile batteries should be charged during operation in chapter 4.2.

4.1 Connected equipment

Cranes, particularly ship-to-shore (STS), RTG, RMG and shore power (cold-ironing) have a distinctive load profile due to their sudden load peaks. RTG cranes, for example, have a wide range of power requirements, varying from 10kW to 350kW, 170kW regen power and a maximum of 30kW auxiliary power [40]. In order to manage these fluctuating loads and reduce costs, an ESS can be implemented to utilize the regenerative energy from the lowering of containers. Due to the characteristics of these load profiles, both energy storage with high power, energy densities and fast response time are required. Installing the most prominent and suitable technology devices such as battery energy storage (BES), supercapacitors (SC) and flywheel energy storage (FES) acting as ESS [78] provides this opportunity. An overview of the different ESS and their characteristics can be seen in Fig. 3.

Peak shaving (PS) can minimize the maximum load demand and facilitate the participation of small renewable generation. One of the challenges for cranes that are solely powered by a diesel generator is that they cannot benefit from regeneration capabilities. Additionally, the diesel generators used had to be oversized to meet the highest peak energy demands during operations, resulting in that the diesel generators would not be operating at their optimum load most of the time. This is also true for an electrical power source, as the grid would have to handle the entire peak demand from which the substation capacity may have to be increased to handle this demand, these peaks could also result in higher electricity bills. To tackle these problems many new hybrid combinations can be implemented, with the aforementioned energy storage systems, taking advantage of their characteristics and optimizing power flows.

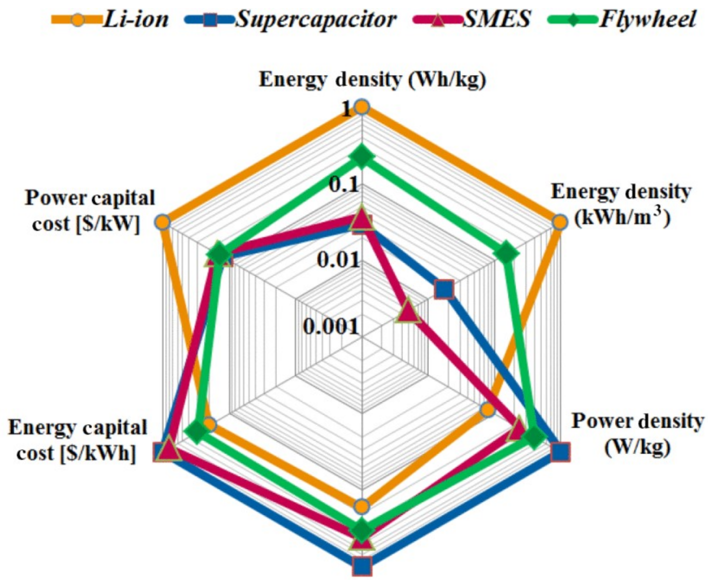

Fig. 3: Energy density of ESS Farhadi and Mohammed [14]

Battery energy storage: One of the possible hybrid combinations is that of a diesel generator combined with a battery. As mentioned before the implementation of such a storage device allows for reducing the diesel Generator Sets (GenSet), as the battery is charged by the GenSet and helps overcome the peak loads and regenerates during loading.

This hybrid combination was dicussed for a port crane by Ovrum and Bergh [11], with a hybrid control strategy. The implemented lithium battery of 156 KWh reduced the diesel GenSet from 3x960 KW to 2x960 KW with one kept for redundancy. Similarly, a RTG crane was turned to this hybrid by Niu et al. [28]. Replacing the old diesel engine of 410 kW and generator of 322 kW to A 128-kWh lithium battery and a 50 kW diesel generator to charge the battery, which output power was controlled by a 60 kW Active Front End (AFE). With the use of a thermostat control method the battery was charged when State Of Charge (SOC) was below 0.5 and turned off when SOC is greater than 0.8. SOC control was also used by Hong-lei, Wei, and Jian-Xin [44] with a lower and a higher threshold. Below the low threshold the GenSet supplies load requirement, when above the high threshold the GenSet is switched off and when in between the thresholds it maintains its last state. The hybrid RTG reduced the conventional 322 KW diesel GenSet to a 50 KW diesel GenSet and 128 KWh (640 Vdc/200 Ah) lithium battery. To improve upon the usual control measures such as the SOC control, Kusakaka, Phiri, and Numbi [66] proposes a deterministic non-linear optimization approach to solve the power dispatch, which is investigated for a hybrid diesel (410 kW)/battery (128 kWh) RTG and minimizes the resulting energy costs.

Supercapacitor energy storage: SC is an energy storage that can charge and discharge much faster than a regular battery by storing energy electrostatically rather than converting the charge to another form, such as mechanical energy in flywheels or chemical energy in batteries. They also have a much higher cycle life compared to li-ion batteries [14], but a lower lifespan. SCs have limited storage capacity, but these characteristics make them ideal for scenarios where burst of energy are required, for example the lifting and loading of a heavy container. A comparison is made by Antonelli et al. [22] between a SC stack versus a battery stack for the application of a hybrid RTG crane with diesel GenSet. In this comparison SCs were the first choice in terms of offered performance and costs, due to the load profile being oriented towards charging or discharging in a few seconds at high current rates. In this aspect the SCs excel due to their high depth of discharge (DOD) and power density. However, high power lithium batteries were found to be competitive as well if correctly sized. A new energy management system was introduced by Corral-Vega, Fernández-Ramírez, and García-Triviño [42], which is able to regulate the operation of the SCs through a DC bus voltage control by using two cascaded control loops. This implementation has a low investment cost while still reducing fuel by 21%, which results in an internal rate of return of 78%, which could make it a worthwhile investment.

Supercapacitors also offer a promising solution to STS cranes. Parise and Honorati [7] suggests an evoluted drive system with a SC for the port cranes in order to optimize the energy absorptions. This solution allows PS of 90 % and reduces energy consumption up to 57%. The economic efficiency of peak demand reduction in STS cranes based on SC energy storage sizing is further investigated by Kermani et al. [56], by applying a particle swarm optimization (PSO) algorithm for the optimization. The results show the SC significantly reduces the peak demand by PS as well as increasing the load factor, load leveling and reducing the energy cost.

Flywheel energy storage: A flywheel can store rotational energy by spinning, the amount of energy is determined by the inertia of the flywheel and its rotational speed. The flywheel can be sped up to store electricity from the grid, generator or while lowering containers and also be slowed down again to utilize the energy. FES also has a higher cycle life when compared to li-ion batteries [14] and a high life span of up to 20 years.

The integration of a harbor crane and flywheel energy storage has been investigated by Ahamad et al. [36], where the dc-link control and modeling of a FES is discussed. Results showed that with the proposed method the dc-link voltage can be held constant and energy can be regenerated into the FES while lowering the containers, which can greatly maintain the supply quality and enhance the energy efficiency. Pietrosanti, Holderbaum, and Becerra [17] implemented a flywheel with a total capacity of 3.34 MJ and a power management strategy to minimize the energy costs of a grid or diesel powered RTG. Besides achieving a 38.47 % reduction of fuel, the percentage of time for peak demands above 150 and 200 KW also reduced significantly from 3.997% to 1.356 % and 0.0437 % to 0.0028 % respectively. Pietrosanti, Alasali, and Holderbaum [58] expanded on previous work with the FES by adding a fuzzy logic controller, which improved on the robustness of the typical PI controller and gained better results comparatively. Kermani et al. [33] used two strategies for peak load shaving of a STS crane: duty cycle coordination between the cranes based on PSO algorithm and utilization of FES to make a power balance between generation and demand side. This method achieved 82.3 % PS for a network of 10 STS cranes.

Generalised Energy storage: Alasali et al. investigated ESSs for an electric RTG (ERTG). Alasali et al. [21] started with a Model Predictive Controller (MPC) to optimize the power flows of a general energy storage and an electric RTG, powered through conductor rail, which reduced the electricity cost and peak power demand. The Model predictive controller outperformed both the optimal energy controller and set-point control. It could also potentially minimize the stress on the electrical infrastructure at the port and avoid the need to upgrade or build a new substation. Alasali, Haben, and Holderbaum [38] followed up on previous paper introducing a stochastic model predictive controller aiming to improve the reliability and economic performance for two RTG cranes, to better forecast the volatile power demand. A central ESS for the two RTG cranes is also compared to two individual ESS per RTG. The annual electricity bill savings for the central ESS and for the two individual ESS were 7.99%, 7.87% respectively. Shortly after this research, Alasali, Haben, and Holderbaum [37] continued with the central ESS for two gantry cranes and now an off-line stochastic optimal controller without the previously implemented rolling forecast model, which assumed knowing the container weights and crane moves ahead of time

Active front end: It is complicated to use all regenerated energy because of the technical and economic constraints of ESS technologies. For this purpose an Active Front End (AFE) could provide a solution. This AFE is a controllable rectifier providing a bidirectional power exchange between AC and DC power. The DC energy created from lowering a container can be fed into the grid, which can subsequently be used by another RTG crane for example to help hoist a container.

Luque et al. [16], Pietrosanti et al. [18] and further worked on by Alasali et al. [39] focus on the implementation of active front end. The latter paper's focus on two RTG cranes network with and without ESS or AFE. The energy storage considered is a FES powered by a 150 kW switched reluctance motor and stores up 3.6 MJ of energy. The AFE as a bi-directional converter allows for the regenerated power during lowering to be fed back into the electrical network of the port terminal, which could then be used by other cranes in this network during e.g. hoisting when modeled as a switch, reducing the peak power demand. This system is modeled using a PI controller, where the model aims to regulate the DC voltage at each RTG crane bus system by setting a reference value which helps to minimize the regenerative power that goes to the dump resistors and also protects the network. The

ESS approach resulted in a total of 30 % energy saving compared to the 47 % of the AFE approach and AFE also showed better PS capabilities.

Battery and supercapacitor energy storage: Combining the battery and SC has the benefit of the large power density from SC for peak power and the large energy density from the battery for greater storage.

Bolonne and Chandima [40] reduced old 400 KW diesel generator with a new energy management system for a RTG. This system consists of a 200 kW variable speed diesel generator (VSDG) with a 250 kW active front end (AFE) to control the output power, along with a 13.8 kWh/75 kW Li-ion battery and a 3.10kWh/250 kW SC to provide the peak power demand. The battery and SC banks absorb the regenerated power and the battery provides the energy for the auxiliary systems when idling. When the batteries' state of charge is less than 40%, VSDG will be used to charge the battery to 60%. Chen et al. [41] proposes another diesel GenSet, battery and SC hybrid for RTG cranes. A 300 KW diesel generator is reduced to only a 20 kW diesel generator combined with an AFE, a battery pack with 73.9 KWh/147.8 KW and a 3.7 MJ SC. The SoC variation of the battery is again limited between 0.5 and 0.8 to avoid the impacts of deep discharging and overcharging and a total of 72.8 % fuel reduction was achieved. Zhao, Schofield, and Niu [20] Propose (ZEBRA) battery as the prime energy source for RTG crane and SC to handle the large peak transient current. The hybrid energy storage systems are designed for both short- and long-period operation, which results in effective energy conversion and lower emissions.

Supercapacitor and flywheel energy storage Similar to the battery and SC approach is the integration of FES and SC. Parise et al. [30] implemented the coordination of STS cranes' duty cycles with a Power Optimization Tool (POT) And a combination of SC and FES. These two ESSs work together in leveling and lowering the maximum power demand. On each crane, a reduced number of SCs are fitted and in the ports' substation a flywheel is operating on the simultaneous behavior of the crane network. With this approach a peakshaving of 85 % could be realised for a group of 5 STS cranes. Whereas PS is focused on reducing peaks, load leveling attempts to flatten the entire load for STS cranes' power supply from two transformers substation increasing the reliability. In contrast to the previous case that an operation delay method was considered, an optimal handling time based on the PSO algorithm is obtained by Kermani et al. [48] to maximize regenerated energy by the cranes into the dc bus which makes other cranes able to use this energy.

Energy savings To give an overview of the potential gains from implementing an ESS, table 2 is made. This table lists the source; equipment and its main power source; The implemented ESS/ESSs; The method for their control; the energy/ fuel saving achieved; the reduction of the peak power used.

Table 2: Overview of ESS applied in cranes.

Source	Equipment, E-Source	BES	SC	FES	GES	Method	Energy/fuel saving	PS
Ovrum and Bergh [11]	Port crane, Diesel GenSet	✓	✗	✗	✗	PID control	30%	-

Continued on next page

Table 2 – continued from previous page

Source	Equipment, E-Source	BES	SC	FES	GES	Method	Energy/fuel saving	PS
Niu et al. [28]	RTG, Diesel GenSet	✓	✗	✗	✗	SOC control	57%	-
Hong-lei, Wei, and Jian-Xin [44]	RTG, Diesel GenSet	✓	✗	✗	✗	SOC control	73.9%	-
Kusakaka, Phiri, and Numbi [66]	RTG, Diesel GenSet	✓	✗	✗	✗	Deterministic non-linear optimization	76.04% (cost)	-
Parise and Honorati [7]	STS, Grid	✗	✓	✗	✗	Logic control	57 %	90 %
Kermani et al. [56]	STS, Grid	✗	✓	✗	✗	PSO	-	62 %
Corral-Vega, Fernández-Ramírez, and García-Triviño [42]	RTG, Diesel GenSet	✗	✓	✗	✗	DC/SOC control	21%	-
Antonelli et al. [22]	RTG, Diesel GenSet	-	✓	✗	✗	SOC control, internal algorithm	30-60%	-
Zhao, Schofield, and Niu [20]	RTG, Battery	✓	✓	✗	✗	Double closed-loop PI control	71.5%	-
Bolonne and Chandima [40]	RTG, Diesel GenSet	✓	✓	✗	✗	State machine controller	27% (to other hybrid)	-
Chen et al. [41]	RTG, Diesel GenSet	✓	✓	✗	✗	Game-based	72.8%	88%
Parise et al. [30]	STS, Grid	✗	✓	✓	✗	POT	-	85%
Kermani et al. [48]	STS, Grid	✗	✓	✓	✗	PSO	-	-
Pietrosanti, Holderbaum, and Becerra [17]	RTG, Diesel or Grid	✗	✗	✓	✗	Optimal control	38.47%	-
Kermani et al. [33]	STS, Grid	✗	✗	✓	✗	PSO	-	82.3 %
Pietrosanti, Alasali, and Holderbaum [58]	ERTG, Grid	✗	✗	✓	✗	Fuzzy logic	32%	-
Alasali et al. [21]	ERTG, Grid	✗	✗	✗	✓	MPC	-	28.9%
Alasali, Haben, and Holderbaum [37]	ERTG, Grid	✗	✗	✗	✓	SMPC	-	32.8%
Alasali, Haben, and Holderbaum [38]	ERTG, Grid	✗	✗	✗	✓	Genetic Algorithm	-	28.7%

E-Source: Main Energy Source, BES: Battery energy storage, SC: Supercapacitor, FES: Flywheel Energy Storage, GES: General Energy Storage (Energy storage not specified, general approach), PS: Peak Shaving

Continued on next page

Table 2 – continued from previous page

Source	Equipment, E-Source	BES	SC	FES	GES	Method	Energy/fuel saving	PS

Because it is difficult to compare the possible energy or fuel savings from all of the implemented hybrid systems, due to the different crane models, different controllers and various sizing of e.g. diesel GenSets before and after hybrid transformation and ESSs equiped. Vlahopoulos and Bouhouras [85] compares the solutions for the RTG diesel and ESS hybrids in a case study and determines an average liter diesel used by the diesel generator per move as the performance indicator.

Papaioannou et al. [29] analyzed the energy usage per motor for a RTG and found that during average operations the following energy distribution holds: hoist energy share was 62 %; gantry energy share 31 % and 7 % for trolley, idle and losses. The potential energy recovery ability for hoisting in normal operations was 84 % to 89 % and for gantry 4 % to 5 %. For a Ship to Shore crane this absorb potential is up to 90 % [49] with similar characteristics of peak loads from hoisting and lowering as that of the RTG. It is assumed that the energy share for hoisting with STS crane is larger than that of the RTG crane, as the horizontal travel distances are shorter and only the trolley moves over the crane, instead of the total weight of the RTG. From graph in [32] it is assumed that the hoisting energy accounts for approximately 75 % of the total energy.

To approximate the energy saving from the potential energy recovery of adding a properly sized ESS (capable of peak load), equation (1) is used considering the Round Trip Efficiency (RTE). Which is an indicator of how much of the mechanical energy from for example lowering the container and then storing it into the ESS, which can be used again to power the motors. The RTE includes the converter efficiency to transmit the electricity to and from the ESS, including the RTE of the ESS itself. For batteries, SCs and flywheels it is usually transmitted to a DC bus which would require a AC/DC and DC/DC converter steps, however there also flywheels which work with AC.

$$Energy\ saving\ RTG = 0.62 * 0.85 * RTE \ + \ 0.31 * 0.04 * RTE \tag{1}$$

$$Energy\ saving\ STS = 0.75 * 0.90 * RTE \tag{2}$$

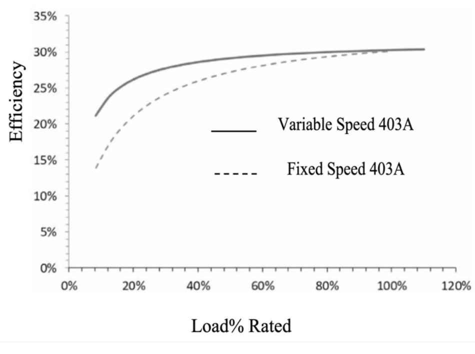

Fig. 4: Diesel generator efficiency curve [81]

Efficiency	Value
$\eta_{DC/AC}$	0.97-0.98
$\eta_{AC/AC}$	0.95-0.98
$\eta_{AC/DC}$	0.95
$\eta_{DC/DC}$	0.98
η_{BES}	0.60-0.90
η_{SC}	0.90-0.95
η_{FES}	0.85-0.95

Table 3: Power converter efficiency [68] and ESS efficiency [53], [23], [52]

Furthermore the extra efficiency from changing the diesel GenSet could also be considered when is chosen for a reduced GenSet plus battery, see Fig. 4.1, as an addition to

	Li-Ion BES	SC	FES
Energy saving RTG, regen	∼ 41 %	∼ 46 %	∼ 44 %
Energy saving STS, regen	∼ 52 %	∼ 58 %	∼ 55 %

Table 4: Energy saving from regeneration

equation (1) and (2). When the total investment cost for the properly sized ESS and the RTE is known, a total cost of ownership can be made to see the benefits of using such a hybrid system.

4.2 Disconnected equipment

For the container transportation on the yard side, besides the gantry cranes mentioned in the previous subchapter, there are many pieces of equipment which can be used for transporting containers. Some of these options are automated guided vehicles (AGV), straddle carriers, reach stackers, empty container handlers, yard trucks and forklifts. These pieces of equipment can not be directly charged through a direct connection, as they move freely through the yard area. This means that for electrification these pieces of equipment will have to switch to a battery alternative. This however comes with the downside that they will have to recharge, which increases there downtime. Battery size and charging speeds are also limited, which poses a challenge for heavy industrial vehicles which have large power demands.

Beside literature about AGVs there exists little literature about the electrification of reachstackers, straddle carriers or yard trucks in container terminals. Four papers have been found in this search discussing the implementation of a fuell cell based yard truck in port operations [96], [61], [79], [63]. However Di Ilio et al. [61] made a preliminary design for a fuel cell and battery hybrid alternative for a yard truck is made and assessed, outperforming its original diesel variant.

For the horizontal transport between the quayside and yard side in large container terminals the Automated Guided Vehicle (AGV) is mostly used, due to their optimizable management and thereby increased throughput. Similar to the batteries and ESSs discussed in the previous section the AGV when shifted to a Battery-AGV (B-AGV) could also benefit from regenerative energy by reclaiming the kinetic energy through braking [77]. However, as these batteries are not connected to a power supply during operations, the B-AGVs must also be able to operate for long periods of time and/or have short recharge times so that the B-AGV can be operational again. For a long time, this was not feasible or economically viable due to insufficient battery performance. Bian et al. [9] noted that the new upcoming battery technology could enable the use of electric AGVs in automated container terminals in the future.

The potential for the B-AGV was assesed and the economic viability was optimized. It was found that electric mobility is economically beneficial in container terminals because the charging and maintenance costs of a B-AGV fleet are significantly lower than their diesel counterpart, which can compensate for the higher investment costs of charging infrastructure and spare batteries [13]. Furthermore it was found that using their controlled charging strategy which used a Battery Swapping Station (BSS) the economic efficiency could be increased even further, as can be seen in Fig. 5.

With this possibility to transition to B-AGVs, many papers have researched this topic to come up with viable charging strategies and scheduling methods within container terminals to minimize B-AGV downtime. In these papers, two main strategies for implementing and charging the B-AGVs emerge: Charging Stations (CS) for charging fixed batteries and BSS for charging removable batteries.

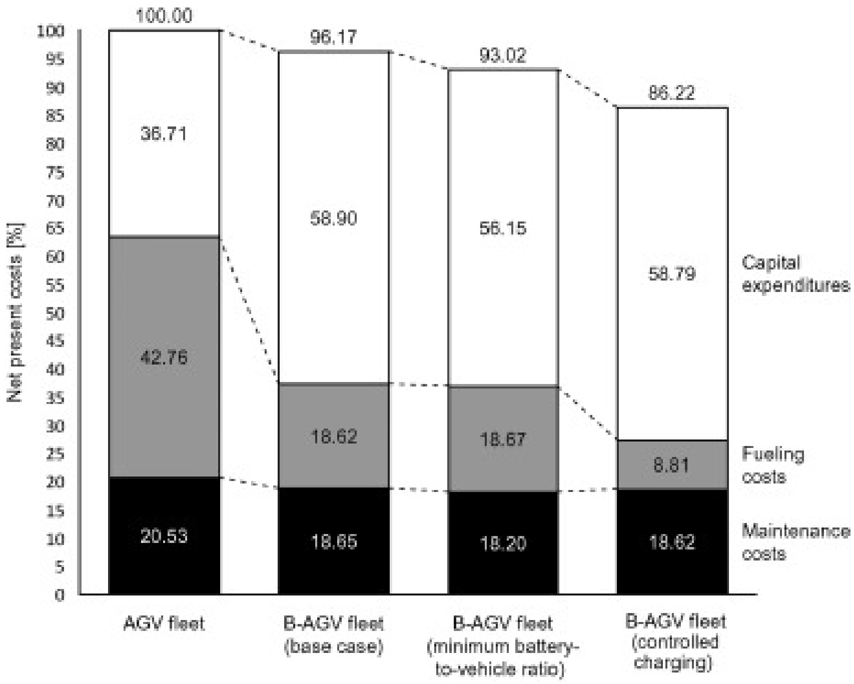

Fig. 5: Economic viability AGV [13]

Charging fixed batteries: Starting with the B-AGVs that have a fixed battery, where the vehicle is plugged in and charged at a Charging Station (CS), which is also the typical method of recharging for regular electric vehicles used today. The downside of this method is that the entire vehicle is not usable for operation instead of just the battery. Recently to optimize this approach papers have investigated the implementation of CS inside an automated container terminal (ACT).

To determine the optimal configuration of the charging stations and B-AGVs, Ma, Zhou, and Stephen [67] made a discrete event simulation model to compare the performance of a decentralized or centalized scheme and a conservative or progressive charging policy. From the results it was determined that the decentralized layout, which are spread out charging locations, and a progressive charging policy performed best.

Due to the dynamically changing environment in which the B-AGVs have to operate, which has a negative on the performance of the B-AGV scheduling problem, Gao et al. [107] proposed a digital-twin based decision support to improve the scheduling efficiency in these complex scenarios. With recent technology allowing for faster charging, Li et al. [95] investigated CS with fast charging capabilities while aiming to reduce the total charging cost and penalty costs such as tardiness.

To improve the efficiency of the ACT, Sun et al. [97] implement a multi-resource collaborative scheduling of quay crane, B-AGV and yard crane to realize the integration of the scheduling plan along with the charging effects for the B-AGV. It then aims to achieve energy saving of the terminal by quantifying the used energy.

Zhou et al. [116] address challenges due to limited charging station capacity and tight vehicle schedules, using a Multiagent Q-Learning approach to optimize recharging decisions. Which showed to perform better than rule-based heuristics and benefits from the consideration of both assignment and scheduling at charging stations.

The disparity in energy consumption between B-AGVs in unloaded and loaded states is adressed by Zhou et al. [117] and allows for more resilient B-AGV scheduling. A mixed-integer programming model is developed with the objective of minimizing energy consumption costs while satisfying AGV battery constraints and is solved with A Large Neighbourhood Search based algorithm. Similarly Song et al. [112] considers more detail of the B-AGV operation with power under loaded and empty conditions as well as the non linearity of battery charging.

Che, Wang, and Zhou [106] approached the B-AGV charging problem as the recharging-considered vehicle scheduling problem (R-VSP) for B-AGVs and aims to minimize the makespan. Limited number of charging stations and tight schedules were considered with scheduling based on the actor-critic multi-agent deep reinforcement learning framework, outperforming distributed-agent deep reinforcement learning and several benchmark heuristics.

Battery swapping: Battery swapping involves replacing the entire battery from the particular equipment and replacing it with a charged battery inside a BSS. This approach has the benefit that it decouples the energy-logistic relation more. As mentioned previously, Schmidt et al. [13] implemented the BSS to asses the total cost of ownership for implementing an ACT and B-AGVs with this approach. It also implements a controlled charging strategy with the goal of minimizing the charging costs by charging the batteries in the BSS at moments with low electricity prices, which proved to be a more cost efficient method.

Xiang and Liu [72] implemented both the CS and Battery Swapping Station approach for battery recovery of the AGV into a Semi-Open Queuing Network (SOQN). The different strategies were investigated by comparing annual cost and results show that the BSS performs better than the CS strategy unless the price of the spare battery is very high.

A speed control strategy was developed by Yang et al. [102] that considers the traffic environment of the terminal with the aim of energy conservation and emission reduction and the BSS's limited handling capacity is modeled to avoid congestion. Yang, Hu, and Jin [101] also considers the limited handling capacity at the BSS. Zhou et al. [118] expanded on the integration of a BSS with the aim for co-optimization of both operation and energy for B-AGV. Minimizing both the makespan of B-AGVs and the maintenance cost of the implemented energy system, using a multi-objective mathematical, which reduced the terminal operation cost significantly.

Due to the heavy logistic environment of ACT, a two-stage stochastic programming model for B-AGV task allocation and battery swapping joint scheduling problem with random tasks in an uncertain environment with double-threshold battery constraint for B-AGVs is investigated by [94].

An integrated scheduling model is created by Li et al. [108] that takes into account different battery degradation for task assignment and battery swap time for B-AGVs, with the aim of minimizing task completion time.

Xiao et al. [113] introduces battery swapping and opportunity charging modes into the B-AGV system and proposes a new B-AGV scheduling problem considering the hybrid mode. This reduced the average number of battery swapping times by 43.48%, and the total costby 7.2%.

Charging constraints: The papers mentioned in the sections over the charging stations and battery swapping stations implement different constraints for the B-AGVs and the decision whether they should charge or not. To make an overview of the implemented battery constraints and when the B-AGVs are scheduled for charging the papers' strategies will be categorized.

- Charged if depleted: The most common method is to check whether the battery is depleted or has sufficient energy left. So the first category will be charging when the B-AGV can no longer perform another task, so the B-AGV is scheduled to recharge.
- Charged lower threshold reached: The second common option is setting a lower threshold for the SOC or used energy, instead of driving till the battery is depleted, avoiding a high DOD.
- Dual threshold charging: Similarly a dual threshold charging strategy works with an opportunity interval from a higher SOC to a mandatory charging SOC for the B-AGV to be scheduled. This is for example implemented by Gao et al. [107] where the opportunity interval starts when the SOC is below the high threshold of 80% SOC and ends at 20%, after which the mandatory interval starts and charging will be enforced.
- Triple threshold charging: Ma, Zhou, and Stephen [67] proposed a triple interval charging strategy. If the SOC drops below 50% the opportunity interval (checks if CS is idle) starts for the nearest CS, when dropped below 30% the oppertunity interval extends to the nearest 3 CS, followed by mandatory charging when SOC reaches 15%.
- Charging is allowed at all times, but is mandatory when the battery reaches a lower SOC threshold

To give an overview of the papers a table 5 is made with the Author and year; the battery recovery method; their optimization goal; Constraints as listed above and additional battery constraints; the method which was used for the implemented model.

Table 5: Overview of battery charging strategies for AGVs

Source	Battery recovery	Objective function	Charging constraints	Method
Schmidt et al. [13]	BSS	Total cost of ownership of B-AGV with BSS	Charged lower threshold reached. Batteries charged at hours with lowest electricity prices, if possible	Simulation
Xiang and Liu [72]	BSS, CS	Optimize the number of AGVs R to match the capacity of QC and YC. Optimal layout design of the yard with the objective of minimizing system throughput time. Optimize task assignment strategy to minimize system throughput time. Which charging strategy is more effective from an economic perspective, with a throughput time constraint.	Charged if depleted. Battery checked after completing task, traveling distance and time taking into account.	Semi-open queueing network model
Ma, Zhou, and Stephen [67]	CS	Minimum number of B-AGVs required for an acceptable waiting time when visiting a CS. Best configuration of CS, how they are distributed. Best recharging policy for charging B-AGVs. Minimum ratio of B-AGVs to Diesel AGVs that achieves similar performance	Triple threshold charging strategy, with upper threshold of 50 % SOC, below this the opportunity charging starts for nearest CS, below 30 % for the nearest 3 CS and mandatory charging below 15 %	Discrete event simulation

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Table 5 – continued from previous page

Source	Battery recovery	Objective function	Charging constraints	Method
Yang et al. [102]	BSS	Speed control strategy that considers traffic and energy conservation/emission reduction. Minimize the CO2 emission cost and penalty costs caused by operational delays	Constraints to ensure B-AGV has sufficient power to travel to battery-swapping station or taks	Mixed integer programming, genetic algorithm
Li et al. [94]	BSS	Minimize the total cost of the B-AGV no-load cost, waiting time cost, task waiting time cost, and tardiness cost	A double-threshold constraint for battery swapping decision-making is adopted	Simulation-based ant colony optimization
Yang, Hu, and Jin [101]	BSS	Minimize the no-load energy consumption of the B-AGVs	Charging when lower threshold is reached	Mixed integer programming, set partitioning
Li et al. [95]	CS	Minimize the charging cost of B-AGVs and penalty cost related to makespan for finishing a set of assigned container jobs	Charging when lower threshold is reached. During charging SOC is bounded between maximum and minimum thresholds to avoid overcharging and DOD.	Mixed integer programming, A decomposition-iteration algorithm
Zhou et al. [118]	BSS	Minimize operation and maintenance cost of the implemented energy system and the makespan of B-AGV.	Dual threshold charging. If remaining energy of an B-AGV is less than upper threshold then checks if swapping can be performed before next earliest operation. Else continues normal operation until reaching lower threshold when swapping must be performed	Multi-objective mathematical model, (DMWOA)
Li et al. [108]	BSS	Minimize task completion time	SOC must remain above safety/lower threshold, based on state of battery degradation	Hybrid genetic algorithm, neighborhood search
Xiao et al. [113]	BSS	Minimize the sum of the energy consumption cost and delay cost of the B-AGVs	Opportunity charging with a lower threshold, battery must have sufficient energy left after task to drive to BSS	Mathematical model, adaptive large-neighborhood search
Gao et al. [107]	CS	Minimize the completion time of tasks	Charging when lower threshold is reached when it is depleted. Check If remaining capacity is sufficient for completing current task.	Digital twin
Che, Wang, and Zhou [106]	CS	Minimize the makespan of the transport jobs	Allowed to charge even at high SOC, not allowed to drop below a threshold, batteries are fully charged after charging	Multi-Agent DRL
Zhou et al. [117]	CS	Minimize travel distance of B-AGVs within the planning horizon	Charging when lower threshold is reached. Ensure that B-AGVs travel to the charging area for recharging after completing a task once SOC is below a lower threshold	Mathematical model, Large neighborhood search
Song et al. [112]	CS	Largest AGV spent the shortest time completing all the tasks	Dual charging strategy. Nonlinear characteristics of lithium battery charging is considered. Partial charging for the B-AGVs is allowed	Metaheuristic algorithm
Zhou et al. [116]	CS	Minimize the total job delay in the planning period	Operates between minimum and maximum SOC, not allowed to drop below minimum SOC. When charged the battery is assumed full	Markov decision process model, Multiagent Q-learning

B-AGV in other setting: If the constraint for port and container terminal were to be lifted from the search results, many more papers can be found about the integration of B-AGVs in a logistic or industrial setting. This can be seen by the search query listed in table 6, which resulted in a total of 167 articles compared to the 44 articles found when limiting it to ports and container terminals.

Search query	**Results**
(Charging OR swap OR swapping) AND "automated guided vehicle"	167
Charging AND (inductive OR wireless) AND "automated guided vehicle"	47

Table 6: Search results AGV and charging

From the remaining articles, ignoring the articles that were found in the previous section, there is a large number of papers addressing the design for inductive charging for B-AGVs. This is also known as wireless charging and is done as an approach to increase the mileage and decrease the down time [1] [10] [31] [45] [57] [86]. This wireless charging capability allows for the AGVs to be charged while driving as these inductive chargers are placed in the roads of which the AGVs are traveling.

Many more articles also discuss the implementation of charging for the AGV or Automatic Mobile Robots (AMR), which also provide capabilities such as lifting and grabbing, in job planning or scheduling [65] [60] [84]. The major difference between container terminals and these warehouse or industrial setting is the coupling and scheduling of different equipment. Where as the latter often compromises of just the AGV fleet, the container terminal has to schedule with the arrival of ships, quay cranes, yard cranes, etc. However, charging strategies, solving methods and other ideas for improving the integration of B-AGV in operations can still be learned and implemented for ports to further improve the efficiency and should also be studied.

5 Demand response possibilities with port's batteries

Batteries powering the equipment, or large stand alone batteries, also offer opportunities in the incentivized management of electricity demand, also known as Demand Response (DR). This can be through the optimization with energy efficiency measures or change of the port's own electrical load and benefit from reduced costs from lower peaks or for example different electricity pricing schemes. Ports could also play a role for the grid through the energy market and their ancillary services. DR is the overarching topic that consists of multiple strategies for balancing the power demands on the grid. To achieve this balance there are three different categories for implementing DR [2]:

- DR Incentive Based Program, classical: Direct Load Control programs, see Fig. 6, and Interruptible/Curtailable Load programs.
- DR Incentive Based Program, market based: Demand Bidding, Emergency DR Programs, Capacity Market, and the Ancillary services market
- DR Price Based Programs: Different pricing schemes

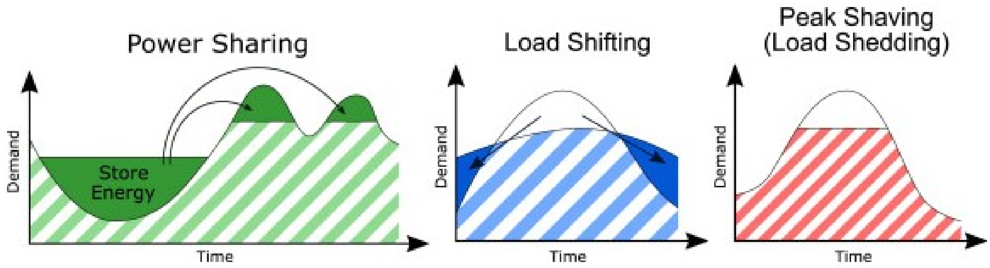


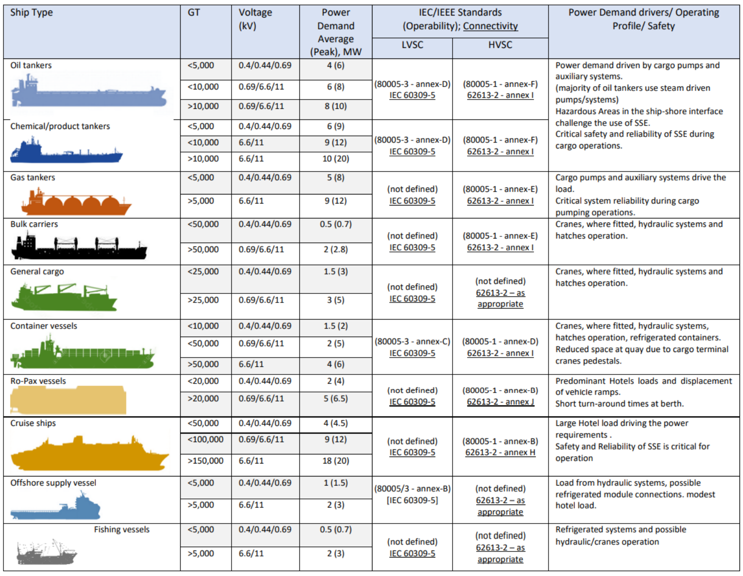
Fig. 6: Peak shaving methods [46]

To achieve the balancing of the different loads within a container terminal and deal with their dynamic and stochastic nature many models, simulations and optimizations, are created to recreate the demand. One of the first steps to making a complete model of the container terminal is knowing all the loads and characteristic profiles of the different equipment used and modeling the operations, these can be based off of calculations or measured with smart meters [120], [15]. With this approach the energy demand can be forecasted and different energy management strategies can be implemented by modeling these demands around the operations.

According to Lee Lam et al. [25] their one of the first in the literature to investigate the costs and benefits of employing energy management system in ports. Unloading and loading process of a ship is simulated along with the respective equipments power usage and solar energy. It is found that the implementation of an energy management system is financially beneficial for terminal operators, giving port authorities and researchers incentive to investigate this area further.

To forecast the short-term energy load and their profiles in a CT, Grundmeier et al. [6] used a simulation based approach of the CT including BSS, which has the benefit of decoupling energy use and logistic operation. The benefit of using the BSS in this manner is that it allows for load shifting and peak clipping, see Fig. 6. A software architecture for demand-side energy integration CTs, leveraging the flexibility provided by the BSS was also developed by Ihle et al. [15]. The simulation of logistics which forecasts the exchange times of batteries and logistic operation, followed by energy demand optimization which determines the optimal battery charging strategy from the forecasted loads. These flexible loads can reduce battery charging energy costs by up to 10%, using day-ahead EPEX-Spot prices and minute reserve auction data. Schmidt et al. [12] and Schmidt, Eisel, and Kolbe [8] examines both the technical feasibility and the commercial viability of several demand-side integration (DSI) programs to utilize the charging flexibility of electric transport vehicles in a logistic facility (BESIC project Altenwerder) to optimize load profiles, control charging based on variable prices or possibly provide minute reserve.

By introducing batteries inside equipment and utilizing ESSs, ports are now able to manage their energy profile even with their operational constraints. This is especially due to the fact that there is a growing amount of predictable load shifting potential due to manipulating the battery charging and discharging cycle [6]. Reefers also have the capability of flexible loads, reefers with frozen goods can for example be cooled ahead if the electricity price is low and stop cooling when the price is high, or when there is limited electricity capacity during heavy operations. This could be counteracted by cooling during off peak hours so that less cooling will have to be done during hours with higher demand.



Ship Type	GT	Voltage (kV)	Power Demand Average (Peak), MW	IEC/IEEE Standards (Operability); Connectivity		Power Demand drivers/ Operating Profile/ Safety
				LVSC	HVSC	
Oil tankers	<5,000	0.4/0.44/0.69	4 (6)	(80005-3 - annex-D) IEC 60309-5	(80005-1 - annex-F) 62613-2 - annex I	Power demand driven by cargo pumps and auxiliary systems. (majority of oil tankers use steam driven pumps/systems) Hazardous Areas in the ship-shore interface challenge the use of SSE. Critical safety and reliability of SSE during cargo operations.
	<10,000	0.69/6.6/11	6 (8)			
	>10,000	0.69/6.6/11	8 (10)			
Chemical/product tankers	<5,000	0.4/0.44/0.69	6 (9)	(80005-3 - annex-D) IEC 60309-5	(80005-1 - annex-F) 62613-2 - annex I	
	<10,000	6.6/11	9 (12)			
	>10,000	6.6/11	10 (20)			
Gas tankers	<5,000	0.4/0.44/0.69	5 (8)	(not defined) IEC 60309-5	(80005-1 - annex-E) 62613-2 - annex I	Cargo pumps and auxiliary systems drive the load. Critical system reliability during cargo pumping operations.
	>5,000	6.6/11	9 (12)			
Bulk carriers	<50,000	0.4/0.44/0.69	0.5 (0.7)	(not defined) IEC 60309-5	(80005-1 - annex-E) 62613-2 - annex I	Cranes, where fitted, hydraulic systems and hatches operation.
	>50,000	0.69/6.6/11	2 (2.8)			
General cargo	<25,000	0.4/0.44/0.69	1.5 (3)	(not defined) IEC 60309-5	(not defined) 62613-2 – as appropriate	Cranes, where fitted, hydraulic systems and hatches operation.
	>25,000	0.69/6.6/11	3 (5)			
Container vessels	<10,000	0.4/0.44/0.69	1.5 (2)	(80005-3 - annex-C) IEC 60309-5	(80005-1 - annex-D) 62613-2 - annex I	Cranes, where fitted, hydraulic systems, hatches operation, refrigerated containers. Reduced space at quay due to cargo terminal cranes pedestals.
	<50,000	0.69/6.6/11	2 (5)			
	>50,000	6.6/11	4 (6)			
Ro-Pax vessels	<20,000	0.4/0.44/0.69	2 (4)	(not defined) IEC 60309-5	(80005-1 - annex-B) 62613-2 - annex J	Predominant Hotels loads and displacement of vehicle ramps. Short turn-around times at berth.
	>20,000	0.69/6.6/11	5 (6.5)			
Cruise ships	<50,000	0.4/0.44/0.69	4 (4.5)	(not defined) IEC 60309-5	(80005-1 - annex-B) 62613-2 - annex H	Large Hotel load driving the power requirements . Safety and Reliability of SSE is critical for operation
	<100,000	0.69/6.6/11	9 (12)			
	>150,000	6.6/11	18 (20)			
Offshore supply vessel	<5,000	0.4/0.44/0.69	1 (1.5)	(80005/3 - annex-B) [IEC 60309-5]	(not defined) 62613-2 – as appropriate	Load from hydraulic systems, possible refrigerated module connections. modest hotel load.
	>5,000	6.6/11	2 (3)			
Fishing vessels	<5,000	0.4/0.44/0.69	0.5 (0.7)	(not defined) IEC 60309-5	(not defined) 62613-2 – as appropriate	Refrigerated systems and possible hydraulic/cranes operation
	>5,000	6.6/11	2 (3)			

Fig. 7: Shore power demand for different ships, European Maritime Safety Agency (EMSA) [121]

The larger BES can also be placed in systems storing the renewable energy, which allows for better utilization of renewable energy. These systems, also known as Hybrid Renewable Energy System (HRES), smart-grids or micro-grids for ports usually consist of renewables, shore power and a BESS. There are many more variations possible some including container terminal operations [64] others incorporating Combined Cooling Heat and power [80], or the use of hydrogen [75]. The optimal management, design and sizing of such energy systems can be very challenging due to the uncertainties of renewable resources and operations, system constraints, and multiple design objectives. To this end many studies have investigated the optimal design or management of these systems for a wide variety of ports. Table 7 and Table 8 aim to give an overview of the literature of what aspects of the port has been investigated, their energy providers and consumers, what has been implemented and which method they used to achieve this. The most commonly modeled aspect for all ports is shore power, as no matter what ship type, ferries, cruises, tankers or container ships are all aiming to diminish their emissions by turning off their auxiliary engines while berthed and are instead supplied with power from shore, also referred to as Cold-Ironing (CI). The estimated power demands for these ships can be seen in Fig. 7. Starting with an overview of the studies focusing on CI implementation with a BES and possibly renewables in seaports. These studies often focus on the sizing of renewables and BES to be optimally used for the seaport. They will also account for ship arrival times and the CI power demands for the respective ships. BES could also play a role here by providing the peak power necessary for these ships, to reduce the burden on the grid and/or to avoid going over the capacity of the ports electric substation.

Table 7: Overview of load management studies in ports

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Wang et al. [54]	Grid, Wind, ESS	CI, ESS	To overcome the dynamic and uncertain nature of seaports and often lack of real energy data, a two-stage optimal framework is proposed. The first stage determines the optimal installed capacity of the sub systems and the second stage models the stochastic characteristics of wind energy and port energy demands to minimize operational costs	Discrete Event Simulation
Hein et al. [62]	Distributed generators, PV, Wind, ESS	CI, ESS	Addresses the uncertainty in the renewable energy sources by modeling the day-ahead operation as a two-stage robust optimization model. The results are used as input parameters for the hour-ahead generation scheduling in the following day.	Two-stage optimization, column and constraint generation algorithm
Sifakis, Konidakis, and Tsoutsos [70]	Grid, PV, Wind, ESS	Port load, ESS	Cycle charging and PS strategies for three different ESSs have been studied, as well as two billing tariffs with PS providing better results and improved energy management and the vandaium redox flow battery being the preferred choice of ESS	Optimization analysis
Bakar et al. [73]	Grid, PV, Wind, ESS	CI, ESS	Design of a hybrid system for a seaport microgrid with optimally sized components. The selected case study is the Port of Aalborg, Denmark.	Hybrid Optimization Model for Electric Renewables (HOMER)
Conte et al. [75]	Grid, PV, Hydrogen, BESS	CI, Electrolyzer, BESS	A model predictive controller is designed to define the best economic strategy to be followed during operations. The control algorithm takes into account the uncertainties of renewable energy generation using stochastic optimization. Components were sized using HOMER	HOMER, Model predictive control
Caprara et al. [74]	Grid, ESS	CI, ESS	Providing CI for cruise ships will require significant power draw from the grid. To avoid installing an extra substation, the possibility of installing a high power and high energy ESS is researched.	Energy Management Simulation Software
Colarossi and Principi [90]	Grid, PV, ESS	CI, ESS	The optimization model proposed aims to provide the best power plant, consisting of PV and ESS, size to support a cold ironing system. The model is based on a life cycle cost approach	Optimization
Darwish [91]	Grid, PV, ESS	CI, ESS	Modular power electronic converter, with an isolated cuk converter as the sub module, for power flow of PV, ESS and shore power	Mathematical analyses, Simulation, Prototype
Vakili and Ölçer [99]	Grid	Ferries, CI, ESS	The Philippines is aiming to significantly reduce its carbon footprint by 75% by 2030 as part of its Nationally Determined Contribution. One step in this process is making its domestic ferries emit zero emissions. To this end, the use of electrified and battery powered vessels is being explored with a life cycle analysis	Life Cycle Analysis
Tao et al. [98]	Grid, Renewables	AES, CI, ESS	This paper discusses flexible scheduling of All Electric Ship (AES), their ESS and CI to satisfy both the transportation demands and mitigate the burden of charging AES on the grid	Temporal Spatial Dynamics

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Table 7 – Continued from previous page

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Buonomano et al. [89]	Grid, PV, CCHP, Biogas production, Ocean energy, ESS	CI, CCHP, ESS	ESS and renewable sources can be designed to be connected to national electricity and natural gas grids and can also include alternative fuels, thermal energy networks and different biomass fluxes. Energy demands of nearby towns and port infrastructure, as well as CI power supply are also included in the dynamic assessments	Constrained optimization
Vakili and Ölçer [100]	Diesel generator, PV, Wind, BES	BES	In this study, the potential use of solar and wind energy and diesel generators in different stand alone and grid connected systems for a port in the Philippines were assessed	HOMER
Abu Bakar et al. [104]	Grid, PV, BES	Ferries, CI, ESS	Two-stage energy management for CI of short berthing ferries with BES and solar energy. Where the first stage sizes the PV, BES and CI installation and the second stage optimizes the operations	Two-stage optimization
Binot et al. [105]	Grid, PV, BES	CI, ESS	Proposes a methodology for optimizing both sizing of PV and storage as well as use of an energy management for a seaport microgrid to minimize costs and CO2 emissions	Bi-objective, Mixed integer Linear programming

Besides modeling the renewables and shore power demand, ports or container terminals can model more of their electric loads to further optimize or forecast their demands. In Figure 8 a typical layout for a smart electrical grid is displayed for a container terminal, making use of BES and renewables to power an electrified terminal. Modeling these can be very complex due to the coupling between energy and logistics, size of the terminals and the uncertainties of ports such as uncertain arrival time of ships and uncertain renewable energy supply which can not be perfectly forecasted. With this extra coupling between more modeled resources different studies investigate this electrified port with different aims.

To get better oversight of energy management in more container terminal oriented energy systems another table is provided. Similar to the layout in Table 7, Table 8 depicts what the paper's energy generators and consumers were, what they investigated and which methods they used. Battery energy storage in these container terminals can not only be used for optimizing the renewable energy usage, but could also function as peak power control and can also be used for energy arbitrage which is for example done by Iris and Lam [64]. This BES could also be effective under different pricing strategies which could reduce the electricity bill. Again it can be seen that most studies include the CI demand for ships replacing their auxiliary engine usage, however these are mostly container ships which have different demands as depicted in Fig. 7. Also a wide variety of energy resources and renewables are implemented. However these studies include more loads which are typically present in container terminals such as the cooling of reefers and crane power loads from hoisting containers. These loads account for a large part of the container terminal's total energy consumption and are also responsible for peak power present in ports. Therefore modeling these demands is significant to forecasting energy demands for container terminals. Modeling and managing energy distribution like this also gives port authorities insight how much they can diminish in terms of costs and emissions, but could also relieve the burden on the grid by some extent.

It is also important to account for uncertainties of renewable energy generation and ship arrivals as these influence the energy management of the port drastically. Uncertain ship

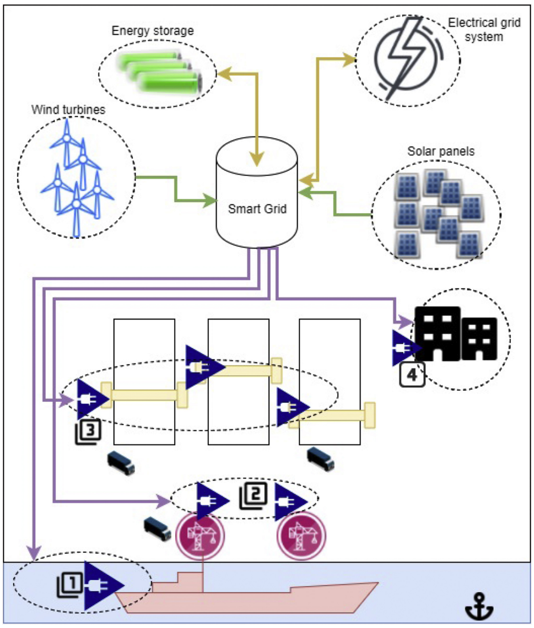

Fig. 8: A smart grid incorporating renewables, energy storage, reefers, container terminal equipment and shore power [64]

arrival will not only account for when CI is provided but the cranes assigned to empty or load the ship will also be affected and this way it propagates through the energy-logistic management. The uncertainty for renewable energy generation affect the power available throughout the day even if the BES is able to partially offset this. Therefore these subjects are also addressed in some of these studies.

As previously mentioned it can also be seen that reefers and BES provide flexibility in the container terminals power supply, while CI and QC operations are more or less tied to ship arrival. Unless the berth allocation problem is solved to account both for the uncertainty of arrival and energy-logistic scheduling, which would allow the power demands to be shifted by adjusting the arrival schedule of ships. However if studies would be solving for all these uncertainties and dispatching decisions the complexity of these models would become very large. As well as the fact that every port is different and researchers are interested in different aspects of the port's energy-logistic operation, it results in a wide variety of studies each contributing their own part for an energy aware port.

Table 8: Overview of load management studies in container terminals

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Lee Lam et al. [25]	Grid, PV	QC, AGV, RMG	According to paper the first in the literature to investigate the costs and benefits of employing energy management system in ports. Unloading and loading process of a ship is simulated along with the respective equipments power usage and solar energy	Discrete Event Simulation

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Table 8 – Continued from previous page

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Manolis et al. [26]	Grid, PV, Wind	Reefers	Distributed demand response application using Multi-Agent System of reefers for improving the voltage in distribution network. Co simulation framework, power system simulator and agent environment	Multi agent system
Kanellos [24]	Grid, Wind	Reefer, PEV	A hierarchical multi-agent system is implemented for the demand response of flexible loads. The port management agent is at the head of operations connected with a wind park agent and followed by a cluster of reefer and PEV agents. Each of these clusters subsequently have agents for each reefer and PEV	Multi-Agent System
Li et al. [51]	Wind, ESS	QC, YC, CI, ESS	Optimizes installation capacity and operation strategy for a container terminal with offshore wind energy using a hybrid renewable energy system	Simulation-based optimization algorithm
Kanellos, Volanis, and Hatziargyriou [47]	Grid	Reefer, PEVs, CI	To combat the large number of decision variables and constraints in large ports, this paper proposes a power management method based on multi-agent systems to maximize the flexibility of power demand. A hierarchical structure is implemented, where each equipment is an individual agent with a cluster agent for the group of equipment and a central port agent	Multi-Agent System
Gennitsaris and Kanellos [43]	Grid, Wind	Reefer, CI	A hierarchical multi-agent system is implemented for the real-time control of flexible port loads. This real-time distributed demand response controls the electric demands with a fuzzy-logic-based system for reefers	Multi-Agent System, Fuzzy Logic
Iris and Lam [64]	Grid, PV, ESS	QC, YC, CI, Reefer, ESS	Port operations and energy management with ESS and renewables with their uncertainties, using a mixed integer linear programming model. Bidirectional energy trading is used between energy sources and ESS allowing for the possibility of energy arbitrage, furthermore different pricing schemes are examined: single price, peak/off-peak price and market price	Mixed Integer Linear Programming
Shi et al. [83]	Grid, Hydrogen storage, Thermal storage, ESS, Wind, PV	QC, YC, CI, Reefer	This paper proposes an optimal operation strategy for the integrated energy-logistics system to minimize the operation cost of a green-port considering a multitude of energy generation options	Mixed Integer Linear Programming
Mao et al. [80]	Grid, PV, Wind, Thermal energy storage, ESS	CI, Thermal energy storage, ESS	An optimization for the multi-energy coordination and berth allocation with the objective of reducing the energy and electricity costs, the dispatch and mooring decision of reefer vessels and cruise ships are established	Mixed Integer Linear Programming
Fang et al. [76]	Grid, Thermal Network	QC, YC, CI, Reefers	An optimization is formulated for the seaport power scheduling, which integrates various logistic demand response methods for cranes' operating speed and ESS as well as reefer areas into an unbalanced multi-phase power network model coupled with a thermal network	Non-Linear, Non-Convex Optimization
Yu, Voß, and Song [87]	Grid	QC, CI	This paper proposes a multi-objective model to optimize the problem of berth allocation and quay crane assignment. The proposed optimization model integrates the decisions on each vessel's berthing position, berthing start and departure time. In this time the duration of using CI and duration of using auxiliary engines is also optimized to minimize the costs of using CI, departure delay and emissions	Multi-objective optimization, Partial optimization Metaheuristic (POPMUSIC)

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Table 8 – Continued from previous page

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Yin et al. [103]	Grid, PV, Wind, Fuel cell, ESS	CI, QC, Electrolyzer, ESS	An energy management and scheduling method for the day-ahead planning with intraday adjustments is proposed to reduce the impact of random power during the day using a scenario tree prediction model and stochastic model predictive control	Stochastic Model Predictive Control
Yin et al. [115]	Grid, PV, Wind, Hydrogen, ESS	CI, QC, RTG, Container truck, BES	A day-ahead energy logistic scheduling model considering carbon emission costs is implemented to improve the economic performance and reduce emissions of port operations. A nested bi-layer energy management and capacity allocation method is made to coordinate the imbalance between hydrogen and electricity supply and demand	Model pursuing sampling algorithm
Sarantakos et al. [110]	Grid, ESS	Cranes, CI, Cargo handling equipment, Reefer, ESS	A robust micro grid for multipurpose ports considering uncertainty of arrival time is developed. An optimal power flow method is made for multiple port logistic assets such as cargo handling equipment, reefers, and renewable energy sources. The aim is to minimize the total operation costs while ensuring that grid limits are not violated due to the uncertainty of ship arrivals	Two-stage adaptive robust optimization
Shi et al. [111]	Grid, PV, Wind, Hydrogen, Thermal Storage, ESS	Reefer,ESS	Establishes an optimal strategy for flexible operations of ESSs and reefers with a multistage stochastic optimization model to minimize costs. It takes into account uncertainties of renewables, load demands, electricity prices and ambient temperatures. The first stage is for the day ahead and power is adjusted intraday with BESS, reefers and thermal storage	Multi Stage Stochastic Optimization
Song et al. [119]	Grid, BSS	CI, BSS	To deal with the uncertainty of renewable energy generation, vessel arrival times and lack of real-time adjustability, a two-layer deep reinforcement learning based energy management strategy is proposed, considering berth allocation, energy management and BSS scheduling	Deep Reinforcement Learning

Ship board microgrid It should be noted that there exists quite extensive literature about ship based microgrid or marine energy systems. These Ship Board Microgrids (SMG) also often called All Electric Ships (AES) are just like other microgrids where the ships have their own energy systems. The main difference compared to previously mentioned studies is that the BES is placed ship side instead of on the shore side. These SMGs are composed of their propulsion load, diesel generators, BES and sometimes PV, all managed on the ship and are also a form of a hybrid energy system. These SMGs have the potential of reducing fuel usage and increasing power production, similar to maximizing the efficiency of diesel generators for hybrid cranes as mentioned in the previous chapter. Alam et al. [88] address energy demand with a SMG containing PV, BES, multiple diesel generators and propulsion on a AC and DC bus with hierarchical control and a sliding mode controller for droop control.

The BES inside these ships allows for the integration of renewables and more flexibility when requiring shore power. The BES will act as a buffer for the ships power supply without having to solely rely on the auxiliary engines of a ship or on the shore power when berthed.

This BES can thereby also control when it receives shore power and change its demand at ports based on electricity supply and price.

This is done by Qiu et al. [82] which analyzes CI for SMG consisting of PV, BES, diesel generator with time of use pricing and locational marginal pricing. Giving better incentive for power congestion management and emission control than fixed and real-time pricing. Tang, Li, and Lai [34] investigates another similar SMG, implementing a PV array, BES, a diesel generator and CI minimizing the electricity costs solved with a particle swarm optimization. Similarly Tang, Wu, and Li [35], has the same SMG layout and accounts for CI prices, but the power dispatch is controlled and solved with MPC.

The decision when to berth for these SMGs can also be adjusted according to predicted prices of shore side electricity. Tang et al. [59] focuses on the modeling and scheduling methodology for these SMGs with an ultrahigh-dimensional HES model. to provide a solution for shipping company to achieve promising performance on operational cost control with the increasingly stringent emission regulations.

Similarly, Wen et al. [71] developed a two-stage hybrid optimization algorithm to improve the energy efficiency and reduce GHG emissions of the AES based on the predicted shore side electricity prices, for scheduling arrival times with minimum cost and emissions.

These SMGs can also coordinate amongst each other to coordinate their power demands when berthed at ports. This can especially be useful to alleviate peak power burdens at these ports and is an additional option to lower the electricity bill. Fan et al. [92] uses this SMG with BES and thereby the flexibility of CI power as a demand response tool. The port will coordinate berthed ships with shipboard microgrid to adjust their CI demand requests, to alleviate peak burden. An incentive-based cooperative coordination framework between port microgrid and berthed ships is proposed by Fan et al. [92]. With the aim of minimizing the net cost comprising energy cost and potential demand charge, the port will differentially coordinate berthed ships to adjust their CI demand requests, to alleviate peak burden. Multiple SMGs could combine their CI services to alleviate peak burden. When multiple ships require shore power at a port that does not have enough capacity or to optimally distribute shore power among the ships, Mutarraf et al. [69] proposes a communication-less method for managing power among multiple SMGs. Their approach uses a decentralized droop control strategy that adjusts power flow based on battery SOC levels. Similarly, Yang et al. [114] also discusses the limitation of port CI quantity and power supply capacity. To solve this problem, this paper proposes a multi-ship power sharing strategy based on two-stage robust optimization. Sadiq et al. [109] investigates next-generation smart ports, wherein the integration of internet of things and sensors transforms ports into intelligent hubs. this paper proposes a seaport microgrid with a DC distribution that would be created by integrating multiple ships with decentralized control mechanisms supplemented by an onshore charging infrastructure Shipboard microgrid.

There is also a future for all electric ships without diesel generators. This will likely only be possible for smaller type ships such as ferries in the near future as changing all the diesel engines will require large amounts of power and storage. This will require large swap-able batteries for these ships or very high charging speeds.

Energy markets Beside the possibility for load management of the Port, the BES and ESS can also be used for actively participating in energy markets, such as ancillary services for Transmission System Operators (TSO). Flexibility of port resources can not only be used for its own energy demand but could also alleviate grid burdens with these types of services. With all these flexibility options from the ESS, Battery equipment, Reefers, SMGs and other energy resources there are many opportunities to partake in these services

Virtual power plant (VPP) is a network that manages decentralized energy resources (DER) which include power generation and storage on the consumer side, its implementation could lower emissions and the electricity bill. Kolenc et al. [50] explore the use of a VPP to operate DERs over public internet infrastructure. The study focuses on utilizing the battery stacks of B-AGVs within a container terminal to provide ancillary services to the TSO

One of these ancillary services is frequency containment reserve (FCR), which is a mechanism used by TSOs to keep the electricity grid stable. The main objective of the FCR is to restore grid frequency back to its nominal value following disturbances, which can for example happen when there is a sudden increase in demand or when a provider stops generating energy, which can for example be caused by cloudier weather than expected. When such a disturbance occurs, the FCR comes into action and the reserve power is immediately injected or withdrawn from the grid to balance the mismatch between supply and demand to stabilize the frequency. In the case of ports, BES and battery-charging processes can be initiated earlier or accelerated to withdraw more from the grid, also known as negative reserve, or can be postponed or injected, decelerated or discharged to offer positive reserve.

Holly et al. [55] discuss how the potential of a fleet of battery vehicles can be used to provide FCR in a logistical context, such as a port. For this an artificial neural networks is used to predict the availability of B-AGVs day-ahead, the marketable flexibility is computed with a heuristic approach and checked if plausible in schedule with a simulation. The B-AGVs are continuously supervised and controlled with a multi-agent system and the electric fleet's flexibility is integrated into a larger pool of DER within a VPP.

Kanellos [24] proposes a decentralized demand response method for a port comprising of flexible loads and power generation from a wind park, using a multi-agent system. This proposed method also proved to be efficient in providing ancillary services. Later Kanellos, Volanis, and Hatziargyriou [47] expanded the research further with the previous multi-agent system for reefer and plug in electric vehicles, with the aspect of cold-ironing instead of a wind park. Gennitsaris and Kanellos [43] then combines the previous two without PEVs for a more complete agent based model of a container terminals flexible load which could be used.

The FCR with batteries has the issue that it could lead to faster degradation of vehicles' batteries due to the additional charging cycles. How much this affects the battery life and what degradation costs are incurred depends on its implementation and is evaluated by Harnischmacher et al. [93]. For their setup Cycle-Count Models best represent battery degradation, showing an increase in battery degradation of just 1.36% through the use for FCR. Improving the business case for its implementation.

6 Research gap and future work

Despite the extensive research that has been done for more sustainable use of port assets, incorporating renewables and optimizing energy management within ports, there is always room for more research in certain areas for the transition to more sustainable and energy aware ports. These suggested proposals for future research will be divided into four sections of energy sources and use; on the topic of battery powered equipment; ships and their cold-ironing power demand and lastly on energy management.

Energy usage and distribution: There are more paths for ports to be more sustainable with for example infrastructure for ESS, Green Hydrogen and Thermal Storage, to name a few. It will be interesting to see the trade off between these different storage methods and what would be suitable for varying ports. This same question also holds for battery based equipment compared to for example their fuel cell based counterparts, to strengthen the case of electrifying these with batteries or provide as an alternative for ports with limited power availability.

An up to date overview of the energy use per asset of ports and container terminal as a percentage of energy use would give insightful results of the development in more sustainable ports and expected growth. For example now that Cold-Ironing is becoming a more adapted method and more battery equipment is being used this difference would be interesting when compared to what has been done by older studies. This can be studied for different layouts, from the biggest automated container terminals to the smaller non automated ones. More accurate measurement and forecast of energy demands with smart meters could also be adapted for this effort, which can also improve the forecasting of power demands of aspects such as cold-ironing for ships.

Battery powered equipment: The AGV has been quite extensively researched from energy efficient pathing in container terminals to correlated planning with yard cranes and as mentioned in this paper, the charging strategies for B-AGV in ports. Due to complexity, most of these charging strategies do not consider partial charging of their batteries as an option to reduce the down time of the B-AGV while still being able to perform for the rest of its listed jobs, which could be studied further. The same holds for the charging of other battery powered equipment, as charging management for other equipment could also be studied in this manner.

The sizing of a battery powered equipment and charging stations or battery swapping stations can be researched further, giving a guide for port authorities into how large the batteries of the equipment should be how fast the charging speed of the chargers should be and still fit withing the ports energy-logistic system.

The possibility of inductive charging for B-AGV in the setting of a container terminal could can also be assessed, to analyze the viability of this solution. As this is already being thoroughly researched within other logistic fields such as warehouses it would be insightful to see if there is any benefit in implementing such a charging method for the battery powered equipment in ports.

For the operation and charging additional battery effects can be modeled, as these are often not taken into account. These effects include battery degradation of equipment and loss of SOC and nonlinear charging effects, especially when fast charging the charging speed will not be consistent throughout its charge time. These affects could make the scheduling of these battery powered equipment more precise, as both the approximated SOC and time spent charging would improve.

Ships and cold-ironing As discussed previously there is already quite extensive literature on shipboard micrgogrid, their energy management and how they could interact with ports to adapt their cold-ironing demand. However an analysis of using sustainable fuels powering ships when berthed versus diesel and their effect on cold-ironing be made. As these SMGs often optimize for costs and emissions, it would be insightful to see how this behaviour would change with more sustainable fuels.

Electric powered vessels, for inland shipping or ferries will require large charging stations or large battery swapping station with for example battery containers. A case could be made how these vessels could charge in rivers and see the viability of such an approach as seagoing vessels will require too much power to be achievable with an electric counterpart and such an approach. These could be implemented at the ports or at communal stations where these ships could recharge.

More precise values for cold-ironing demand of ships and their profile characteristics can be analyzed as current estimates fluctuate in average and maximum demand for different types of ships. This will allow for better modeling of these loads for ports and reduce the possibility of underestimating or overestimating this demand.

Energy management for ports Current literature on energy management within ports already model and implement many different port assets and energy sources, however there are still areas that could be explored further.

To start, the charging of the B-AGV's batteries and other battery powered equipment used in ports bring an extra load on the grid as the large fleets will have to be charged with either a charging station or a battery swapping station. Both these approaches also have uniquely different effect on when they require power and how they fit into the loigstic operations. However, currently there are few studies also incorporating the charging of these batteries for equipment inside energy management systems for the entire port, accounting for most of the port loads but few consider these different charging implementations into those studies.

Because the path of electrification is one of the more popular ways for more sustainable operations it also brings extra burden on the grid which has to adapt to the rapid growth of electricity demand. Ancillary services such as FCR can be investigated further with the growing amount of shift-able loads in ports such as the reefers, ESS, SMGs and battery powered equipment. Ports can play a larger role when it comes to keeping the keeping the grid stable and can still be incentivized while doing so. This could be added to the already existing energy port models and account for day-ahead and intraday disturbances in the grid. One of the most straightforward methods of doing so would be to use the ESS, with possibly sotred renewable energy to this end.

Studies also seem to largely focus on the costs related to electricity price and sometimes greenhouse gas prices, but costs related to DSO's and TSO's distribution and transimission services is often not incorporated. Some of these variable costs can be significant and should not be ignored when optimizing energy management systems for costs. Costs such as maximum power and peak power becoming more relevant, flexible resources such as ESS can help mitigate these higher penalties.

The ESS for cranes or use of AFE can be studied further in the context of energy-logistic management as the use of these allows for energy capture and a reduction in power demand which the effects of will propogate through the energy management optimization and operations

7 Conclusion

The transition to an electrified and energy efficient port is a complex task but necessary step in response to increasing energy costs and sustainability goals. This literature review highlights the growing role of battery and electric energy storage systems in port operations, which can be implemented and enhance many different assets in a port. The efficiency of cranes can be improved within ports by outfitting them with electric energy storage systems to capture energy during lowering, which can save a significant amount of energy as well as reduce the peak power from these cranes. Furthermore, batteries enable the electrification of mobile equipment and have been proven to haven an economic benefit with numerous of studies investigating charging station or battery swapping operations for this mobile equipment in ports. Battery energy storage also allows for storing generated renewable energy, peak shaving and along with other flexible loads for load leveling. This flexibility of power can help reduce costs and also be used for ancillary services. However, challenges remain in accurately modeling battery health degradation, non-linear charging, complex charging logistics, and uncertainties from renewable energy generation and vessel arrivals. Overall, battery and electric energy storage provide an effective way of managing the electrical loads and provides flexibility even in logistically demanding ports.

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Journal Paper

Two-Stage Optimization for Electrification and Power Demand Management of Container Terminals considering Uncertain Ship Arrival

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Abstract

The transition to more sustainable operations is being widely adapted to reduce the green house gas emissions and meet the future sustainability requirements. This transition most often utilizes electrification as a means to reduce emissions and utilize renewable energy. This transition comes with extra burden on container terminal authorities who have to manage their power demands and grid service operators. This comes with extra costs as service operators have to build and maintain a larger network and larger power capacities can not always be ensured for consumers such as container terminal due to grid congestion. To achieve electrification for container terminals these distribution service operator costs as well as electricity costs should be taken into account.

Scheduling power demands for container terminals is not trivial as they operate in a dynamic environment. To ensure a container terminal has sufficient electric capacity and can manage its power demand a two-stage power optimization is made considering uncertain arrival time of ships. The charging decisions for the electric yard fleet as well as charging and discharging of battery energy storage system and cooling of reefers are scheduled for the next day. The necessary capacity is optimized considering the flexible resources which would be required and the electricity pricing is taken into account, with dynamic electricity pricing outperforming a fixed price. A Time Constraint Transport Right is also analyzed, which could work for container terminals with many flexible loads, but does not save costs for this terminal.

Keywords: Container Terminal, Power Management, Uncertain arrival, Load shifting, Electrification

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1. Introduction

There is a shift towards more sustainable operations as ports as an industry account for 3% of global greenhouse gas (GHG) emissions [25]. In light of these sustainability goals and steps towards greater sustainability, port authorities will have to take on a new role to include more energy efficient measures and better management of their energy loads [1]. This can lead to energy savings, improve the green image of the port and provide a competitive advantage.

In terms of energy generation, port authorities can continue to invest in renewable energy generation for their own use, such as wind power or solar energy, and the possibility of storing excess energy generated in batteries for later use.

Container terminal can achieve more sustainable operations and reduce greenhouse gas (GHG) emissions by adapting their energy consumption through alternative energy sources, efficiency measures, and better energy management. This can be applied to port equipment by replacing typical diesel fuel powered equipment with electric, hydrogen, or other alternative/bio-fuels. It also involves assessing energy consumption within port operations and minimizing it while still maintaining the high operational throughput a container terminal requires. Additionally, managing available energy in an efficient manner, whether through self-generation, grid electricity, or other fuel sources, ensures more efficient and sustainable power use.

For this transition to more sustainable port operations, electrification is a promising solution [15]. All of the equipment used in container terminals can be or is electrified, from quay cranes, cold-ironing, cranes and reefers to battery powered equipment such as automated guided vehicles, also allowing for regenerative capabilities.

Furthermore, it also offers a universal solution to manage the energy usage in container terminals and able to utilize generated renewable energy. However, going fully electric has some caveats, it can introduce large peaks of electricity demand when equipment is simultaneously drawing power. Another problem that arises is the downtime of battery equipment due to charging, as this process still takes significantly longer than simply refueling and will have to be accounted for by either larger batteries, faster charging speeds or larger fleets.

With many businesses opting for electrification this also places a burden on the grid as electricity demand is rapidly increasing and grid operators having to keep up with this rising demand. This paper proposes scheduling of the flexible loads: reefers, Battery Energy Storage (BES) and charging of battery powered equipment within a container terminal to assess the required demand for a fully electrified container terminal with uncertain ship arrival times. It will also compare fixed and dynamic electricity pricing and account for Distribution Service operator (DSO) fees which are applicable for large electricity consumers in the Netherlands. Additionally, a Time Constrained Transport Right (TCTR) contract offered by this DSO will be investigated.

2. Literature

There is extensive literature on modeling electric loads for container terminals including different loads such as shore power demand, cranes, reefers and renewable energy. Container terminals can model these electric loads to further optimize or forecast their demands and possibly reduce their costs or emissions. In Figure 1 a typical layout for a smart electrical grid is displayed for a container terminal, making use of Battery Energy Storage (BES) and renewable energy to power an electrified terminal. Modeling these type of smart grids can be very complex due to the coupling between: energy and logistics, size of the terminals and the uncertainties of ports such as uncertain arrival time of ships and uncertain renewable energy generation which can not be perfectly forecasted. With this extra coupling between more modeled resources, different studies investigate this electrified port with different aims.

To get better oversight of power management in container terminal oriented energy systems, Table 1 is provided. This table depicts what the paper's energy generators and consumers were, what was investigated and which methods were used. Battery energy storage in these container terminals can not only be used for optimizing the renewable energy usage, but could also function as peak power control and can also be used for energy arbitrage which is for example done by [12]. These flexible loads could also be effective under different pricing strategies which could reduce the electricity bill.

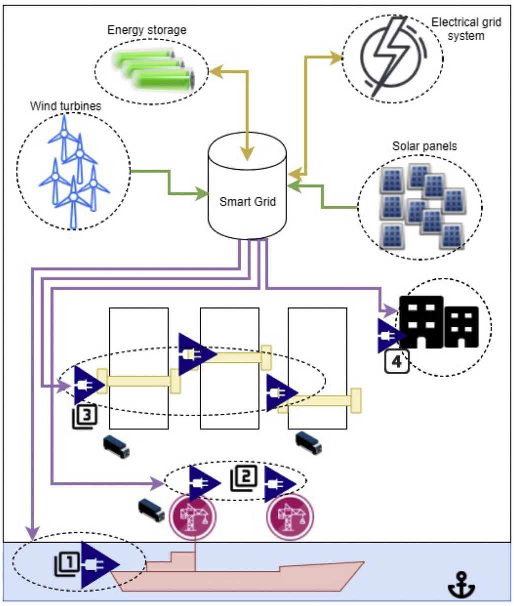

Figure 1: A smart grid incorporating renewables, energy storage, reefers, container terminal equipment and shore power [12]

From this table it can be noted that a wide variety of energy resources are being analyzed for different types of terminals. It can also be seen that reefers and BES provide flexibility in the container terminals power supply, while CI and QC operations are tied to ship arrival. Unless the berth allocation problem is solved to account both for the uncertainty of arrival and energy-logistic scheduling, which would allow the power demands to be shifted by adjusting the arrival schedule of ships. However, this will quickly become too computationally expensive due to its complexity. Accounting for uncertainties relating to ship arrival is important as it influences much of the container terminal's logistic and energy scheduling.

Table 1: Overview of load management studies in container terminals

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Lee Lam et al. [20]	Grid, PV	QC, AGV, RMG	According to paper the first in the literature to investigate the costs and benefits of employing energy management system in ports. Unloading and loading process of a ship is simulated along with the respective equipments power usage and solar energy	Discrete Event Simulation
Manolis et al. [23]	Grid, PV, Wind	Reefers	Distributed demand response application using Multi-Agent System of reefers for improving the voltage in distribution network. Co simulation framework, power system simulator and agent environment	Multi agent system

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Table 1 – Continued from previous page

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Kanellos [14]	Grid, Wind	Reefer, PEV	A hierarchical multi-agent system is implemented for the demand response of flexible loads. The port management agent is at the head of operations connected with a wind park agent and followed by a cluster of reefer and PEV agents. Each of these clusters subsequently have agents for each reefer and PEV	Multi-Agent System
Li et al. [21]	Wind, ESS	QC, YC, CI, ESS	Optimizes installation capacity and operation strategy for a container terminal with offshore wind energy using a hybrid renewable energy system	Simulation-based optimization algorithm
Kanellos, Volanis, and Hatziar-gyriou [15]	Grid	Reefer, PEVs, CI	To combat the large number of decision variables and constraints in large ports, this paper proposes a power management method based on multi-agent systems to maximize the flexibility of power demand. A hierarchical structure is implemented, where each equipment is an individual agent with a cluster agent for the group of equipment and a central port agent	Multi-Agent System
Gennitsaris and Kanellos [8]	Grid, Wind	Reefer, CI	A hierarchical multi-agent system is implemented for the real-time control of flexible port loads. This real-time distributed demand response controls the electric demands with a fuzzy-logic-based system for reefers	Multi-Agent System, Fuzzy Logic
Iris and Lam [12]	Grid, PV, ESS	QC, YC, CI, Reefer, ESS	Port operations and energy management with ESS and renewables with their uncertainties, using a mixed integer linear programming model. Bidirectional energy trading is used between energy sources and ESS allowing for the possibility of energy arbitrage, furthermore different pricing schemes are examined: single price, peak/off-peak price and market price	Mixed Integer Linear Programming
Shi et al. [31]	Grid, Hydrogen storage, Thermal storage, ESS, Wind, PV	QC, YC, CI, Reefer	This paper proposes an optimal operation strategy for the integrated energy-logistics system to minimize the operation cost of a green-port considering a multitude of energy generation options	Mixed Integer Linear Programming
Mao et al. [24]	Grid, PV, Wind, Thermal energy storage, ESS	CI, Thermal energy storage, ESS	An optimization for the multi-energy coordination and berth allocation with the objective of reducing the energy and electricity costs, the dispatch and mooring decision of reefer vessels and cruise ships are established	Mixed Integer Linear Programming
Fang et al. [6]	Grid, Thermal Network	QC, YC, CI, Reefers	An optimization is formulated for the seaport power scheduling, which integrates various logistic demand response methods for cranes' operating speed and ESS as well as reefer areas into an unbalanced multi-phase power network model coupled with a thermal network	Non-Linear, Non-Convex Optimization
Yu, Voß, and Song [40]	Grid	QC, CI	This paper proposes a multi-objective model to optimize the problem of berth allocation and quay crane assignment. The proposed optimization model integrates the decisions on each vessel's berthing position, berthing start and departure time. In this time the duration of using CI and duration of using auxiliary engines is also optimized to minimize the costs of using CI, departure delay and emissions	Multi-objective optimization, Partial optimization Metaheuristic (POPMUSIC)
Yin et al. [39]	Grid, PV, Wind, Fuel cell, ESS	CI, QC, Electrolyzer, ESS	An energy management and scheduling method for the day-ahead planning with intraday adjustments is proposed to reduce the impact of random power during the day using a scenario tree prediction model and stochastic model predictive control	Stochastic Model Predictive Control

Continued on next page

Table 1 – Continued from previous page

Source	Energy Suppliers	Energy consumers	What is implemented	Method
Yin et al. [38]	Grid, PV, Wind, Hydrogen, ESS	CI, QC, RTG, Container truck, BES	A day-ahead energy logistic scheduling model considering carbon emission costs is implemented to improve the economic performance and reduce emissions of port operations. A nested bi-layer energy management and capacity allocation method is made to coordinate the imbalance between hydrogen and electricity supply and demand	Model pursuing sampling algorithm
Sarantakos et al. [30]	Grid, ESS	Cranes, CI, Cargo handling equipment, Reefer, ESS	A robust micro grid for multipurpose ports considering uncertainty of arrival time is developed. An optimal power flow method is made for multiple port logistic assets such as cargo handling equipment, reefers, and renewable energy sources. The aim is to minimize the total operation costs while ensuring that grid limits are not violated due to the uncertainty of ship arrivals	Two-stage adaptive robust optimization
Shi et al. [32]	Grid, PV, Wind, Hydrogen, Thermal Storage, ESS	Reefer,ESS	Establishes an optimal strategy for flexible operations of ESSs and reefers with a multistage stochastic optimization model to minimize costs. It takes into account uncertainties of renewables, load demands, electricity prices and ambient temperatures. The first stage is for the day ahead and power is adjusted intraday with BESS, reefers and thermal storage	Multi Stage Stochastic Optimization
Song et al. [34]	Grid, BSS	CI, BSS	To deal with the uncertainty of renewable energy generation, vessel arrival times and lack of real-time adjustability, a two-layer deep reinforcement learning based energy management strategy is proposed, considering berth allocation, energy management and BSS scheduling	Deep Reinforcement Learning

2.1. Contracts at Distribution Service Operator

Beside the standard transmission fee costs there are also flex contracts options available at Stedin which would give incentive for parties to adjust their power by increasing or decreasing their demand or supply [26]. These contracts are different in that they are not continuously fixed power contracts but alter their capacity throughout time or are combined into groups. These contracts aim to reduce grid congestion and resolve disturbance and maintenance, which allows for better utilization of the grid. An overview of the current flexible electricity contracts at Stedin can be seen in Figure 2.

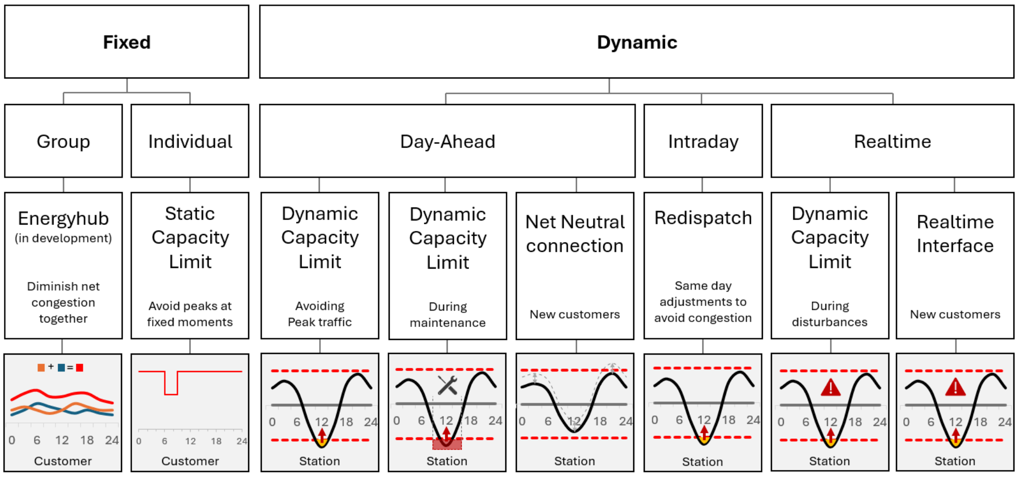

Figure 2: Flex contract options at Stedin [26]

There are many contract options, however the Time Constrained Transport Right (TCTR) will be analyzed. The Time Constrained Transport Right is being introduced in the Netherlands and enables businesses to increase their contracted capacity, typically between 00:00 and 06:00, depending on region. This can supplement the existing contracted capacity. This is especially useful for parties who need to charge their equipment in the morning but do not require extra capacity throughout the day. Container terminals that do not operate on a 24/7 basis could also use this time slot in the morning to charge their battery container handling equipment. However, not every region allows this type of contract due to congestion and is not always available at the same time slots mentioned previously. The amount of additional power is determined by the container terminal, but, as previously mentioned, depends on whether this contract will be made available in this region.

3. Literature Gap

With these many energy management studies in mind, this paper aims to expand upon them with the following aspects:

- Few studies adapt the charging scheduling of battery container handling equipment through charging stations in power management systems. This study aims to provide power scheduling of when to charge this equipment, considering the uncertain arrival times of ships.
- Little to no studies consider the distribution service operator fees such as contracted capacity costs and maximum power used in 15 minute averages, inside the optimization. This also allows for optimization of necessary contracted capacity for an electrifying container terminal. Furthermore, another capacity contract (Time Constrained Transport Right) will be analyzed, which has also not been implemented in the literature.
- This model will have a small time step of 15 minutes to account for the fees mentioned above, as well as allow for shorter berth times which occur at smaller container terminals.

- To ensure the capacity is sufficient and represent more real-life decision making the decisions for charging of the battery container handling equipment, cooling of refrigerated containers and charging and discharging of a battery energy storage, are considered first stage. While only shore power and crane power will be provided when the ship actually arrives and ensured there is enough power.

4. Methodology

To achieve these goals the mathematical model formulation will be provided. In this mathematical model the parameters will be denoted with a small letter and the decision variables will be denoted by a capital letter. Table 2 denotes the sets and indices used for all parameters and variables used for this optimization. The parameters used can be viewed in Table 3 along with their description and unit. Similarly Table 4 denotes the decision variables for this problem.

Set	Description	Indice
I	Set of BCHE types at the port	$i \in I$
J	Set of Reefer clusters at the port	$j \in J$
V	Set of vessels arriving at the port	$v \in V$
T	Set of time periods in the day	$t \in T$
S	Set of possible scenarios for ship arrivals	$s \in S$

Table 2: Sets and Indices

Parameters	Description	Unit
dt	Size of timestep	[h]
t_{max}	Total number of time steps in the model	[int]
$soc^{\min}$, $soc^{\max}$	Minimum and maximum SOC	[%]
w_i^{lim}	Maximum work rate per BCHE type i	[TEU/h]
$p^{bche,ch}$	Maximum charging speed for BCHE	[kW]
j_i^{bche}	Average power usage of BCHE i per job	[kWh]
b_i^{bche}	Battery size of BCHE i	[kWh]
η^{bche}	Charging efficiency BCHE i	[%]
cs	Number of available charging stations	[int]
m	Number of available employees	[int]
b^{BES}	Capacity of Battery Energy Storage	[kWh]
$p^{bes,max}$	Max charge/discharge power of Battery Energy Storage	[kW]
η^{BES}	Efficiency of BES	[%]
p^{lim}	Power limit from the station	[kW]
n_j^{reefer}	Number of reefers per cluster	[int]
T_j^{des}	Desired temperature of reefer j	[°C]
$T_j^{tolerance}$	Temperature tolerance of reefer j	[°C]
$w_j^{loss}, sur_j, cp_j, m_j$	Thermal parameters for reefer j	
T_t^{amb}	Ambient temperature at time t	[°C]
$T_j^{initial}$	Initial temperature for reefers	[°C]
$p^{reefer,max}$	Maximum cooling power of reefer	[kW]
ep_t	Electricity price at time t	[€/kWh]
ec	Monthly cost of contracted electricity capacity of the DSO	[€/kW]
em	Monthly cost of peak electricity used in a 15 minute interval	[€/kW]
eo	Penalty cost for going over contracted electric capacaity	[€/kW]
cr	Maximum container handling per crane per time period	[Teu]
q	Total number of cranes available	[int]
z_i	Number of battery equipment per type	[int]
$a_{v,s}$	Arrival time of vessel v for scenario s	[int]
k_t	Truck arrivals per time step t	[int]
l_v	Total containers to handle for vessel v	[Teu]
p^{crane}	Maximum power consumption per crane per time unit	[kW]
p_v^{shore}	Shore power usage when vessel v is berthed	[kW]
P^{con}	Positive contracted power capacity	[kW]
$P^{undercon}$	Negative contracted power capacity	[kW]

Table 3: Paramters

Variable	Description	Unit
$X_{i,t}$	Amount of BCHE type i charging at time t	[Num]
$Y_{i,t}$	Amount of BCHE type i working at time t	[Num]
$SOC^{bche}_{i,t,s}$	SOC of BCHE type i at time t in scenario s	[%]
$SOC^{init,bche}_{i}$	Initial SOC of BCHE type i	[%]
$W_{i,t,s}$	Working rate of BCHE type i at time step t in scenario s	[TEU/h]
$P^{charge}_{i,t}$	Charging speed of BCHE type i at time step t	[kW]
$P^{reefer}_{j,t,s}$	Power used by reefer j at time t	[kW]
$P^{bes,ch}_{t}$	Charging power for BES	[kW]
$P^{bes,dch}_{t}$	Discharging power for BES	[kW]
SOC^{bes}_{t}	SOC of BES at time t	[%]
$SOC^{init,bes}$	Initial BES capacity	[%]
$T^{reefer}_{j,t}$	Temperature of reefer cluster j at time t	[°C]
$P^{total}_{t,s}$	Total power used at time t in scenario s	[kW]
P^{max}_{s}	Maximum power used in a 15 minute interval during the day in scenario s	[kW]
$D_{v,s}$	Departure time of vessel v in scenario s	[int]
$H_{v,t,s}$	Containers handled for vessel v at time t in scenario s	[Teu]
$C_{v,t,s}$	Cranes assigned to vessel v at time t in scenarios s	[int]
$B_{v,t,s}$	Whether vessel v is berthed at time t in scenario s	[0,1]
$P^{crane}_{t,s}$	Total crane power usage at time t in scenario s	[kW]
$P^{shore}_{t,s}$	Total shore power usage at time t in scenario s	[kW]

Table 4: Decision variables

4.1. Objective function

The objective minimizes the electricity costs and the fees from the DSO, which are a monthly fee for the contracted capacity and the maximum average power used measured in a 15 minute interval. There is also a penalty for exceeding the contracted capacity.

$$\min \quad \pi_s \sum_{s\in S}(\sum_{t\in T}(P^{total}_{t,s} \cdot ep_t \cdot dt) + (P^{over}_{s} + P^{under}_{s}) \cdot eo + P^{max}_{s} \cdot em + P^{con} \cdot ec) \tag{1}$$

4.2. Global power constraints

The global power constraint of the port considers the power of cooling the reefers; power of charging the battery energy storage; the discharged power from the battery energy storage; the power of charging the batteries of the battery electric container handling equipment; The shore power of berthed ships and the cranes working on these berthed ships. The electric contracted capacity is enforced by penalizing the power over and under their respective capacities. This is done so the contracted power can also be optimized as well as operating as a more feasible constraint, because stringent constraints might be numerically violated with the chosen decomposition method by a tiny margin.

$$P^{total}_{t,s} = \sum_{j\in J} P^{reefer}_{j,t} + P^{bes,ch}_{t} + P^{bes,dch}_{t} + \sum_{i\in I} P^{charge}_{i,t} + P^{shore}_{t,s} + P^{crane}_{t,s}, \quad \forall t \in T,\ s \in S \tag{2}$$

$$P^{total}_{t,s} \leq P^{max}_{s}, \quad \forall t \in T,\ s \in S \tag{3}$$

$$P^{total}_{t,s} - P^{con} \leq P^{over}_{s}, \quad \forall t \in T,\ s \in S \tag{4}$$

$$P^{under}_{s} \leq P^{undercon} - P^{total}_{t,s}, \quad \forall t \in T,\ s \in S \tag{5}$$

The limits for the power usage of these are described in constraint 6 for reefer cooling power; 7 for BCHE charging power; 8 and 9 for charging and discharging of BES respectively.

$$0 \leq P^{reefer}_{j,t,s} \leq p^{reefer,max}, \quad \forall j \in J,\ t \in T\ s \in S \tag{6}$$

$$0 \leq P^{charge}_{i,t} \leq p^{charge,max}, \quad \forall i \in I,\ t \in T \tag{7}$$

$$0 \leq P^{bes,ch}_{t} \leq p^{bes,max}, \quad \forall t \in T \tag{8}$$

$$-p^{bes,max} \leq P^{bes,dch}_{t} \leq 0, \quad \forall t \in T \tag{9}$$

(10)

4.3. Constraints of Ships and cranes

For the ship arrivals and the cranes loading or unloading the ship the following constraints are created. The ships are planned according to a typical working rate at the terminal to determine the length of stay at the port. Ships however can deviate from their estimated time of arrival due to delays or they could be ahead of schedule. Furthermore ports typically have multiple cranes on the quay which could work simultaneously on one ship or could spread over multiple ships.

$$H_{v,t,s} \leq C_{v,t,s} \cdot cr, \quad \forall v \in V,\ t \in T,\ s \in S \tag{11}$$

$$C_{v,t,s} \leq q \cdot B_{v,t,s}, \quad \forall v \in V,\ t \in T,\ s \in S \tag{12}$$

$$\sum_{t\in T} B_{v,t,s} = D_{v,s} - a_{v,s}, \quad \forall v \in V,\ s \in S \tag{13}$$

$$B_{v,t,s} \cdot (t+1) \leq D_{v,s}, \quad \forall v \in V,\ t \in T,\ s \in S \tag{14}$$

$$t \cdot B_{v,t,s} + (1 - B_{v,t,s}) \cdot t_{max} \geq a_{v,s}, \quad \forall v \in V,\ t \in T,\ s \in S \tag{15}$$

$$D_{v,s} \leq a_{v,s} + \frac{l_v}{cr}, \quad \forall v \in V, s \in S \tag{16}$$

$$\sum_{t\in T} H_{v,t,s} = l_v, \quad \forall v \in V,\ s \in S \tag{17}$$

$$\sum_{v\in V} C_{v,t,s} \leq q, \quad \forall t \in T,\ s \in S \tag{18}$$

$$P^{crane}_{t,s} = \sum_{v\in V} \left(\frac{H_{v,t,s}}{cr} \cdot p^{crane} \right), \quad \forall t \in T,\ s \in S \tag{19}$$

$$P^{shore}_{t,s} = \sum_{v\in V} p^{shore}_{v} \cdot B_{v,t,s}, \quad \forall t \in T,\ s \in S \tag{20}$$

Constraint 11 specifies the handling rate for a ship must be smaller or equal to the assigned cranes and their maximum working rate. Constraints 13, 14, 15 specify that the ship is berthed during its arrival up untill its departure, and can not be berthed before its arrival or after its departure. Constraint 16 sets an upper limit on the departure time with the maximum allowed stay time, which is based on the handling rate used for scheduling purposes. Constraint 17 denotes that the amount of containers handled by the cranes for each ship must be equal to the amount of containers to be loaded and/or unloaded from each ship. Constraint 18 sets the limit for the sum of the assigned crane for each ship to not be larger than the total amount of cranes available. Constraint 19 specifies the power used by each crane by dividing it by its max work rate and multiplying by its power when working at its maximum rate. Constraint 20 sets the total shore power to be equal to shore power of each ship multiplied by whether they are berthed or not at every time step.

4.4. Constraints of battery handling equipment

To model the State Of Charge (SOC) of the batteries equations 21 and 22 are composed, which take into account at every time step whether they are charging or performing jobs at a certain rate and the resulting gain or loss in SOC. This SOC must stay between the minimum and maximum threshold according to 23 to prolong battery life. Furthermore it is assumed that the SOC of the BCHEs start with some capacity, this capacity needs to be the same as which it started with, as can be seen in constraint 24.

$$SOC_{i,0}^{bche} = SOC_i^{init,bche} + \frac{P_{i,0}^{charge} \cdot dt \cdot \eta^{bche}}{n^{bche} \cdot b^{bche}} \cdot 100 - \frac{W_{i,0,s} \cdot j_i^{bche} \cdot dt}{n^{bche} \cdot b_i^{bche}} \cdot 100, \quad \forall i \in I,\ t = 0 \quad (21)$$

$$SOC_{i,t}^{bche} = SOC_{i,t-1}^{bche} + \frac{P_{i,t}^{charge} \cdot dt \cdot \eta^{bche}}{n^{bche} \cdot b_i^{bche}} \cdot 100 - \frac{W_{i,t,s} \cdot j_i^{bche} \cdot dt}{n^{bche} \cdot b_i^{bche}} \cdot 100, \quad \forall i \in I,\ t > 0 \quad (22)$$

$$SOC^{min} \leq SOC_{t,s}^{bche} \leq SOC^{max}, \quad \forall i \in I, t \in T \quad (23)$$

$$SOC_{i,|T|-1}^{bche} = SOC_i^{init,bche}, \quad \forall i \in I \quad (24)$$

Constraint 25 sets the maximum arrival rate of jobs must never be larger than the combined work rate of the BCHEs at every time step. This constraint can be redefined more specifically to specify which BCHE type does what, but for ports with only the same equipment type this constraint holds. Constraint 30 ensures that the BCHE can not simultaneously charge and perform jobs at the same time with the integer decision variables. Constraints 26 and 27 set the limits for the continuous decision variables, by multiplying the integer variables with the maximum charge/work rate. The total amount of BCHEs that can charge simultaneously is limited by the amount of charging stations that are available at that time step, denoted by constraint 28. And the amount that can work at the same time is also limited for non-automated ports by constraint 29.

$$k_t + \sum_{v \in V} H_{v,t,s} - \sum_{i \in I} W_{i,t,s} = 0, \quad \forall t \in T,\ s \in S \quad (25)$$

$$W_{i,t,s} \leq Y_{i,t,s} \cdot w_i^{lim}, \quad \forall t \in T,\ s \in S \tag{26}$$

$$P_{i,t}^{charge} \leq X_{i,t} \cdot p^{bche,ch}, \quad \forall i \in I,\ t \in T \tag{27}$$

$$\sum_{i \in I} X_{i,t} \leq cs, \quad \forall t \in T \tag{28}$$

$$\sum_{i \in I} Y_{i,t} \leq m, \quad \forall t \in T \tag{29}$$

$$X_{i,t} + Y_{i,t,s} \leq z_i \quad \forall i \in I \tag{30}$$

$$\tag{31}$$

4.5. Reefer constraints

The Reefers need to maintain a set temperature and are allowed minor fluctuation, but product health is crucial. Constraint 32 sets the relation of the internal temperature of the reefer to the loss with the outside temperature and the cooling power. Constraint 33 sets the bounds for the allowed temperature fluctuation of the content inside the refrigerated container. Furthermore it is assumed that the starting temperature and end temperature must be at the desired temperature, denoted in constraint 34.

$$T_{j,t}^{reefer} = T_{j,t-1}^{reefer} + \left(T_t^{amb} - T_{j,t-1}^{reefer}\right)\left(1 - e^{-\frac{w_j^{loss} \cdot dt \cdot sur_j}{m_j \cdot cp_j}}\right) - \frac{P_{j,t}^{reefer} \cdot dt}{m_j \cdot cp_j \cdot n_j^{reefer}}, \quad \forall j \in J,\ t > 0 \tag{32}$$

$$T_j^{des} - T_j^{tolerance} \leq T_{j,t}^{reefer} \leq T_j^{des} + T_j^{tolerance}, \quad \forall j \in J,\ t \in T \tag{33}$$

$$T_{j,0}^{reefer} = T_{j,|T|-1}^{reefer} = T_j^{des}, \quad \forall j \in J \tag{34}$$

4.6. Battery Energy Storage constraints

Similar to the constraints for the batteries of the battery handling equipment, the battery energy storage system has constraints describing the SOC transition in equation 35 and 36. Charging and discharging the battery has some efficiency loss accounted for both in the charging power increasing the SOC less and discharging decreasing the SOC more than the discharging power. The battery energy storage also starts with some initial stored capacity which needs to be the same at the end, according to constraint 37.

$$SOC_0^{bes} = SOC^{init,bes} + \frac{\eta^{bes} \cdot P_0^{bes,ch} \cdot dt}{b^{BES}} + \frac{P_0^{bes,dch} \cdot dt}{\eta^{bes} \cdot b^{BES}}, \quad t = 0 \tag{35}$$

$$SOC_t^{bes} = SOC_{t-1}^{bes} + \frac{\eta^{bes} \cdot P_t^{bes,ch} \cdot dt}{b^{BES}} + \frac{P_t^{bes,dch} \cdot dt}{\eta^{bes} \cdot b^{BES}}, \quad t > 0 \tag{36}$$

$$SOC_{|T|-1}^{bes} = SOC^{init,bes} \tag{37}$$

4.7. First and second stage variables

Similar to real life decision making, not every decision can be made real-time. For example it is not certain when exactly the ship will arrive. To account for this uncertainty it is preferred to make decisions that would hold up for all possible scenarios that could come along. The decisions that can be made for the next day can be: when to charge the container handling equipment; when to charge or discharge the battery; when to cool the reefers. The second stage variables can also be interpreted by the index s under the variables, denoting a changing variable for every scenario.

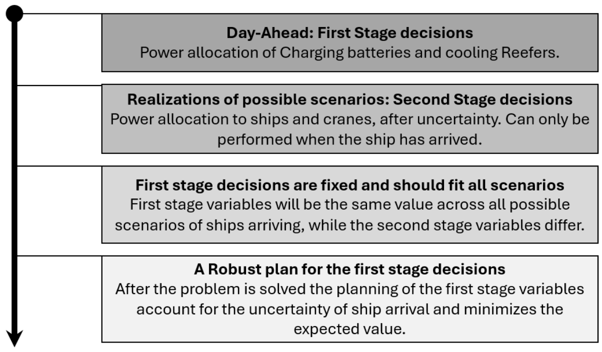

Figure 3: Timeline of two stage optimization

The allocation of power during the first stage is further described in Figure 3. For the day ahead, considering the electricity price and temperature, the power supplied to the batteries from the equipment and the stand-alone BES, as well as the cooling of reefers, is determined. This accounts for the unrealized power required by ships that need shore power and crane power for loading or unloading of these ships.

4.8. Decomposition method: Progressive hedging

Even with relatively few scenarios, solving the extensive form of such an optimization problem is not trivial [29], therefore a decomposition algorithm will be utilized to obtain a solution which will split the extensive form into smaller subproblems by scenario which can be solved significantly faster. To solve this Two-stage stochastic optimization model the progressive hedging technique will be used with mpi-sppy library [18].

Furthermore, this model implements the risk neutral approach as this gives a realistic expected cost and still enforces the constraints of the contracted capacity on the grid with a high penalty for exceeding this value. This way it minimizes for the average outcome, or expected value, while still maintaining the power constraints.

The progressive hedging algorithm decomposes the problem by scenario and uses a quadratic term to penalize a lack of consensus among the first-stage variables which all should be the same value across all the individual scenarios, i.e. subproblems. Firstly all the individual scenarios are solved, then the average first stage decisions will be calculated of each first stage variable based on the probability of each scenario and then the difference between this average and the first stage variable values across the scenarios will be penalized with a quadratic term, as can be seen in Figure 4.

Algorithm 1 The Progressive Hedging Algorithm for Two-Stage SMIPs

1: **Initialization**: Let $\nu \leftarrow 0$ and $w^\nu(\xi) \leftarrow 0, \forall \xi \in \Xi$. For each $\xi \in \Xi$, compute:

$$(x^{\nu+1}(\xi), y^{\nu+1}(\xi)) \in \underset{(x,y)\in X(\xi)}{\arg\min}\ c^\top x + g(\xi)^\top y$$

2: **Iteration Update**: $\nu \leftarrow \nu + 1$
3: **Aggregation**: $\hat{x}^\nu \leftarrow \sum_{\xi\in\Xi} p_\xi x^\nu(\xi)$
4: **Price Update**: $w^\nu(\xi) \leftarrow w^{\nu-1}(\xi) + \rho(x^\nu(\xi) - \hat{x}^\nu)$
5: **Decomposition** : For each $\xi \in \Xi$, compute:

$$(x^{\nu+1}(\xi), y^{\nu+1}(\xi)) \in$$
$$\arg\min_{(x,y)\in X(\xi)} \{c^\top x + g(\xi)^\top y + w^\nu(\xi)^\top x + \tfrac{\rho}{2}||x - \hat{x}^\nu||^2\}$$

6: If all scenario solutions $x(\xi)$ are equal, stop. Else, go to step 2.

Figure 4: Ph algorithm

In Figure 4 the progressive hedging stops until all scenario solutions are equal, however this stopping criteria can be user defined as convergence is not always guaranteed for mixed-integer problems [9]. For this model a different stopping criteria is chosen which will be discussed more in depth in the tuning chapter. It stops when the first stage variables are considered close enough to obtain quality solutions.

5. Case Study

For the implementation of the model, container terminals/depots for the inland waterway transport will be examined. To get realistic values for this model, interviews have been done with inland shipping ports in the Port of Rotterdam. The values for the case are therefore based on these small container terminals that serve inland container vessels, also known as barges, and truck transported containers.

5.1. Ships and shore power

Unlike the power demand for large cruises, container ships or RORO vessels, the demand for shore power of inland shipping vessels is much lower. The most common inland shipping vessels visiting these ports are inland container vessels, also known as larger Rhine vessels. The estimated shore power demand varies per report [3] [35] [22] [19] [2] [11] [27] [10], but will be estimated at 10 kW for these specific types of ships.

5.2. Reefers

These inland terminals or river terminals also often store reefers. The most common type of reefer here is the 40 foot refrigerated container storing frozen goods between -18 and -20 degrees, these will be assumed as upper and lower limits with a set temperature of -19. These reefers have the following common characteristics for frozen goods/meats. An average weight of 25000 kg [15], specfic heat 2.6 KJ/(Kg °C) [17], thermal insulation 0.5 W/m^2 °C [4] and a maximum cooling power of 6.0 kW [15]

5.3. Cranes

To model the estimated maximum average power for the cranes when working at its maximum rate can unfortunately not be determined by its diesel usage. Instead a simple calculation will be made to estimate its maximum average power usage. This results in a rough estimate of 42 kW per hour at its maximum handling rate of 20 containers per hour. Furthermore, for the particular terminal which schedules were used, the cranes make use of a stack underneath the crane as a well beside the more common stack in the yard. It can be assumed that about half of the containers handled by the crane will be passed along to a reach stacker as well.

5.4. Battery container handling equipment

The container handling equipment in the port will be replaced by battery electric alternatives. This specific terminal operates with 4 reachstackers. For this study a large commercially available battery size of 600 kWh [13] will be chosen because of the extended working hours. The charging speed will have an upper limit, which is the lowest charging speed that is offered for this model with a maximum charging rate of 175 kW[13] with an effiency of 95 % [13]. The reachstackers handle 20 containers per hour and an average move will be 3 kWh, based on fuel use of its hybrid counterpart. It is assumed that these batteries can charge at any rate. Furthermore, it is assumed that the amount of charging stations will be equal to the amount of battery container handling equipment which is 4. This assumption is made because most of these terminals do not operate on a 24 hour basis and the charging will have to be performed manually. Additionally, the SOC will be limited to a lower threshold of 20 % to avoid a too high depth of discharge, similar to what is done in literature.

5.5. Battery Energy Storage

As there currently is no battery energy storage system installed at these ports, again values will be determined based on literature and what currently is available. The BES is sized at 200 kW / 400 kWh to match the port's current contracted capacity while enabling load shifting and peak shaving for anticipated future electrification. The BES has a round trip efficiency of 90 % [33], which corresponds with an efficiency η^{bes} of 0.95.

5.6. Ship arrivals and uncertainty

From the Estimated Time of Arrivals (ETA) and Actual Time of Arrivals (ATA) gathered at these terminals the delay was calculated. As the gathered data size is not significantly large a distribution will be fitted to remove roughness and remove outliers. These distributions were fitted with the fitter library [7] and scipy distributions [36] were tested with the Sum Squared Error (SSE), Akaik Information Criterion (AIC), Bayesian Information Criterion (BIC), and Kolmogorov Smirnov (KS) test. The top 10 best fitting distributions can be found in Table **??** in appendix A. The generalized normal distribution is chosen for this thesis to simulate the delay from the estimated time of arrival.

From this distribution will be sampled to create possible arrival scenarios of these ships. However, not all ship arrivals are possible by just sampling delays from this distribution, either because they would arrive outside working hours or arrive outside of the time range of this model. To counteract this the distribution will be truncated in these edge cases to fit inside the range of working hours 38. This sampling will be performed a 100 times to build an estimate and not become to computationally expensive.

$$f^{PDF}_{X|a\leq X\leq b}(x) = \begin{cases} \dfrac{f_X(x)}{F_X(b) - F_X(a)}, & a \leq x \leq b \\ 0, & \text{otherwise} \end{cases}, \quad F^{CDF}_{X|a\leq X\leq b}(x) = \begin{cases} 0, & x < a \\ \dfrac{F_X(x) - F_X(a)}{F_X(b) - F_X(a)}, & a \leq x \leq b \\ 1, & x > b \end{cases} \tag{38}$$

A medium and heavier operational working day have been chosen with their respective ETAs to generate the uncertain arrivals on and to depict different operational levels of the terminal. This will also have influence on total energy use, charging times and cooling opportunities.

5.7. *Electricity pricing and weather*

In addition to the ship arrival scenarios that can occur within a day and within the optimization, different electricity prices and temperature conditions will also be considered. To generate unique weather and day-ahead electricity pricing scenarios, k-means clustering will be performed using the scikit-learn library [28], which utilizes equation 39.

$$\arg\min_{C} \sum_{i=1}^{n} \min_{\mu_j \in C} \|x_i - \mu_j\|^2 \tag{39}$$

To achieve this, the hourly historical temperature data for Rotterdam in 2024 from the Royal Netherlands Meteorological Institute (KNMI) [16] is used alongside the day-ahead prices of 2024 from ENTSO-E [5]. Only the weekdays will be selected as the specific port usually does not operate during the weekend. The electricity price and temperature are scaled using the robust scalar from scikit-learn and then jointly clustered according to their hourly profile 24-hour arrays. The amount of clusters is based on the elbow method and the silhouette score and results in three unique clusters. The clustered electricity prices and temperatures can be seen in Figure 5 and Figure 6, showing which hourly profiles fit into their respective clusters.

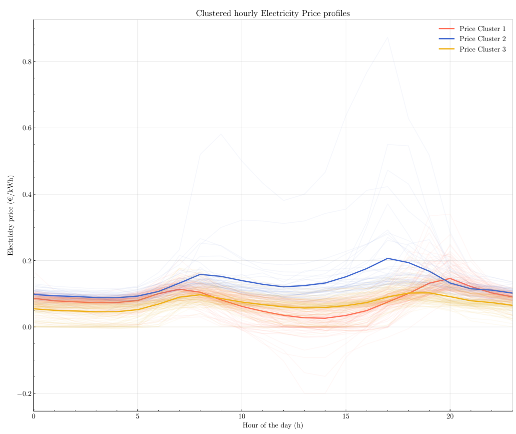

Figure 5: Overview of selected hourly electricity profiles

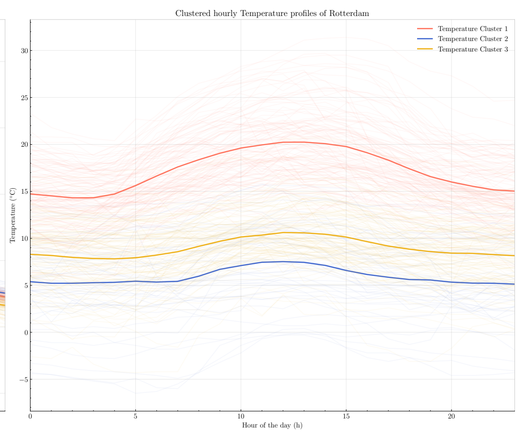

Figure 6: Overview of selected hourly temperature profiles

The mean values of the clustered groups are chosen as to not neglect the outliers present in one of the groups for electricity price. To this electricity price additional levies and taxes will be added which are present in the Netherlands.

6. Progressive hedging tuning

The Progressive hedging algorithm parameters needs to be tuned to a specific problem and case, for its penalty term and stopping criteria. The chosen stopping criteria for the progressive hedging algorithm is a convergence metric gap of 1x10^{-5} specified in equation 40. This equation gives the distance between the common or average non-anticipative variables $\bar{x}_n$ (i.e. first stage variables) and the non-anticipative variables used in every scenario $x_{s,n}$ divided by the total number of scenarios, as in this case each scenario is equally likely.

$$\bar{x}_n = \frac{1}{|S|} \sum_{s \in S} x_{n,s}, \quad CM = \frac{1}{|S|} \sum_{s \in S} \left[\frac{1}{N_f} \sum_{n \in N_f} \left| x_{n,s} - \bar{x}_n \right| \right] \tag{40}$$

Choosing proper values for the penalty term is not an easy endeavor [37] and requires tuning. To fine tune this for every first stage variable per different scenario were running, for example weather, electricity price, operational load, with or without batteries etc, would be tedious. Because of this, consistent use of the same rhos will be used for all the generated results.

Another problem here lies in the trade-off between a high quality solution and convergence speed for this specific problem. As choosing a large penalty term rho will reach consensus faster among the first stage variables, however this does not have to be an optimal one. Choosing a smaller rho will not force consensus fast after the initial phase as the penalty size will become very small, but can reach a more optimal solution compared to higher rho starting values which could drive the solution towards suboptimal solutions [41]. With these characteristics in mind, an increasing rho value approach [41] has been chosen as specified in equation 41.

$$\rho^{k+1} = \tau_\rho \cdot \rho^k, \quad \tau_\rho \geq 1 \tag{41}$$

- The starting ρ^0 penalty has been set to 1x10^{-4} for every variable.
- With each iteration the rho penalty will be increased with a factor τ_ρ of 1.04.
- Iterations stop when the convergence metric of 1x10^{-5} has been reached.

Furthermore, progressive hedging does not give an optimality gap as this is a heuristic algorithm. However, it does give a Trivial Bound (TB), which is the objective value of the scenarios in the list without enforcing non-anticipativity, meaning optimization of the individual scenarios with perfect information. It can be interpreted as the average of all individually optimized scenarios. This does not give a very tight lower bound which can be used to compare the solution with, as it does not solve the exact same problem. It does give the objective value of what can be achieved with real-time perfect information, which is also known as Wait and See (W&S), referring to no decisions being made before others and all information known simultaneously. To obtain a more realistic lower bound to quantify the performance of the model, multiple runs will be made for an average day where the full extensive form is run for an extended duration to obtain a lower bound it has computed in this time, similar as done by Watson and Woodruff [37].

$$\textbf{Given:} \quad \bar{x}_n = \frac{1}{|\mathcal{S}|}\sum_{s\in\mathcal{S}} x_n^s, \quad \sigma_n = \sqrt{\frac{1}{|\mathcal{S}|}\sum_{s\in\mathcal{S}}(x_n^s)^2 - \bar{x}_n^2}, \tag{42}$$

Compute for each scenario $s \in \mathcal{S}$:

$$d(s) = \sum_{n\in\mathcal{N}} \min\left(3, \frac{|x_n^s - \bar{x}_n|}{\sigma_n}\right), \tag{43}$$

$$\textbf{Select:} \quad s^* \in \arg\min_{s\in\mathcal{S}} d(s), \tag{44}$$

$$\textbf{Define:} \quad \hat{x} := x^{s^*}, \text{by resolving the model for scenario } s^*. \tag{45}$$

Finally, the xhatclosest extension from mpisppy [18] was used to obtain a final xhat result, which utilizes a truncated z-score and obtains these values according to steps depicted in equations 42, 43, 44, and 45. It will choose the first-stage variable from scenario s which is closest to the value of $\bar{x}$, this will give a more numerically stable feasible outcome for this model compared to directly using $\bar{x}$. Afterwards it is checked that all scenarios are feasible given the nonanticipativity variables.

7. Results and Discussion

With the container terminal's current contracted capacity, full electrification is not feasible. For this transition to full electrification an approach is made to determine the required contracted capacity. For this the contracted capacity will be set as a variable. An overview of the different electricity price and temperature scenarios analyzed can be found in Table 5.

Scenario	Electricity Price	Temperature
Scenario 1	Fixed EP (0.239 €/kWh Eurostat)	Cluster 1 Temp. (17.20 °C Avg.)
Scenario 2	Fixed EP (0.239 €/kWh Eurostat)	Cluster 2 Temp. (5.94 °C Avg.)
Scenario 3	Fixed EP (0.239 €/kWh Eurostat)	Cluster 3 Temp. (8.97 °C Avg.)
Scenario 4	Cluster 1 EP (0.18 €/kWh Avg.)	Cluster 1 Temp. (17.20 °C Avg.)
Scenario 5	Cluster 2 EP (0.24 €/kWh Avg.)	Cluster 2 Temp. (5.94 °C Avg.)
Scenario 6	Cluster 3 EP (0.17 €/kWh Avg.)	Cluster 3 Temp. (8.97 °C Avg.)

Table 5: Electricity price and temperature scenarios

Before continuing a comparison will be made to assess the quality of the results obtained with the progressive hedging method by running the extensive form for 3 hours per scenario, notating the best incumbent and the associated gap and compare it with the solution from progressive hedging algorithm. In table 6 the difference between the objective value obtained from the progressive hedging algorithm and the extensive form of the problem can be seen. The gap between the optimal solution found in the extensive form and the progressive hedging is determined and the optimal gap in the Extensive Form (EF) solution is denoted.

Config	Scenario	OBJ PH (€)	OBJ EF (€)	Opt. Gap EF-PH	EF gap
No BES, Flex Reef	Scenario 1	1140.82	1140.14	0.060 %	0.02 %
	Scenario 2	917.37	916.16	0.13 %	0.02 %
	Scenario 3	977.15	976.40	0.077 %	0.02 %
	Scenario 4	778.15	777.73	0.054 %	0.02 %
	Scenario 5	844.73	844.18	0.065 %	0.00 %
	Scenario 6	673.22	672.86	0.053 %	0.00 %
With BES, Flex Reef	Scenario 1	1140.80	1140.11	0.061 %	0.02 %
	Scenario 2	916.76	916.15	0.067 %	0.02 %
	Scenario 3	977.27	976.40	0.089 %	0.02 %
	Scenario 4	776.81	776.20	0.078 %	0.02 %
	Scenario 5	845.15	844.14	0.12 %	0.00 %
	Scenario 6	673.72	672.86	0.13 %	0.00 %

Table 6: Comparison PH results and solved EF

Given the reasonable results of the progressive hedging algorithm for an average working day it will be used for further analysis. The aforementioned electricity price scenarios and temperature scenarios as well as the hottest day of 2024 in Rotterdam were analyzed for heavy operational days. These were performed to determine the necessary capacity for a traditional continuous electric contracted capacity as well as a Time Constraint Transport Right (TCTR) contract on top of the existing contracted capacity. Full results of these runs can be found in the appendix.

	No BES, Fix reef	BES, Fix reef	No BES, flex reef	BES, flex reef
Fixed pricing	300 kW	300 kW	300 kW	300 kW
Dynamic pricing	320 kW	360 kW	440 kW	455 kW

Table 7: Capacities, for chosen configurations

From these runs the capacities were determined requiring at least enough to sustain the heaviest combination or using more when it is considered beneficial, in the case of dynamic pricing. Then the capacity is based on the weighted average. It can be observed that for fixed electricity pricing it aims to minimize DSO costs relating to fees for contracted capacity and maximum power used, while for dynamic electricity pricing it is more beneficial to use more power during times with lower prices, despite the higher DSO costs. Now with these given capacities for their respective configurations the average daily costs throughout the year can be calculated using the generated scenarios for an average working day. Table 8 present these results for their configuration and cluster and the resulting weighted average.

	No BES, Fix reef	BES, Fix reef	No BES, Flex reef	BES, Flex reef
Fixed pricing				
Cluster 1	€ 1156.95	€ 1159.86	€ 1147.20	1147.69
Cluster 2	935.54	937.73	926.76	926.76
Cluster 3	995.08	997.33	985.95	985.94
Weighted Avg.	1056.36	1058.89	1047.01	1047.22
Dynamic pricing				
Cluster 4	861.72	839.60	800.22	803.84
Cluster 5	904.30	892.36	853.78	867.76
Cluster 6	705.01	703.90	686.47	702.84
Weighted Avg.	806.50	794.39	763.86	774.24

Table 8: Results for chosen configurations and contracted capacities

All the first stage power decision are plotted for a scenario in Figure 7. In these pictures the top left plot depicts the total power used for each of these scenarios, its mean, minimum and maximum along with the electricity price for that scenario. The other three plots display the scheduled first stage power decisions, with the top right plot showing the power the reefers use and its internal temperature. The bottom left plot displaying the charging throughout the day and the aggregated SOC. The bottom right plot shows the charging, discharging and change in charge if applicable. It can be seen that not explicitly disallowing simultaneous charging and discharging of the BES can lead to an outcome doing just that. The reason for this is that the BES will be used in the first iteration when each scenario is solved individually, but these scenarios differ quite significantly so the charging and discharging will be penalized. However, these are acting as two different variables so when they are pushed to a common first stage value they can overlap. Furthermore, from this figures it can be seen that the battery capacity for the BCHE is on the high end as its not fully utilizing the range of its SOC. Other battery capacities for these BCHE can be tested using this model, but it should be noted that this is an aggregated SOC so some play within this range is desired. Additionally, even the lowest offered charging speed for this reach stacker brand is on the high end for this container terminal and could possibly get away with slower charging stations if possible.

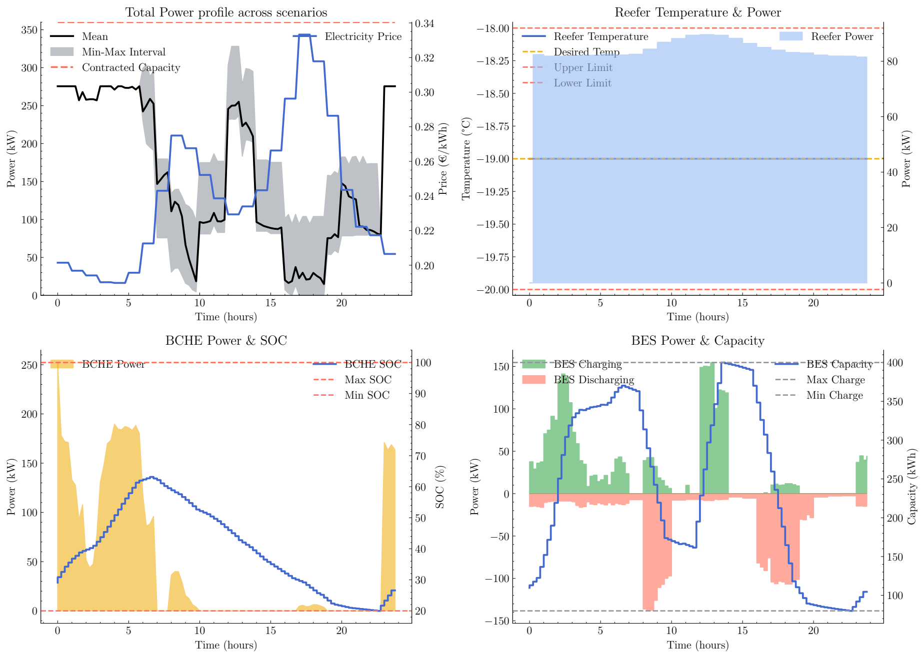

Figure 7: Dynamic electricity price cluster 5, fixed reefers, with battery energy storage

To summarize these results, currently dynamic electricity pricing is always the better option, as given in percentages in Table 9 and Table 10. No BES and no flexible reefer cooling will be set as base case, from which the other configurations are compared percentage wise. Furthermore, flexible cooling of reefers will be the best load shifting option given the possibility.

Fixed EP	No BES	with BES
No Flexible Reefer	0.0 %	+0.24%
With Flexible Reefer	-0.89 %	-0.87 %

Table 9: Case 2, Fixed EP

Dynamic EP	No BES	with BES
No Flexible Reefer	-23.65 %	-24.80%
With Flexible Reefer	-27.69 %	-26.71 %

Table 10: Case 2, Dynamic EP

A similar approach is taken for assessing the required additional capacity between 00:00 and 06:00 on top of the original 200 kW contracted capacity. Table 11 depicts the necessary extra capacity, from which it can be seen that this contract would not work for reefers that can not flexibly cool during the day. This is due to the combined power of still having to cool reefers during for example ship arrivals and crane operation, which will exceed the contracted capacity.

	No BES, Fix reef	**BES, Fix reef**	**No BES, flex reef**	**BES, flex reef**
Fixed pricing	-	-	300 kW	300 kW
Dynamic pricing	-	-	300 kW	300 kW

Table 11: Extra capacity necessary for chosen configurations

For the TCTR the same plot is made to compare the difference between total power usage and how the first stage powers are scheduled. It can be seen that battery container handling equipment, reefers as well as BES will use as much power during this time with extra capacity to compensate for the rest of the day.

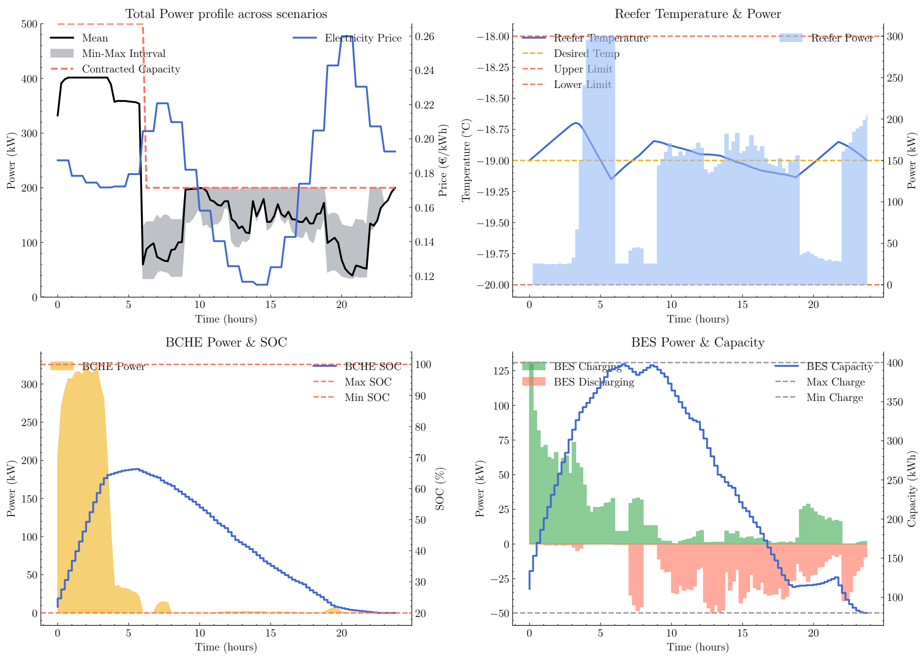

Figure 8: TCTR, Dynamic electricity price cluster 4, flexible reefers, with battery energy storage

However, this TCTR does not give enough incentive for container terminals to change their scheduling this drastically as can be seen in Table 12 and Table 13. The percentage in these tables are compared against the no BES, no flexible cooling in Table 9. The TCTR contract performs slightly worse compared to the traditional fixed contracted capacity.

Fixed EP	No BES	with BES
With Flexible Reefer	-0.16 %	+0.14 %

Table 12: TCTR, Fixed EP

Dynamic EP	No BES	with BES
With Flexible Reefer	-24.0 %	-23.9 %

Table 13: TCTR, Dynamic EP

8. Conclusions

This paper aims in assisting container terminals towards fully electrifying, by scheduling powers such as charging batteries and cooling of reefers to ensure the container terminal stays within its contracted capacity even with uncertain arrival of ships. This contracted capacity can be optimized with this model for a terminals configuration by considering the fees from the DSO to determine an appropriate capacity by analyzing multiple scenarios. It is found that with current electricity prices, the dynamic electricity pricing is always more beneficial despite the slightly higher DSO costs by utilizing a higher contracted capacity, which would put more strain on the grid in the Netherlands. However, these fees could increase in the future as the electric infrastructure in the Netherlands is increasing and grid congestion becomes a larger topic. The TCTR contract aimed at providing power outside peak-hour demand, often between 00:00-06:00 would also come with an incentive in the form of a reduction in DSO fees. For this specific terminal this reduction is not enough to consider this type of contract, especially as it also involves significant load shifting and would likely choose for a larger continuous contracted capacity. For avoiding local grid congestion, adjustments in power behavior would need more incentive to avoid businesses using simultaneous power during for example times with low electricity prices.

9. Appendix

Config.	Scenario	OBJ (€)	CC (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Flex Reef	Scenario 1	1270.49	257.40	1260.60	4.86×10^{-6}	270
	Scenario 2	1046.65	218.88	1037.10	9.53×10^{-6}	302
	Scenario 3	1107.13	229.25	1097.18	7.11×10^{-6}	268
	Scenario 4	864.96	586.47	858.30	9.76×10^{-6}	301
	Scenario 5	980.30	364.09	977.80	8.26×10^{-6}	225
	Scenario 6	766.24	313.25	762.31	9.23×10^{-6}	253
With BES, Flex Reef	Scenario 1	1270.61	255.23	1260.60	9.22×10^{-6}	305
	Scenario 2	1046.80	217.37	1037.10	6.13×10^{-6}	316
	Scenario 3	1106.98	227.61	1097.18	8.16×10^{-6}	310
	Scenario 4	863.53	622.47	846.89	9.53×10^{-6}	317
	Scenario 5	980.25	376.68	961.55	7.54×10^{-6}	376
	Scenario 6	767.04	306.33	756.63	7.42×10^{-6}	333

Table 14: Heavy operation level results grouped by their configurations 1 of 2, continous contract

Config.	Scenario	OBJ (€)	CC (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Scenario 1	1277.52	246.04	1271.87	8.92×10^{-6}	279
	Scenario 2	1052.95	208.41	1046.78	6.58×10^{-6}	296
	Scenario 3	1113.36	218.54	1107.26	1.67×10^{-6}	336
	Scenario 4	932.33	417.10	925.89	7.90×10^{-6}	264
	Scenario 5	1031.73	254.46	1029.75	7.27×10^{-6}	150
	Scenario 6	788.69	240.75	785.90	4.66×10^{-6}	242
With BES, Fix Reef	Scenario 1	1277.23	246.43	1271.26	1.94×10^{-6}	341
	Scenario 2	1052.96	208.70	1046.31	8.75×10^{-6}	289
	Scenario 3	1113.31	218.84	1106.75	7.77×10^{-6}	322
	Scenario 4	904.77	463.97	897.09	9.37×10^{-6}	264
	Scenario 5	1009.67	293.90	1003.74	8.36×10^{-6}	258
	Scenario 6	781.98	288.24	776.69	9.55×10^{-6}	254

Table 15: Heavy operation level results grouped by their configurations 2 of 2, continuous contract

Config.	Electricity price	OBJ (€)	CC (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Fixed	1437.47	273.42	1434.00	7.79×10^{-6}	273
	Dynamic	1011.81	522.55	1004.67	9.40×10^{-6}	250
With BES, Fix Reef	Fixed	1437.42	273.61	1432.62	9.40×10^{-6}	295
	Dynamic	947.70	589.50	940.14	6.61×10^{-6}	315
No BES, Flex Reef	Fixed	1431.90	284.44	1421.88	9.71×10^{-6}	300
	Dynamic	875.37	655.11	868.24	8.76×10^{-6}	268
With BES, Flex Reef	Fixed	1432.00	282.31	1421.88	9.68×10^{-6}	315
	Dynamic	858.15	722.25	838.14	9.38×10^{-6}	299

Table 16: Hottest day of 2024 and heavy operation level results grouped by their configuration, continuous contract

Config.	Scenario	OBJ (€)	ECC (kW)	Max PE (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES, Fix Reef	Scenario 1	-	138.26	8.48	-	9.18×10^{-6}	102
	Scenario 2	1057.57	22.46	0.00	1048.50	3.63×10^{-7}	215
	Scenario 3	1121.55	52.03	0.00	1108.09	7.51×10^{-6}	150
	Scenario 4	-	135.74	8.48	-	9.90×10^{-6}	143
	Scenario 5	1034.36	71.25	0.00	1027.98	2.76×10^{-6}	33
	Scenario 6	794.03	49.55	0.00	785.77	1.98×10^{-6}	147
With BES, Fix Reef	Scenario 1	1305.50	149.94	0.00	1279.39	1.63×10^{-8}	182
	Scenario 2	1061.24	10.37	0.00	1048.22	2.72×10^{-7}	224
	Scenario 3	1127.39	43.4	0.00	1107.81	9.38×10^{-7}	202
	Scenario 4	991.04	211.22	0.00	960.04	1.77×10^{-7}	237
	Scenario 5	1025.82	165.81	0.00	1001.48	9.24×10^{-6}	63
	Scenario 6	794.35	189.57	0.00	776.35	1.50×10^{-6}	124
No BES, Flex Reef	Scenario 1	1297.40	154.34	0.00	1266.81	3.98×10^{-6}	136
	Scenario 2	1051.09	3.28	0.00	1039.18	9.43×10^{-6}	200
	Scenario 3	1117.43	39.49	0.00	1098.44	6.84×10^{-6}	175
	Scenario 4	978.99	239.78	0.00	946.81	1.11×10^{-6}	211
	Scenario 5	988.61	249.92	0.00	977.28	6.72×10^{-7}	110
	Scenario 6	780.53	160.17	0.00	765.35	9.33×10^{-6}	58
With BES, Flex Reef	Scenario 1	1300.87	151.30	0.00	1266.80	2.12×10^{-6}	199
	Scenario 2	1052.94	2.94	0.00	1039.18	3.51×10^{-6}	153
	Scenario 3	1120.04	38.90	0.00	1098.43	9.81×10^{-6}	177
	Scenario 4	976.95	268.10	0.00	944.60	5.92×10^{-6}	279
	Scenario 5	998.97	338.45	0.00	959.29	2.56×10^{-6}	138
	Scenario 6	785.10	229.24	0.00	760.61	3.02×10^{-6}	132

Table 17: Heavy operation level results grouped by their configurations for TCTR contracts

Config.	Elec. price	OBJ (€)	ECC (kW)	Max PE (kW)	TB/W&S (€)	CM Gap	# Iter.
No BES,	Fixed	-	135.53	45.54	-	1.98×10^{-6}	132
Fix Reef	Dynamic	-	128.64	45.54	-	7.15×10^{-6}	128
With BES,	Fixed	-	251.36	36.62	-	9.66×10^{-6}	319
Fix Reef	Dynamic	-	249.15	36.62	-	2.22×10^{-6}	295
No BES,	Fixed	1483.32	325.16	0.00	1442.97	9.93×10^{-6}	188
Flex Reef	Dynamic	1153.11	320.66	0.00	1096.55	7.59×10^{-6}	126
With BES,	Fixed	1480.22	275.22	0.00	1442.96	2.91×10^{-6}	235
Flex Reef	Dynamic	1136.57	339.59	0.00	1090.62	5.57×10^{-6}	207

Table 18: Hottest day of 2024 and heavy operation level results grouped by their configuration, TCTR contracts

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